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Building A Sustainable Future

How Energy Retrofits Are Reshaping The Construction Industry

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Building A Sustainable Future : How Energy Retrofits Are Reshaping The Construction Industry

Abstract

Residential construction accounts for roughly 40% of final energy use and greenhouse gas emissions within the European Union. Consequently, since the 1970s, public policy has aimed to improve the energy efficiency of dwellings, through regulation and public aid schemes. While these programmes were initially intended to reduce energy import dependency, beginning in the 2000s, environmental challenges started becoming an increasing focus, with energy poverty becoming an additional area of concern in the 2010s. These three objectives translated into increasingly ambitious regulatory and incentive programs regulating new constructions and renovations. In practice, they encouraged industrial actors to improve building materials, and tried to stimulate households into commissioning renovations through financial aid.

This dissertation examines the web of economic relations these programmes have drawn between these different actors, and how they've impacted policy objectives, by focusing specifically on the role of construction firms. Indeed, construction firms occupy a crucial intermediary position between households who rely on their labor and expertise, industrial actors developing technical solutions, and the governmental institutions seeking to deploy policies. The construction sector thus stands out as a locus of problems and opportunities when it comes to bettering Europe's construction sector's energy efficiency along the three priorities outlined above : energy efficiency, sovereignty, and poverty.

The construction market is both highly fragmented and competitive : very small firms represent 99% of the firms in the market, and strikingly account for more than 2/3rds of full-time equivalent jobs and value added. Regulating this market, however, can prove surprisingly difficult, not least because it is difficult for consumers to assess whether they are receiving quality services or not : in most cases households cannot precisely identify their needs, nor implement the appropriate technical solution themselves, creating information asymmetries augmented by the lack of quality signals. These market failures can lead to fraud and poor workmanship that can undermine the effectiveness of energy renovations. This thesis explores how renovations are supplied to the market, focusing on European and

French policy from 2010 to 2020, underlining the role of upskilling, promoting innovations and removing financial barriers for households. The first chapter presents theoretical insights on the impact of information asymmetries. The second and third chapters explore the dynamics of innovation diffusion among contractors with contrasting approaches. The fourth and final chapter evaluates the efficiency of retrofits, relying on panel data on French policies and households.

Keywords : Energy efficiency, Energy retrofits, Innovation, Information asymmetries, Policy evaluation, Spatial econometrics.

Bâtir un avenir durable : Impact des rénovations énergétiques sur le secteur de la construction

Résumé

Le secteur de la construction est responsable de 40% de la consommation finale d'énergie et des émissions de gaz à effet de serre dans l'Union européenne. Depuis les années 1970, les politiques publiques visent en conséquence à améliorer l'efficacité énergétique des logements, par le biais de réglementations et de programmes d'aide publique. Bien que ces programmes soient initialement destinés à réduire la dépendance aux importations d'énergie, à partir des années 2000, les défis environnementaux ont commencé à prendre de plus en plus d'importance, la pauvreté énergétique devenant un sujet de préoccupation supplémentaire dans les années 2010. Ces trois objectifs se sont traduits par des programmes réglementaires et incitatifs de plus en plus ambitieux régissant les nouvelles constructions et les rénovations. En pratique, ils ont encouragé les acteurs industriels à améliorer les matériaux de construction et ont tenté d'inciter les ménages à entreprendre des rénovations par le biais d'aides financières.

Cette thèse de doctorat examine les relations économiques que ces programmes ont tissées entre ces différents acteurs, et la manière dont elles ont influencé les objectifs politiques, avec une emphase sur le rôle des entreprises de construction. Ces entreprises occupent une position clé d'intermédiaire entre les ménages, qui comptent sur leur travail et leur expertise, les acteurs industriels qui développent des solutions techniques et les institutions gouvernementales qui cherchent à déployer des politiques. Le secteur de la construction est donc à la croisée de problèmes et d'opportunités vis-à-vis des trois priorités décrites ci-dessus : l'efficacité, la souveraineté et la précarité énergétiques.

Le marché de la construction est à la fois très fragmenté et très concurrentiel : les très petites entreprises représentent 99% du marché et, fait frappant, et sont surtout responsables de plus de deux tiers des emplois équivalents temps plein et de la valeur ajoutée. La régulation de ce marché peut toutefois s'avérer complexe, notamment parce qu'il est difficile pour les consommateurs d'apprécier la qualité des services qu'ils reçoivent : dans la plupart des cas, les ménages ne peuvent ni identifier précisément leurs besoins, ni évaluer la qualité de la solution technique apportée, ce qui crée des asymétries d'information renforcées par l'absence de signaux de qualité fiables. Ces défaillances de marché peuvent conduire à des malfaçons nuisant à l'efficacité des rénovations énergétiques. Cette thèse explore l'offre de rénovations, en se concentrant sur les enjeux des politiques européennes et françaises de 2010 à 2020 : montée en compétence, soutien à l'innovation et aides financière aux ménages. Le premier chapitre présente des apports théoriques sur l'impact des asymétries d'information. Les deuxième et troisième chapitres explorent les dynamiques diffusion des innovations avec des approches complémentaires. Le quatrième et dernier chapitre évalue l'efficacité des rénovations en pratique, en exploitant des données de panel sur le contexte français.

Mots Clés : Efficacité énergétique, Rénovation énergétique, Innovation, Asymétries d'information, Evaluation de politique publique, Econométrie spatiale.

Résumé détaillé

Le secteur résidentiel est actuellement au cœur des politiques environnementales et énergétiques. Il est responsable d'environ 30% de la consommation finale d'énergie en France (CGEDD 2020), et la rénovation des bâtiments est nécessaire pour permettre de combler l'écart d'efficacité énergétique entre les anciennes et nouvelles constructions. Le stock immobilier français est composé d'environ 35 millions de logements, dont 60% ont été construits avant toute réglementation thermique (Insee 2021). A partir des chocs pétroliers des années 1970, la performance thermique des logements a fait l'objet de réglementations et d'aides publiques, avec un objectif d'indépendance énergétique suite à l'inflation des prix de l'énergie au niveau mondial. Les enjeux environnementaux, comme la réduction des émissions de gaz à effet de serre du secteur, ont été intégrés à ces politiques au début des années 2000, au niveau européen et en France avec le Programme National de Lutte Contre le Changement Climatique (PNLCC). Enfin, la décennie 2010 a vu l'émergence de politiques visant plus particulièrement les ménages modestes et la précarité énergétique. En pratique, ces trois objectifs se déclinent en réglementations et programmes incitatifs de plus en plus ambitieux, encadrant la construction neuve et la rénovation. Les acteurs industriels sont poussés à améliorer la performance des matériaux de construction pour suivre les évolutions réglementaires et les ménages sont aidés dans le financement des travaux. Bien qu'ils soient les cibles finales de ces politiques et de ces innovations, les ménages doivent toutefois recourir à des entreprises de construction pour en bénéficier.

Ces entreprises occupent ainsi une place d'intermédiaire entre les ménages et les acteurs industriels développant des solutions techniques, ainsi que les institutions gouvernementales. Le marché de la construction est par ailleurs très fragmenté et compétitif : les très petites entreprises représentent 99% des entreprises du marché, mais comptent surtout pour plus de 2/3 des emplois en équivalent temps plein et de la valeur ajoutée hors taxe (Insee 2017). A titre de comparaison, le secteur industriel français est également composé de 99% de petites structures, mais elles ne représentent que 1/3 des emplois et de la valeur ajoutée. A cette fragmentation s'ajoutent des asymétries d'information et un manque de signaux *ex ante* indiquant la compétence des entreprises pour les ménages. Les entreprises jouent ainsi un rôle d'expert auprès des ménages, qui dans la plupart des cas ne peuvent ni identifier précisément leurs besoins, ni mettre en œuvre la solution technique appropriée. Cette situation d'information imparfaite peut entraîner de la fraude et des malfaçons nuisant à l'efficacité des rénovations énergétiques. Cette thèse vise à explorer l'offre de rénovations, en s'appuyant sur les piliers de la politique européenne et le contexte français de 2010 à 2020. Comment engager la montée en compétence du secteur pour s'assurer de l'efficience

des rénovations ? Comment le marché réagit-il à l'introduction d'innovations techniques ? Les politiques publiques d'aide aux ménages ont-elles entraîné des économies d'énergie substantielles en pratique ?

Montée en compétence

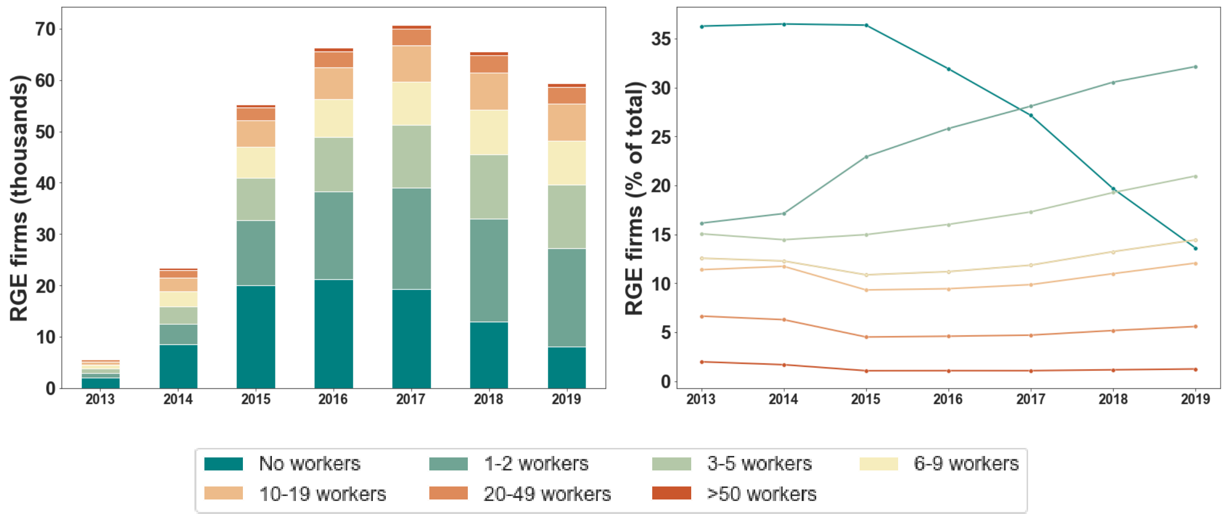
Les objectifs de massification des rénovations énergétiques efficientes nécessitent une montée en compétence du secteur. Il y a donc un besoin de formation et de requalification des professionnels du bâtiment, notamment en ce qui concerne l'isolation et l'installation d'équipements producteurs d'énergie renouvelable. Selon les rapports publiés à la suite du "*Green Deal*" européen de 2019, environ 120 milliers d'emplois dans le secteur de la construction devront être requalifiés au cours des cinq prochaines années pour atteindre les objectifs de rénovation. De nouveaux emplois liés à l'efficacité énergétique doivent être créés, tandis que les compétences traditionnelles sont amenées à être profondément transformées. L'Observatoire Européen du Secteur de la Construction (ESCO) a ainsi estimé que 35% des travailleurs ont vu leur travail quotidien changer radicalement au cours des cinq dernières années, en raison de l'apparition de nouveaux matériaux, de nouvelles techniques et de nouvelles machines. Cette tendance devrait se poursuivre : "*Skills needed in construction are likely to change to meet demands for "green" and energy efficient buildings that follow new designs and use new materials, as well as digitization trends. [...] Demand for people with high-level qualifications could double, to account for one third of all jobs in construction by 2025*" [1]. La demande de formation professionnelle continue est cependant relativement faible par rapport à d'autres secteurs. Cela peut s'expliquer par la nature concurrentielle du marché de la construction, dominé par de petites entreprises : "*hours spent on training can be perceived especially by small and micro enterprises as a loss of working hours, with no guarantee of return on investments. The economic crisis has put many SMEs in "survival" mode, forcing them to prioritize short-term work over long-term investments*" [2].

Les travailleurs très qualifiés devenant de plus en plus difficiles à trouver, il est nécessaire de créer des signaux de qualité pour les consommateurs finaux afin de minimiser le risque

1. ECSO 2020b, p33. On peut le traduire par : "*Les compétences requises dans la construction vont probablement évoluer pour répondre à la demande de bâtiments "verts" et économes en énergie, avec de nouvelles conceptions et utilisant de nouveaux matériaux, ainsi qu'en réponse aux tendances en matière de numérisation. [...] La demande de travailleurs possédant des qualifications de haut niveau pourrait doubler, pour représenter un tiers de tous les emplois dans la construction d'ici 2025*"

2. ECSO 2020b, p51 ; "*Les heures consacrées à la formation peuvent être perçues, en particulier par les petites et micro-entreprises, comme une perte d'heures de travail, sans garantie de retour sur investissement. La crise économique a mis de nombreuses PME en mode "survie", les obligeant à donner la priorité au travail à court terme plutôt qu'aux investissements à long terme*".

de malfaçons. En France, divers labels ont été mis en place, en commençant historiquement par les nouvelles constructions puis ciblant les entreprises. La labélisation des entreprises a été initiée par la création de l'agence *Qualit'EnR* en 2006. Son objectif était de mettre en place des labels signalant des professionnels hautement qualifiés, afin de stimuler le développement des compétences sur le marché. La marque "*Eco-Artisan*" a ainsi été lancée deux ans plus tard par la CAPEB, la principale fédération patronale des petites entreprises du bâtiment. En parallèle, la Fédération française du bâtiment (FFB) a créé le label "*Pros de la performance énergétique*" sur le même modèle. Ces deux certifications mettaient en avant des entrepreneurs capables d'évaluer l'efficacité énergétique des logements, de conseiller précisément leurs clients et de réaliser les travaux de rénovation.



Sources :Données de l'ADEME et de l'Insee.

Note : L'axe des ordonnées indique le nombre d'entreprises RGE pour chaque année, en milliers (graphique de gauche) et en proportion du nombre total d'entreprises RGE (graphique de droite) Par exemple, il y avait 8 088 entreprises RGE sans employés en 2019, ce qui correspond to à 14% des entreprises RGE.

FIGURE 1 – Evolution des entreprises RGE selon leur taille (2013-2019)

La gestion de ces labels a été transférée à l'agence de certification Qualibat en 2010, afin de consolider les efforts de qualification du secteur par un système de labélisation unique, destiné à promouvoir l'efficacité énergétique. La charte fixant le label de référence actuel, la certification *Reconnu Garant de l'Environnement* (RGE), a été signée l'année suivante, avec un double objectif. En premier lieu, il vise à renforcer la confiance portée par les ménages aux entrepreneurs et à faciliter leurs recherches. En second lieu, il incite les entreprises à former leurs employés à l'efficacité énergétique, le label RGE ayant été dès sa création destiné à devenir réglementaire. Cela s'est concrétisé en 2013, lorsque certaines aides financières aux ménages ont été conditionnées à l'embauche d'une entreprise RGE par à la mise en œuvre de la loi dite d'"*Eco-conditionnalité des aides publiques*" votée en 2013. Le nombre d'entreprises labélisées a augmenté de façon régulière jusqu'en 2017, après une forte augmentation en 2014, avant de décliner par la suite (Figure 1).

La labélisation des entreprises est-elle suffisante pour garantir des rénovations efficaces ? D'une part, les clients ne disposent pas de signaux *ex ante* pour évaluer correctement la qualité de l'offre d'un entrepreneur. D'autre part, les entreprises peuvent ne pas avoir les compétences nécessaires pour résoudre un problème ou utiliser leur avantage informationnel pour augmenter leurs prix sans améliorer la qualité du service. L'effet de cette asymétrie d'information sur l'équilibre du marché a été approché *via* une approche théorique dans le chapitre 1. D'après Nelson (1970), les biens et les services peuvent être classés en fonction de la facilité avec laquelle les consommateurs peuvent obtenir des informations à leur sujet. Il a ainsi défini les "*search goods*" [3] comme les biens dont les attributs peuvent être observés avant la décision d'achat. Les consommateurs peuvent s'appuyer sur les informations figurant sur les étiquettes, sur leur expérience antérieure ou sur les avis d'autres utilisateurs pour prendre une décision maximisant leur utilité. C'est typiquement le cas pour la plupart des marchandises ordinaires : vêtements, produits alimentaires, etc. La catégorie des "*biens de confiance*", telle qu'elle a été définie initialement par Darby et Karni (1973), est apparue comme mieux adaptée à la provision de services de rénovation. D'une manière générale, il s'agit de toute situation dans laquelle "*customers are not able to evaluate whether information provided by the expert is accurate or not - even after purchase*" [4]. La littérature sur ces biens de confiance est vaste, puisque ces asymétries d'information s'appliquent à une grande variété de sujets : traitements médicaux, réparations de voitures, courses en taxi, conseils financiers, etc.

Dulleck et Kerschbamer (2006) ont proposé une analyse approfondie de la littérature sur le sujet et développé un cadre théorique englobant un grand nombre de ces modèles. En utilisant leurs notations, on suppose dans le chapitre 1 que les clients finaux sont définis par la nature de leur problème, qui peut être facile à résoudre (noté $\overline{c}$) ou nécessiter un traitement plus sophistiqué (noté $\underline{c}$). Ils ne connaissent pas leur propre type et doivent donc se fier au diagnostic d'un expert. Cet expert diagnostiquera $\overline{c}$ ou $\underline{c}$, et proposera de les résoudre aux prix $\overline{p}$ et $\underline{p}$ respectivement. En fonction de la structure de l'information et de la nature des institutions du marché, la fraude peut prendre plusieurs formes. Le "*sous-traitement*" renvoie à des situations où le client avait un problème complexe, auquel une

3. "*Biens normaux*".
4. Gottschalk (2018), p2 ; "*les clients ne sont pas en mesure d'évaluer si les informations fournies par l'expert sont exactes ou non - même après l'achat*".

solution simple a été apportée. En conséquence, leur problème persiste après l'intervention de l'expert. *A contrario*, le "*sur-traitement*" fait référence à des situations où un client de type $\underline{c}$ reçoit une solution de type $\overline{c}$ - par exemple un plombier qui changerait tout un système de chauffage quand la fuite ne concernait qu'un seul tuyau. Le problème initial est ainsi résolu, mais en utilisant trop de ressources. Enfin, la "*sous-facturation*" et la "*sur-facturation*" décrivent des situations dans lesquelles le client a payé le mauvais prix pour la solution qui a été effectivement mise en œuvre. Payer $\overline{p}$ tout en recevant une solution $\underline{c}$ serait une sur-facturation, et vice-versa. La sous-facturation n'est généralement pas prise en compte dans une configuration statique, mais elle peut être utilisée stratégiquement pour dissuader l'entrée de concurrents sur le marché dans un cadre dynamique. Selon ce que le consommateur peut observer avant, pendant et après l'intervention de l'expert, la fraude est plus ou moins probable et peut prendre ces différentes formes. Des stratégies peuvent par ailleurs être strictement dominantes pour l'expert du fait de la séquentialité des décisions. Ainsi, si le consommateur ne connaît uniquement pas son type, le sur-traitement est probable, mais s'il ne peut pas observer la phase de mise en œuvre ni évaluer la solution mise en place *ex post*, et si la solution $\overline{c}$ est plus coûteuse, la sur-facturation dominera.

Le modèle développé dans le chapitre 1 vise à étudier l'effet de ces asymétries d'information sur l'efficience de l'équilibre de marché, et à comparer l'impact de différentes politiques publiques en statique comparative. On suppose ici que les ménages n'ont pas les compétences nécessaires pour évaluer ni ce dont ils ont précisément besoin, ni si la solution technique figurant sur le devis a été effectivement mise en œuvre. Les entreprises sont elles-mêmes définies par leur type, qu'elles sont les seules à pouvoir observer : les professionnels "*compétents*" ($\overline{\beta}$) peuvent traiter tout type de problèmes, alors que ceux qui sont "*incompétents*" ($\underline{\beta}$) ne peuvent s'atteler qu'aux problèmes simples. L'impact de l'hétérogénéité des compétences a déjà été abordé dans la littérature, en premier lieu en supposant des différences entre les experts du point de vue de leur choix d'effort de diagnostic (Dulleck, Gong et Li 2015 ; Pesendorfer et Wolinsky 2003) ou de leurs coûts marginaux (Alger et Salanie 2006), inobservables par le consommateur. Ces contributions supposent donc que les entreprises ne diffèrent que par leur niveau d'effort et que les asymétries d'information induisent un aléa moral. Elles ont néanmoins toutes le même niveau de compétence, ce qui signifie que l'ensemble des experts peuvent résoudre tout type de problème mais qu'ils *choisissent* de mentir. Un autre courant de littérature a abordé cette question en établissant des différences explicites dans les compétences des experts, mais en supposant que leurs types étaient observables par leurs clients (Dulleck et Kerschbamer 2009 ; Bouckaert et Degryse 2000 ; Emons 2000 ; Glazer et McGuire 1996). Ces modèles trouvent des équilibres efficaces et différenciés puisque les consommateurs peuvent choisir le type de leur expert. En d'autres termes, ils prennent un risque ou non en fonction de leurs préférences et de la valeur qu'ils accordent au bien ou service en question. Cela suppose que des signes de qualité fiables existent sur le marché, ce qui n'est pas le cas pour le secteur de la construction. Des types d'entreprises inobservables ont donc été introduits dans le chapitre 1, ce qui permet d'étudier l'impact de cette hétérogénéité de compétence sur le sur-traitement et le sous-traitement d'équilibre.

Contrairement à ces contributions, le chapitre 1 suppose donc que le consommateur ne peut pas choisir le type d'entreprise approprié avant d'engager les travaux, et qu'il sélectionne au hasard des entreprises sur le marché, qui lui proposeront des devis concurrents. L'équilibre obtenu est cohérent avec les marchés du bâtiment en Europe. Les entreprises sont atomiques, les prix sont bas et non-discriminants et la fraude persiste à l'équilibre sous deux formes : les entreprises compétentes $\overline{\beta}$ sur-traitent les consommateurs qui ont des problèmes simples, et les entreprises incompétentes $\underline{\beta}$ sous-traitent les consommateurs ayant un problème complexe. L'introduction d'un label de qualité, similaire dans son fonctionnement à la certification RGE, est modélisée comme l'ajout d'un troisième type dans la formulation initiale, les entreprises compétentes labélisées ($\overline{\beta^l}$) dont le consommateur connaît le type *ex ante*. L'analyse en statique comparative indique que le label n'empêche pas l'entrée des entreprises incompétentes, et peut même la favoriser en empêchant les entreprises compétentes non-labellisées ($\overline{\beta^n}$) de sur-traiter à l'équilibre. Par contraste, augmenter la part globale d'entreprises compétentes via des barrières à l'entrée ou de la formation semble être le seul levier engageant la montée en compétence du secteur, nécessaire pour assurer la qualité des rénovations.

Diffusion des innovations

Au-delà des compétences et de l'exécution, l'efficacité énergétique des bâtiments dépend fortement de la qualité des matériaux utilisés pour les construire ou les rénover. Il n'existait pas en France de cadre législatif régulant les caractéristiques des logements avant l'implémentation de la Réglementation Thermique (RT) en 1974. Elle ne s'appliquait cependant qu'aux nouvelles constructions, pour lesquelles elle a établi les premières normes en matière d'isolation et de systèmes de chauffage. Elle a par la suite été révisée, devenant de plus en plus contraignante (1982, 1988, 2000, 2005, 2012). Un logement sur dix a néanmoins été construit avant 1949, et seulement 40% du parc de logements a été construit après 1970 (Insee 2017). En d'autres termes, une grande majorité du parc immobilier a été construite avant la mise en place de toute réglementation. Les bâtiments anciens sont nettement moins efficaces sur le plan énergétique que les constructions neuves, comme l'a notamment estimé le *Conseil national de l'information statistique* (CNIS) à partir des résultats de l'enquête "*Performance de l'Habitat, Équipements, Besoins et Usages de l'énergie*" (Phébus) en 2013. Il y a ainsi entre 7 et 8 millions de passoires énergétiques sur le territoire métropolitain, c'est-à-dire avec un Diagnostique de Performance Energétique (DPE) F ou G.

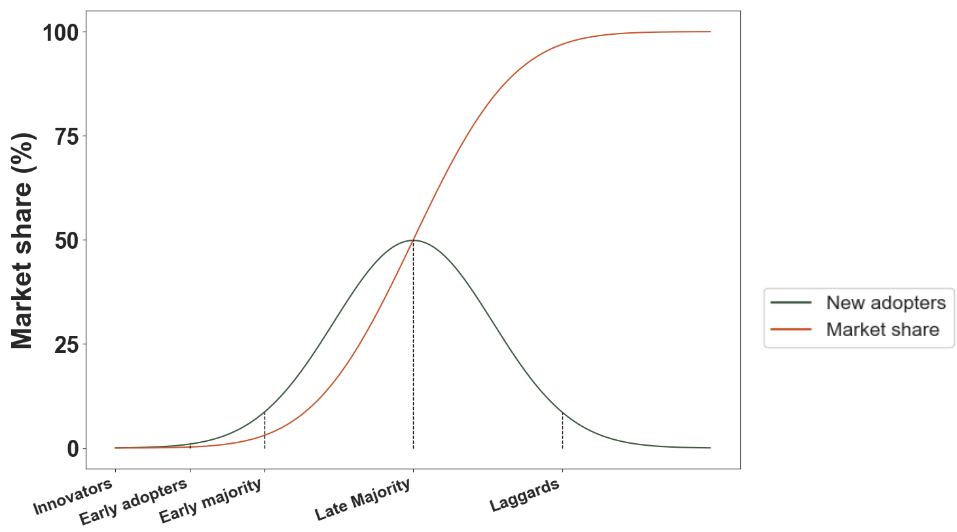
La réglementation thermique pour les bâtiments existants ne date que de 2007. Elle a en particulier défini les seuils minimaux de résistance thermique (R) devant être respectés après les travaux de rénovation d'ampleur. Ces exigences réglementaires varient toutefois en fonction de trois zones climatiques, qui ont été attribuées en fonction des températures hivernales de chaque département français. L'exigence minimale est actuellement de 2,2KW/m^2 pour une paroi latérale opaque dans la zone H3, mais passe à 2,9 dans les départements H1 dont le climat est plus froid (ADEME 2018b). L'isolation est devenue obligatoire en 2016 lorsque des travaux de rénovation importants sont entrepris, comme un ravalement de façade. L'amélioration de la qualité des matériaux et des techniques employés en rénovation est devenue essentielle, ne serait-ce que pour compenser la hausse des prix induite par les révisions des normes thermiques. Les deux réglementations thermiques ont été consolidées et remplacées par la "*Réglementation Environnementale*" (RE), applicable depuis 2022. Elle a notamment introduit l'obligation de réaliser un DPE pour vendre ou louer un bien immobilier et fixé de nouvelles exigences en matière d'isolation et de chauffage.

Les RT ont ainsi permis de contraindre les pratiques professionnelles, tout en favorisant l'émergence de nouvelles pratiques grâce à des politiques de soutien à l'innovation. La France est un pays moteur en Europe en termes de brevets liés à la construction, avec quatre entreprises françaises du secteur se classées parmi les 1 000 premières du tableau de bord de l'UE sur les investissements en R&D industrielle, à savoir Saint-Gobain, Bouygues, Tarkett et VICAT (ECSO 2022). En moyenne, les brevets liés à la construction ont représenté de 3,5 à 5,2% de toutes les dépôts par des pays de l'UE-15. L'innovation dans la construction est assez stable dans le temps, mais relativement faible par rapport à l'importance économique du secteur. À titre d'exemple, les dépenses de R&D ne représentaient que 0,1% de la valeur ajoutée annuelle en 2018 (Crépon et Charrue 2018). En outre, l'adoption de ces innovations est freinée par des barrières structurelles. Les entreprises étant généralement mises en concurrence sur leur devis, elles ont tendance à maintenir leurs coûts aussi bas que possible, ce qui rend des technologies innovantes plus onéreuses moins attrayantes. Les innovations radicales, comme le caoutchouc recyclé ou le bois lamellé-croisé, semblent avoir du mal à trouver un public, malgré leurs très bonnes performances environnementales. D'un point de vue assurantiel, les entrepreneurs sont par ailleurs responsables du bon fonctionnement à long terme des appareils et matériaux qu'ils installent. Ils ont donc tendance à privilégier des produits ayant fait leurs preuves et avec lesquels ils ont déjà travaillé. En outre, l'installation de certains nouveaux matériaux peut nécessiter des compétences issues de différents corps de métier, d'où la nécessité d'une offre de formation professionnelle actualisée pour favoriser leur diffusion. Le soutien à l'innovation dans le secteur de la construction était donc un objectif explicite du "*Plan de Rénovation Énergétique des Bâtiments*" (PREB) établi en 2018 en France, dont le budget prévisionnel consacre 40 milliards d'euros à la stimulation de l'innovation. Il a également été prévu d'affecter 30 milliards d'euros supplémentaires à la formation professionnelle, ce qui devrait à terme bénéficier à environ 65 000 travailleurs.

Il est donc essentiel de comprendre ce qu'il advient de ces nouveaux produits lorsqu'ils sont mis sur le marché : "*Innovation is more than a new idea or an invention. An innovation requires implementation, either by being put into active use or by being made available for use by other parties, firms, individuals or organizations. The economic and social impacts of inventions and ideas depend on the diffusion and uptake of related innovations*" [5] (OECD 2018). Dans la théorie standard, une innovation *positive*, par exemple qui diminuerait les coûts de production pour chaque entreprise, devrait immédiatement remplacer la technologie qui l'a précédée. Dans la pratique, cependant, la diffusion est loin d'être un processus automatique et immédiat. Tout nouveau produit comporte un risque, puisque sa performance réelle reste incertaine *ex ante*. Rogers (1962) a ainsi défini des profils de consommateurs, en fonction de la rapidité avec laquelle ils essaieront un nouveau produit une fois qu'il est mis sur le marché, allant des "*primo-adoptants*" aux "*retardataires*" (Figure 2). Sous l'hypothèse d'une distribution normale, il obtient une courbe d'adoption cumulative en forme de S, qui peut être interprétée en termes d'évolution de la part de marché que représente cette innovation. Cette courbe en S était observée empiriquement mais manquait de fondements théoriques jusqu'aux contributions de Mansfield (1963) et de Bass (1969). Le modèle épidémique de Mansfield repose sur l'hypothèse que les entreprises adoptent dès que leurs bénéfices espérés avec le nouveau produit, net du coût de l'investissement, deviennent positifs. La diffusion est donc progressive puisque les agents auraient des prix de réserve hétérogènes. Le coût de l'innovation diminuant avec le temps par économie d'échelle, son prix serait amené à baisser jusqu'à devenir inférieur au prix de réserve de plus en plus de consommateurs. Le modèle de Bass a quant à lui permis d'envisager la diffusion comme un processus autoporté. Il conditionne la pénétration du marché d'une innovation

5. OECD (2018), p44 ; "*L'innovation est plus qu'une nouvelle idée ou une invention. Une innovation doit être mise en œuvre, soit en étant utilisée activement, soit en étant mise à la disposition d'autres parties, entreprises, individus ou organisations. L'impact économique et social des inventions et des idées dépend de la diffusion et de l'adoption des innovations connexes*".

à trois paramètres : la taille du marché, le coefficient d'innovation mesurant l'impact des facteurs externes (par exemple, la publicité) sur la probabilité d'adoption, et le coefficient d'imitation mesurant l'effet du bouche-à-oreille. La probabilité d'adoption augmente ainsi à mesure les consommateurs ont accès à de plus en plus d'information *via* les primo-adoptants. Ces premiers modèles ont été amendés de différentes manières, notamment avec l'approche microéconomique de Stoneman (1981), qui suppose des entreprises maximisant leurs profits dans un cadre d'apprentissage bayésien. Des applications empiriques ont par la suite montré que les courbes de diffusion varient en fonction des caractéristiques technologiques, des contextes nationaux et des spécificités du marché.



Source : Adapté à partir de -Rogers (1962).

Note : On suppose que le nombre d'adoptants dans le temps suit une distribution normale, d'où la forme en S de la distribution cumulée.

FIGURE 2 – Diffusion des innovations selon Rogers (1962)

Les chapitres 2 et 3 abordent la diffusion des innovations techniques sur le marché de la construction avec deux approches complémentaires. Le chapitre 2 présente un modèle économétrique adapté à des données de panel, qui permet d'analyser les déterminants de la diffusion d'une nouvelle plaque de plâtre à partir de données de ventes. La notion de "*diffusion*" y est envisagée de deux manières : la diffusion "*inter-entreprises*", qui renvoie au nombre de nouveaux adoptants au fil du temps, et la diffusion "*intra-entreprise*", qui décrit l'intensité de l'utilisation par ces adoptants. Les déterminants de la diffusion inter sont les plus documentés, notamment les caractéristiques de l'entreprise (Zolas et al. 2021), les profits (DeCanio et Watkins 1998) et la structure du marché (Karaca-Mandic, Town et Wilcock 2017 ; Allen, Clark et Houde 2009). La diffusion intra semble favorisée par la taille de l'entreprise (Astebro 2004), parfois avec des effets différenciés sur la première adoption et sur l'intensité de l'utilisation (Hollenstein 2004, Arvanitis et Ley 2013 ; Battisti, Canepa et Stoneman 2009). Cette littérature porte en majeure partie sur les technologies de l'information et des communications (TIC), et de façon systématique sur des innovations concernant les moyens de production. Ces dernières sont par essence supposées réduire les coûts des entreprises, et constituent généralement des investissements de long terme. Dans le cas du secteur de la construction, la plupart des innovations sont conçues pour améliorer le confort et la sécurité des personnes résidant dans les bâtiments. Certaines innovations vont ainsi maximiser l'utilité des occupants finaux du logement, mais ce sont les entreprises qui prennent les décisions de production. Les préférences des entreprises de construction concernant les matériaux sont méconnues, alors que leur rôle d'intermédiaire est essentiel pour la diffusion de nouveaux produits sur le marché du logement. Il y a également peu de contributions s'appuyant sur des données de panel, et à ce jour aucune contribution prenant en compte le bouche-à-oreille en plus de la dimension temporelle.

Le cadre économétrique présenté dans le chapitre 2 part d'une adaptation du modèle en double obstacle de Cragg (1971) : la décision de première adoption est modélisée par une régression logistique à effets fixes, et le choix portant sur la quantité achetée prend la forme d'une régression de Poisson tronquée. Seules deux contributions ont généralisé ces modèles en double obstacles aux données de panel. Dong, Chung et Kaiser (2004) ont étendu la formalisation standard Probit-Normal de Cragg pour estimer la demande de lait, et Gillingham et Tsvetanov (2019) ont utilisé une approche Logit-Poisson à effets fixes sur les installations de panneaux solaires. Ces deux articles se sont toutefois concentrés sur des choix de consommateurs, et non sur les comportements d'entreprises. Par ailleurs, le modèle développé au chapitre 2 tient compte d'effets de bouche-à-oreille, contrairement à Gillingham et Tsvetanov (2019). La circulation de l'information a été prise en compte en étendant l'indice spatial d'adoption de R. Dubin (1995) à une configuration de panel, incluse dans les deux obstacles. La décision d'adoption de chaque entreprise va ainsi impacter celle des autres, cet effet diminuant à mesure que la distance géographique entre les entreprises augmente. Ce modèle peut donc capter les effets liés à la circulation de l'information sur la diffusion du nouveau produit, qui peuvent varier dans le temps et entre les deux obstacles. Le modèle est estimé à partir de données de vente contenant des informations sur les achats de plaque de plâtre par des entreprises de construction françaises de 2017 à 2020, auxquelles ont été ajoutées des informations administratives (expérience, RGE, taille, etc.) et locales (revenus des ménages, concurrence, etc.). Les coefficients sont estimés par une procédure GMM combinée à un processus par étapes pour identifier les paramètres de l'indice d'adoption. Les résultats indiquent que les caractéristiques de l'entreprise et les déterminants du marché local sont au cœur de la demande de produits innovants. Ils montrent également un effet positif du bouche-à-oreille sur la diffusion intra-entreprise, mais cet effet disparaît lorsque l'on contrôle par le principal magasin visité, suggérant que la fidélité au niveau du dépôt est un facteur clé. Dans l'ensemble, ces résultats éclaires des pistes intéressantes pour les politiques de diffusion et les stratégies industrielles dans le secteur de la construction.

Dans le chapitre 2, les préférences des professionnels de la construction sont ainsi déduites de leurs comportements d'achat : leurs choix de matériaux indiquent la façon dont ils classent leurs options. En outre, l'analyse est limitée à un seul produit, alors que l'innovation peut porter sur diverses caractéristiques. Le chapitre 3, issu d'une collaboration avec Edouard Civel, vise à étudier cet angle mort en explorant la façon dont les professionnels prennent des décisions dans un cadre plus général. La diffusion relativement lente des innovations dans le secteur a souvent été attribuée à une forme de conservatisme des professionnels concernant leurs savoir-faire et les matériaux qu'ils utilisent (eg. Du et al. 2014). Pour autant, supposer que tous les entrepreneurs du BTP font preuve d'une aversion à l'innovation semble réducteur. L'économie expérimentale fournit des outils pour étudier ces processus de prise de décision en se basant sur les préférences déclarées. Plutôt que d'observer des comportements réels, ces méthodes présentent aux participants à l'expérience des scénarios hypothétiques. Elles permettent ainsi de prédire des comportements futurs vis-à-vis d'innovations qui n'existent peut-être pas encore, et ont l'avantage d'éviter les facteurs confondants comme les chocs de prix. En d'autres termes, puisque le contexte est contrôlé, les informations recueillies sur les préférences sont moins bruitées et peuvent être plus précises.

Parmi ces méthodes, la *Discrete Choice Experiment*[6] (DCE) a été présentée par Louviere et Woodworth (1983) comme une alternative aux préférences déclarées sur des échelles numériques. L'hypothèse centrale est que les biens de consommation sont des ensembles indivisibles de caractéristiques. Une classe de biens peut donc être considérée comme une liste d'attributs, chaque bien étant caractérisé par le niveau de ces attributs. En pratique, les personnes interrogées dans le cadre d'une enquête DCE se voient présenter des cartes de choix décrivant des situations hypothétiques et sont invités à classer les différentes alternatives. Contrairement aux méthodes d'évaluation des préférences déclarées sur des échelles, il ne leur est pas demandé d'attribuer une valeur numérique à l'un ou l'autre de ces attributs. *A contrario*, la valeur qu'ils accordent aux différents attributs est déduite de la série de choix qu'ils ont faits, à partir d'un modèle d'utilité aléatoire.

6. "*Expérience en choix discret*".

Plus précisément, le protocole expérimental du chapitre 3 caractérise des matériaux innovants hypothétiques à l'aide de trois attributs (améliorations écologiques, améliorations techniques et source d'information) comportant trois niveaux, tandis que la variable prix comporte cinq niveaux. Les professionnels utilisant différents matériaux dans leur travail quotidien en fonction de leur corps de métier, il a fallu présenter ces matériaux hypothétiques de façon homogène pour tous les participants. Cette difficulté supplémentaire a été abordée en demandant aux enquêtés de sélectionner un produit qui leur était familier dans une liste. Chaque participant a ainsi reporté un matériau de référence (mortier, plaque de plâtre, etc.), puis s'est vu proposer des matériaux théoriques différant de ce dernier par son prix, ses caractéristiques écologiques (eg. réduction des déchets de chantier), ses caractéristiques techniques (eg. réduction du temps de pose) et la source de l'information sur ce nouveau produit (eg. un vendeur dans un magasin de matériaux). A chaque itération, deux questions ont été posées : quelle est la meilleure option parmi les deux produits hypothétiques, et seraient-ils disposés à l'essayer spontanément ? Seules des améliorations strictes ont été envisagées, ce qui signifie que les répondants n'ont jamais eu à sacrifier un niveau d'attribut pour obtenir une amélioration sur une autre dimension.

Les facteurs d'adoption ont ensuite été déterminés en définissant le matériau de référence comme un choix ne comportant aucune amélioration ni augmentation de prix, et dont la source d'information était la propre expérience du répondant. Des informations supplémentaires ont été recueillies sur les enquêtés afin d'explorer des scénarios de politiques publiques, notamment l'impact des labels et du niveau d'éducation. Le "*Technology Readiness Index*" [7] (TRI) développé par Parasuraman et Colby (2015) a également été inclus dans le questionnaire pour analyser la validité interne de la conception de la DCE. Les résultats de régression suggèrent de l'hétérogénéité parmi les professionnels de la construction. Tous les coefficients ont par ailleurs une valeur positive, mais le consentement à payer pour les améliorations techniques est apparu plus élevé que pour les caractéristiques écologiques. Les caractéristiques innovantes sont donc valorisées, mais devoir faire confiance à un interlocuteur plutôt que de se fier à sa propre expérience induit un coût plus élevé. Cela contribue à expliquer pourquoi l'adoption d'innovations est relativement lente dans ce secteur et fournit des pistes pour l'élaboration de politiques publiques. Les labels semblent par ailleurs refléter des biais de préférence des enquêtés, ce qui valide la qualité du signal qu'ils envoient aux clients finaux.

7. "*Indice de Réceptivité Technologique*".

Aides au ménages

La première barrière à la mise en œuvre d'une rénovation reste le coût qu'elle représente pour le ménage. Au cours de la décennie 2010-2020, les politiques publiques sur la performance thermique ont conduit à la mise en œuvre de programmes d'aide financière pour les rénovations énergétiques. A terme, la législation vise ainsi à rendre ces rénovations énergétiques obligatoires pour les propriétaires. En 2007, la Réglementation Thermique des Bâtiments Existants (RTE) *par Elément* a notamment défini la performance énergétique de référence à atteindre après une rénovation d'ampleur, pour tout logement construit après 1948 ou dont la surface est supérieure à 1000m^2. Elle concerne les rénovations qui comprennent des travaux conséquents visant les murs, le toit, les sols, les parois vitrées, le chauffage, la production d'eau chaude, la ventilation, l'éclairage et les appareils utilisant des énergies renouvelables. La "*RTE globale*" a été adoptée l'année suivante, applicable aux projets dont les coûts dépassent 25% de la valeur du bâtiment. Elle établit en particulier un maximum de consommation d'énergie de 195 kWh/m^2 suite à la rénovation de ces logements. À plus long terme, les passoires énergétiques seront interdites à la location. D'ici 2025, les propriétaires ne seront en effet plus autorisés à mettre sur le marché des logements dont la consommation dépasse 420 kWh/m^2, ce qui correspond aux catégories F et G de l'échelle DPE et représente 17% du parc immobilier (CGEDD 2020).

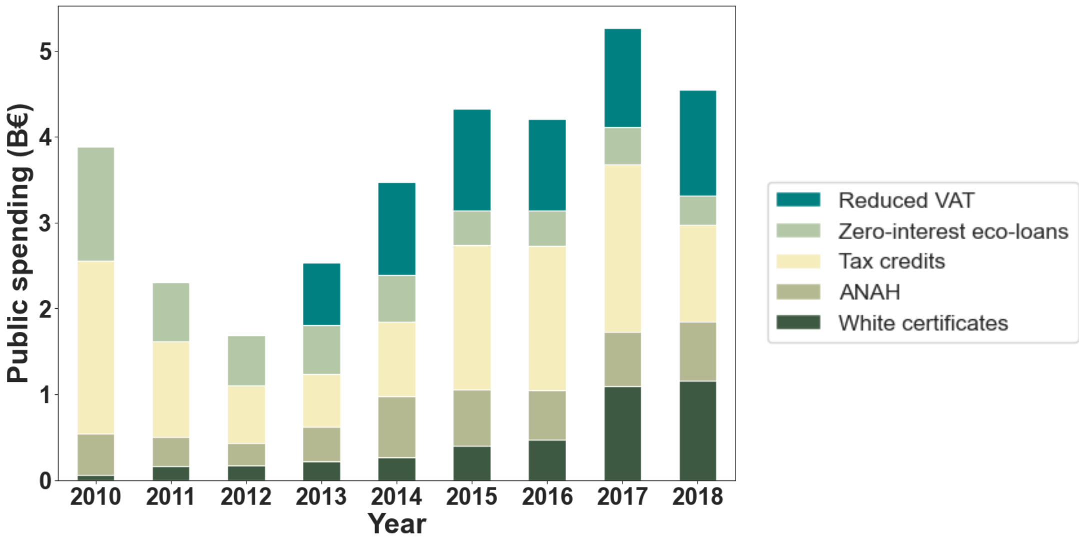
Les ménages sont également incités à rénover *via* des subventions et des prêts aidés. La loi de 2005 de Programmation fixant les Orientations de la Politique Energétique (POPE) a créé les *Certificats d'Economie d'Energie* (CEE), obligeant les producteurs d'énergie à investir dans des rénovations énergétiques pour leurs clients (ménages, entreprises, organismes publics). Les CEE permettent aux obligés d'atteindre leurs objectifs de différentes manières, soit en finançant directement les rénovations, soit en achetant des certificats à leurs concurrents, ou encore en payant une amende s'ils n'atteignent pas leur objectif. Ce programme a été la première des cinq politiques actuelles d'aide à la rénovation énergétique en France. Les CEE ont connu quatre périodes d'application à ce jour, caractérisées par des objectifs d'économies d'énergie de plus en plus ambitieux. La première période s'est étendue de 2006 à 2008, avec un objectif cumulé de 54 TWh - une réduction de 65 TWh cumac aura finalement été atteinte (ADEME 2019a) - et la deuxième période (2011-2014) avait un objectif cumulé de 345 TWh. La troisième période, de 2015 à 2017, a vu l'introduction des "*CEE précarité énergétique*", avec 150 TWh d'économies cumulées fléchées vers les ménages en situation de précarité énergétique, en plus d'un objectif de 700 TWh cumulés pour la période. Les économies d'énergie mesurées pour chaque période ayant largement dépassé les attentes, un objectif beaucoup plus élevé de 1 200 TWh a été établi pour la quatrième période (2018-2021).

La loi POPE a également créé le Crédit d'Impôt pour le Développement Durable (CIDD), qui rembourse une partie du coût des appareils et des matériaux. Il a été révisé en 2012 afin d'en limiter les bénéficiaires, ciblant les ménages à faibles revenus, et pour inciter les propriétaires à s'engager dans des travaux de rénovation de grande ampleur plutôt que dans des travaux ponctuels et répétés dans le temps. Le CIDD "*bouquet de travaux*" comportait ainsi un crédit d'impôt de 25% si au moins deux actions de rénovation avaient été effectuées - isolation et double vitrage par exemple -, tandis que le CIDD "*Action unique*" n'était fixé qu'à 15%. Une nouvelle réforme a été votée en 2014, qui remplace le CIDD par le Crédit d'Impôt à la Transition Energétique (CITE). Celui-ci comporte des taux différenciés en fonction de l'efficacité présumée des travaux effectués ; le crédit d'impôt pour le double vitrage ayant notamment été abaissé à 15%.

Trois autres aides sont disponibles pour les ménages. Les *Eco-prêts à taux zéro* (EPTZ) ont été mis en place en 2009 *via* les banques privées, dont la perte en termes d'intérêts est ensuite remboursée par l'État. Cette politique se rapproche des programmes de prêts développés pour les primo-accédants à la propriété dans les années 1970-1980, ce qui illustre le rapprochement progressif des politiques d'aide au logement et des politiques énergétiques en France. Les ménages français n'avaient contracté que 40 000 EPTZ au total en 2019, un bilan largement en-deçà des objectifs initiaux. Le manque d'attractivité du dispositif peut en partie s'expliquer par les faibles taux d'intérêt sur la période et à la concurrence avec les autres aides financières (AN 2021). Les CEE, le CITE et les EPTZ sont sujets à la loi dite d'"*Eco-conditionnalité des politiques publiques*" adoptée en 2013 et appliquée à partir de 2014. Les ménages doivent désormais faire appel à une entreprise RGE pour bénéficier de l'un de ces dispositifs. Cette mesure a été prise pour garantir une qualité minimale des rénovations, étant donné le coût important de ces politiques pour l'État. En parallèle, le Fonds d'Aide à la Rénovation Thermique (FART), désormais connu sous le nom "*Programme Habiter Mieux*", a été créé en 2010 et géré par l'ANAH pour fournir des subventions aux ménages en situation de précarité énergétique. Des taux de TVA réduits sont également applicables aux activités de rénovation depuis 2013, dans le but de réduire les coûts pour les entreprises. Ces deux dernières politiques ne requièrent pas le recours à une entreprise RGE.

Ces cinq dispositifs représentent coût non négligeable pour l'État, atteignant plus de 4 milliards d'euros en 2018 (Figure 3). Outre ces politiques nationales, des dispositifs complémentaires à plus petite échelle ont été mis en place. A titre d'exemple, la Fondation Abbé

Pierre a lancé le programme *Toits d'abord*, destiné aux personnes en situation de très grande précarité. Soutenue par des assemblées départementales, elle apporte ainsi des fonds pour construire ou rénover des logements sociaux. Dans le cadre des CEE, le groupe Effy a également mis en place le *Pacte Energie Solidarité* en 2013, offrant des rénovations aux ménages modestes au prix symbolique de 1€. Une grande variété de programmes ont également été développés par les gouvernances locales (régions, départements et villes) afin de fournir des fonds supplémentaires pour la rénovation, mais ils ne sont pas tous répertoriés. Ils diffèrent dans leur mode de financement, leur budget global et le type de ménages concerné.



Source : Documentation officielle (voir le chapitre 4 pour les détails).

Note : L'information "*Public spending*" indique ce que les ménages ont effectivement perçu au cours de chaque année. Par exemple, les ménages français ont perçu 3,9 milliards d'euros en 2010.

FIGURE 3 – Aides perçues par les ménages (2010-2018)

Les premières évaluations de ces programmes d'aide financière ont porté sur leur rentabilité, explorant l'effet de rebond [8] et les comportements de passager clandestin - qui renvoie ici aux ménages utilisant les subventions de l'État pour financer un projet de rénovation qu'ils auraient entrepris de toute façon en utilisant leurs fonds privés. En France, l'effet rebond s'est avéré plus important chez les ménages en situation de précarité énergétique *ex ante* (Belaïd, Ben Youssef et Lazaric 2020) et à long terme (Belaïd, Bakaloglou et Roubaud 2018). Les passagers clandestins sont le plus souvent des ménages plus aisés (Nauleau 2014). Ces estimations du rapport coût-efficacité des politiques reposent toutefois sur l'hypothèse que

8. Voir Greening, D. L. Greene et Difiglio (2000) pour une revue de la littérature sur les différentes méthodes de caractérisation de l'effet de rebond

des économies sont effectivement réalisées grâce à ces dispositifs. Un courant de littérature plus récent a cherché à déterminer si ces programmes induisaient des économies d'énergie en pratique. Les économies estimées à partir des données *ex post* sont systématiquement inférieures aux économies projetées, mais il n'y a pas de consensus sur l'ampleur de la différence. L'accent a également été mis sur les abattements fiscaux et les subventions, laissant de côté d'autres modes de financement comme les prêts à taux zéro. Par ailleurs, les analyses sont très concentrés sur l'effet rebond et l'impact de la *qualité* des rénovations reste peu exploré.

Le chapitre 4 présente une évaluation spatio-temporelle de l'impact de ces aides sur la consommation de gaz et d'électricité des ménages français. La conditionnalité des CEE, des EPTZ et des crédits d'impôt au recours à une entreprise RGE depuis 2014 permet en outre d'explorer l'effet de l'accès à ces professionnels qualifiés sur les économies d'énergie réalisées. Les aides aux ménages ont-elle stimulé l'implantation d'entreprises RGE localement ? L'accès aux entreprises RGE a-t-il entraîné des économies d'énergie supplémentaires ? L'accessibilité des entreprises RGE a été calculée en mesurant le nombre de d'entreprises labélisées dans un rayon de 5 à 50km autour de toutes les IRIS de résidence sur le territoire métropolitain. La stratégie empirique repose sur le modèle de panel spatial développé par Kapoor, Kelejian et Prucha (2007) et les entreprises RGE ont été instrumentés par le nombre global d'entreprises de construction localement, en contrôlant pour les aides perçues ainsi que pour les caractéristiques des ménages et des bâtiments. Les résultats de régressions indiquent que l'implantation d'entreprises RGE est fortement stimulée par les dépenses perçues *via* les trois aides éco-conditionnées, alors qu'une augmentation des dépenses de TVA à taux réduit est reliée à une baisse du nombre d'entreprises RGE. On note également une hétérogénéité de l'impact de l'investissement public selon le mode de financement. Enfin, une partie de la réduction de la consommation d'électricité semble compensée par une augmentation de celle de gaz, ce qui peut s'expliquer en partie par un effet délétère lié au mode de calcul du DPE sur la période.

Discussion des résultats

Les quatre chapitres de cette thèse explorent ainsi le rôle joué par les entreprises de construction dans l'amélioration de l'efficacité énergétique du secteur résidentiel et suggèrent des implications en termes de politiques publiques. En premier lieu, les variations régionales semblent impacter la montée en compétence et la diffusion des innovations, mais aussi l'efficacité des investissements publics. Le secteur du bâtiment est très localisé, puisque les logements ne peuvent, par nature, pas être déplacés et que les entreprises ne sont pas particulièrement mobiles. En outre, les différences de climat influencent l'architecture et les matériaux utilisés pour construire les logements. Ces disparités ont induit des différences de réglementation, en particulier au niveau des exigences de performance définies par les RT. L'accent mis sur l'isolation contre le froid, afin de réduire les besoins de chauffage, a conduit à un net clivage Nord-Sud en France, à la fois du point de vue du nombre de rénovations réalisées et du montant d'aide perçu. Les besoins en matière de confort d'été et de climatisation sont encore négligés alors qu'ils auront un poids croissant dans la consommation d'énergie du secteur résidentiel. Les résultats du chapitre 4 indiquent ainsi une grande hétérogénéité d'accès aux entreprises RGE sur le territoire métropolitain. Étant donné ces inégalités spatiales, la loi de 2013 sur l'éco-conditionnalité des aides publiques a de fait créé et renforcé des inégalités d'accès aux subventions publiques, puisque le dépôt de dossier dépend de la facilité avec laquelle les ménages peuvent embaucher un entrepreneur RGE.

Le chapitre 2 montre également l'importance de l'impact des caractéristiques du marché local dans la diffusion d'une innovation technique. Les matériaux étant dans la plupart des cas choisis par les entrepreneurs, cela peut *in fine* renforcer les différences de qualité des services de rénovation au niveau local. Le marché français de la construction est donc fortement marqué par ces disparités spatiales, qui génèrent des différences dans la qualité de l'offre et qui sont renforcées par la gouvernance nationale des politiques publiques. La nature locale des marchés de la construction n'a pas encore été prise en compte par les décideurs politiques, dans la mesure où les réglementations et les aides publiques sont conçues uniquement sur des prérequis techniques. Les résultats de cette thèse appellent à une plus grande implication et intégration des acteurs locaux dans la gouvernance du marché pour en renforcer l'efficacité.

Au-delà de ces disparités spatiales, des obstacles structurels freinent la massification des rénovations énergétiques. Les politiques de logement et de la construction ont historiquement ciblé les nouvelles constructions, et leurs efforts n'ont été orientés vers la rénovation que récemment. Du point de vue des ménages, le principal obstacle à la rénovation de leur logement reste l'incertitude quant au retour sur leur investissement. Il n'existe pas de signaux forts concernant les compétences *ex ante* des entrepreneurs, et ils peuvent à juste titre craindre des coûts cachés liés aux délais d'achèvement et aux erreurs d'installation. Comme l'illustre le chapitre 1, le label RGE ne semble pas être la solution appropriée pour modifier efficacement la répartition des compétences sur le marché. L'incertitude quant à la fiabilité des entrepreneurs persiste, puisque des entreprises non compétentes sont actives sur le marché. Compte tenu de l'absence de barrières à l'entrée pour les professionnels, qui permet à certains d'entreprendre des projets malgré leur manque de compétence pour les mener à bien, les particuliers peuvent, à juste titre, hésiter à engager des travaux. Les ménages peuvent également être soumis à des contraintes de crédit, puisque le coût initial des investissements de rénovation est généralement élevé, tandis que les gains en termes de dépenses énergétiques ne seront ressentis qu'à long terme.

Par ailleurs, les entreprises ne sont pas efficacement incitées à se spécialiser dans les rénovations énergétiques, et elles n'ont pas toutes les compétences nécessaires pour fournir ces services. Les entrepreneurs sont soumis à une forte pression concurrentielle et leur modèle économique consiste à maintenir des prix bas afin de remporter des projets. Le label RGE a également été créé pour permettre aux artisans qualifiés de se distinguer de leur concurrents, dans le but d'entraîner une montée en compétence du secteur à long terme. Les apports théoriques du chapitre 1 ont mis en évidence d'importantes limites à ce système de certification, notamment en ce qui concerne son incapacité à dissuader l'entrée de professionnels non qualifiés. Il semble toutefois bien fonctionner pour signaler des comportement favorables aux innovations : les entreprises RGE avaient une probabilité plus élevée d'adopter dans le chapitre 2, et leurs travailleurs avaient des préférences plus marquées pour les caractéristiques écologiques dans le chapitre 3. Cependant, le label pourrait simplement refléter le fait que les entreprises orientées vers l'innovation ont plus tendance à se labéliser, plutôt qu'un effet incitateur vers des matériaux de pointe. Il n'existe à ce jour pas de réelle politique visant à promouvoir les innovations au-delà du financement de la R&D privée, malgré les faibles taux d'adoption observés dans le secteur. Devant l'importance du coût de l'incertitude pour les entrepreneurs estimé dans le chapitre 3, et la faible valeur attribuée aux matériaux verts, il est nécessaire de promouvoir davantage ces produits pour accélérer la décarbonation du secteur. La formation professionnelle continue pourrait encourager les entrepreneurs à acquérir de nouvelles compétences, mais il est probable que la demande restera faible si ces diplômes ne peuvent pas se traduire par une augmentation des prix. La mise en place de barrières à l'entrée sous la forme d'une exigence minimale de diplôme, quel que soit le corps métier, pourrait permettre aux professionnels qualifiés de tirer pleinement parti de leur expertise et d'accroître la qualité des rénovations qu'ils proposent. Ces barrières pourraient de surcroît réduire les incertitudes des ménages, ce qui augmenterait d'un point de vue théorique leur disposition à payer selon le modèle du chapitre 1.

Les réglementations peuvent s'avérer plus efficaces que les politiques incitatives, compte tenu des enjeux et du nombre insuffisant de rénovations que ces mesures ont entraîné jusqu'à présent. Les activités de construction et de rénovation sont déjà soumises à des réglementations, et les résultats de cette thèse peuvent éclairer leur efficacité. En premier lieu, les propriétaires de logements n'ont pas été directement ciblés par les réglementations au cours de la décennie 2010-2020. La principale contrainte des ménages provenait de la loi sur l'éco-conditionnalité leur imposant le recours aux entreprises RGE pour accéder à certaines aides. L'efficacité de cette mesure suscite de plus en plus de questionnements, dans la mesure où le label ne serait pas suffisant pour garantir une qualité minimale des rénovations puisque les chantiers sont trop peu contrôlés (CGEDD 2017). Les estimations du chapitre 4 ont montré qu'un meilleur accès aux entreprises certifiées a eu un effet positif sur la qualité des rénovations, mais cet impact est faible. Alternativement, l'obligation de recours aux entreprises RGE pourrait être remplacée par des audits obligatoires une fois les rénovations terminées, ou au cours du processus. Cela réduirait la probabilité de fraude, tout en garantissant que les fonds publics soient efficacement investis.

En second lieu, les entreprises sont bien plus concernées par les réglementations que les ménages. Les activités de construction ont toujours été soumises à des directives strictes, l'accent étant mis sur la performance thermique depuis les années 1970. La performance des rénovations n'a fait l'objet de réglementations qu'à partir de 2007, la RTE en fixant des exigences minimales en matière d'efficacité énergétique des bâtiments rénovés. Au vu des résultats présentés dans chapitre 3, on pourrait orienter davantage ces efforts réglementaires vers les matériaux à haute performance écologique, par exemple en fixant des exigences sur leur empreinte carbone, puisque ces innovations sont les moins susceptibles d'être adoptées spontanément par les entrepreneurs. En outre, le manque d'exigence concernant leur niveau de compétence, à l'exception des plombiers et des électriciens qui doivent être titulaires d'une licence, est particulièrement problématique à la lumière de la faible montée en compétence soulignée précédemment. Le secteur de la construction étant appelé à jouer un rôle de premier plan dans la transition énergétique, il est urgent de renforcer ces exigences de formation professionnelle. Enfin, un type de réglementation brille par son absence : les externalités carbone du secteur résidentiel ne sont pas directement taxées. Une taxe carbone pourrait envoyer un signal-prix efficace aux entreprises et aux ménages, réaffirmant le rôle du secteur dans les politiques environnementales. Elle augmenterait le coût de l'inefficacité énergétique, entraînant une augmentation du retour sur investissement des ménages. Toute taxe carbone devrait cependant être conçue avec précaution, pour empêcher d'éventuels effets régressifs pour les ménages à faible revenu ou en situation de précarité énergétique.

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«Un roman est un miroir qui se promène sur une grande route. Tantôt il reflète à vos yeux l'azur des cieux, tantôt la fange des bourbiers de la route. Et l'homme qui porte le miroir dans sa hotte sera par vous accusé d'être immoral ! Son miroir montre la fange et vous accusez le miroir ! Accusez bien plutôt le grand chemin où est le bourbier, et plus encore l'inspecteur des routes qui laisse l'eau croupir et le bourbier se former.»

Stendhal – *Le Rouge et le Noir.*

* * *

General Introduction

1 From energy regulation to house renovations

1.1 The emergence of energy and climate concerns in Europe

Fighting climate change has become a clear and central component of energy policies, yet it was not always their primary objective. Cost-cutting, national sovereignty, international cooperation, and European union-building were instead more typical goals of 1970-2000 policies. However, as such efforts gradually made space for climate change mitigation, their success in that regard suffered from unclear objectives and weak regulation. 21st century policies introduced concrete benchmarks for progress and became increasingly sophisticated and holistic, seeking to address social inequalities, promote asset retrofitting and develop the skills of relevant workers, with a marked focus on the construction sector.

The 1970s were a turning point in the way energy usage was perceived and regulated. Two oil shocks, in 1974 and 1979, and the steep increase in energy prices that followed led a debate on energy efficiency and consumption. After decades of cheap energy and economic prosperity during the post-war reconstruction period, European nations were suddenly faced with their dependency on the rest of the world. The 1972 Paris summit was the first building block of a common energy policy among members of the European Economic Community (EEC). Of primary importance were the establishment of European norms for the members to avoid competition distortions induced by differences in national policies. Cooperation on environmental policy was further incentivized with the creation of the Directorate General for the Environment in 1981, established to plan and coordinate national policy schemes. Every member of the EEC adapted these objectives to their national context. In France, the *Agence pour les Economies d'Energie* (AEE) [9] had already been created in 1974 to inform the public on new energy challenges. They notably defended the daylight saving time law, which was adopted in 1976. The agency still exists to this day, even though its name evolved

9. It can be translated to: "*Agency for Energy Savings*".

throughout the years: from *Agence Française pour la Maîtrise de l'Energie*[10] (AFME) in 1982 to the current *Agence de l'environnement et de la maîtrise de l'énergie*[11] (ADEME) in 1991. The AFME's primary mission in the 80s was still increasing energy independence, in part by diversifying the energy mix, while the ADEME's charter introduced the need to reduce carbon emissions.

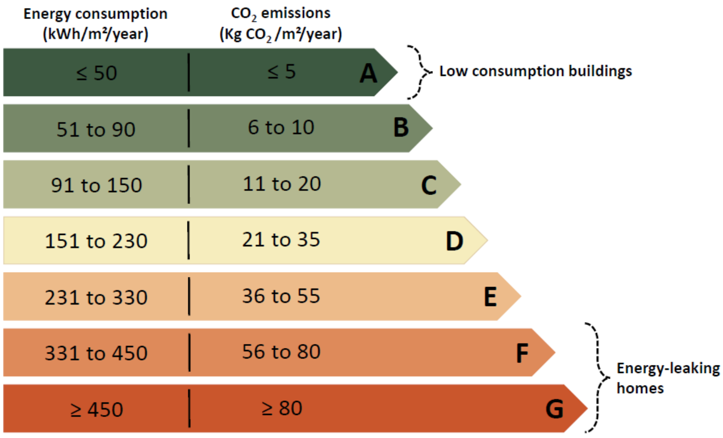
Pollution and climate became key elements of energy policies after the 1986 Single European Act, which was the first major revision of the 1957 Rome Treaty. It established the "*polluter pays*" principle as the core component of EEC policies in its Article 25.2: "*Action by the Community relating to the environment shall be based on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source, and that the polluter should pay. Environmental protection requirements shall be a component of the Community's other policies*". Climate change became a prominent topic for policymakers in the 90s, as exemplified by the Rio Summit in 1992, where the principles for sustainable development were defined. In the same year, the Maastricht treaty was ratified, creating the European Union (EU) and reiterating that reducing greenhouse gas emissions was a core principle of the Union. National policies followed - for instance, in 1995, France adopted the Barnier law cementing the "*polluter pays*" principle. The international commitments to reduce emissions were renewed in 1997, with the ratification of both the Kyoto Protocol and the Amsterdam Treaty for EU members. However, a major shift in policy occurred with the 2000 European Climate Change Program, adapted to the French context with the *Programme National de Lutte Contre le Changement Climatique*[12] (PNLCC). Indeed, for the first time, the policy set quantifiable emission reduction targets, to be met over the 2000-2010 decade. Overall, the 1970-2000 period witnessed the emergence of energy policies in a context of rising prices and growing concerns for the environment. However, while broad goals were set, they proved hard to reach due to the lack of precise regulations for each market.

1.2 Turning general guidelines into sector-specific policies

The 2004 French Climate Plan first introduced sector-specific targets. This aimed to increase transparency to get economic actors to cooperate. The construction sector and individual housing were identified as key areas, and progressively became one of the main pillars of the French energy transition strategy. On a wider scale, EU states adopted the

10. "*French Agency for the Control of Energy*".
11. "*French Agency for Ecological Transition*".
12. "*National Program to Fight Against Climate Change*".

Directive on the Energy Performance of Buildings in 2004, translating the Kyoto Protocol commitments to actual regulations for the sector. It mostly targeted new builds, with norms in terms of insulation and ventilation and set a 20% energy consumption reduction goal by 2020, taking the 1990 levels as reference. It called for harmonized tools to measure the energy consumption of buildings.



Source: Ministry of Ecological Transition (France).

Note: The numbers presented here correspond to the latest version of the DPE at the time of writing, that is, the 2021 revision.

Figure 1 – French energy performance certificates for buildings (DPE)

In France, it led to the creation of the *Diagnostic de Performance Energétique*[13] (DPE) for buyers and renters. The DPE is a grading system for buildings, reflecting their energy consumption and their carbon gas emissions (Figure 1). Regulations were already in place to ensure that dwellings would not damage their occupants' health, imposing asbestos diagnoses (Carrez Law, 1996) and lead diagnoses (ERAP Law, 1998). The DPE was however the first type of energy label designed to measure the contribution to global warming of dwellings, which reflects a major change for the sector. It became mandatory in 2007 for any new construction and renting. Environmental policies have been revised and fine-tuned at an increasing pace over the 2000-2010 period, setting new objectives and regulations. At the EU level, the 2008 Climate and Energy Package established the "3 × 20" strategy, setting 20% as the goal for the reduction of greenhouse gases, the share of renewables in the energy mix and the reduction of energy consumption. In France, it inspired the first *Grenelle de l'environnement* conference in 2007, which reinforced the importance of improving the energy efficiency of the building stock by 2020. The resulting Grenelle law, adopted in

13. "*Energy Performance Certificate*".

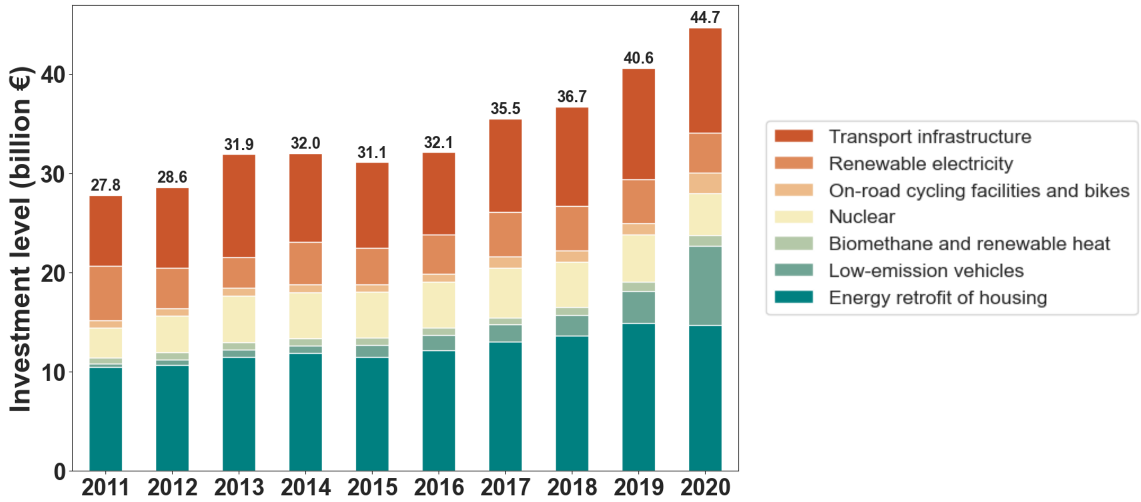
2009, was the first regulatory text limiting greenhouse gas emissions in the housing sector. Combined with the 2010 second Grenelle law, they set a goal of dividing the housing sector's emissions by a factor four before 2020, through the renovation of existing dwellings and setting a zero-emission standard for new builds.

These national laws marked a clear shift in policy towards financing renovations of existing dwellings, setting a rate of 500 000 retrofits per year as a goal. EU policies also focused more and more on the retrofit of existing dwellings rather than regulating new builds, starting with the Energy Efficiency Directive in 2012. Its goal was to improve the housing stock's energy efficiency by 20% by 2020, with a yearly decrease target of energy consumption equivalent to at least 1.5% of yearly energy sales - excluding transport. Member states were also instructed to come up with their own national global retrofit strategy and to renovate 3% of State-owned buildings. This legislation also reflected a growing concern with living standards and energy access. For instance, the second Grenelle law defined the notion of energy poverty in its very first article: "*Est en situation de précarité énergétique au titre de la présente loi une personne qui éprouve dans son logement des difficultés particulières à disposer de la fourniture d'énergie nécessaire à la satisfaction de ses besoins élémentaires en raison de l'inadaptation de ses ressources ou de ses conditions d'habitat*"[14]. In practical terms, a household is considered to be energy-poor if more than 10% of its revenue is spent on energy. Ending energy poverty became a priority objective for every climate regulation afterwards. The *Observatoire national de la précarité énergétique*[15] (ONPE) was created in 2011 to monitor progress on that front, while the national strategy to fight climate change was revised accordingly.

The *Transition Energétique pour la Croissance Verte*[16] (TECV) law passed in 2015 synthetized the overall direction of energy policy objectives in France: "*La politique énergétique garantit la cohésion sociale et territoriale en assurant un droit d'accès de tous les ménages à l'énergie sans coût excessif au regard de leurs ressources*"[17] (Article 1). It reiterated the goal of 500 000 retrofits per year, while imposing that half of the renovated dwellings should be occupied by low-income households. Its overall objective was to reduce energy poverty by 15% by 2020. Practically speaking, it made insulation mandatory for any large-scale project after 2017, and raised the carbon component of interior taxes. More ambitious targets were set in the 2017 French Climate Plan, which aimed for carbon neutrality by 2050.

14. "*Is suffering from energy poverty, as defined by the present law, a person who in their dwelling experiences specific problems to obtain the energy necessary to the satisfaction of their elementary needs due to inadequate resources or habitat conditions*".
15. "*National Observatory of Energy Poverty*".
16. "*Energy Transition for Green Growth*".
17. "*The energy policy ensures social and territorial cohesion by giving all households a right to energy without any excessive cost given their resources*".

This meant dividing emissions by a factor nine compared to their 1990 levels. Among the four "*key measures*" the Plan listed, three targeted the building sector.



Source: I4CE 2021.

Note: The Y-axis provides total amounts invested to address climate change in France, in billion euros. For instance, 27.8 billion euros were invested to address climate change in 2011, among which 10.5 were dedicated to energy retrofit of dwellings.

Figure 2 – Climate investments per sector in France

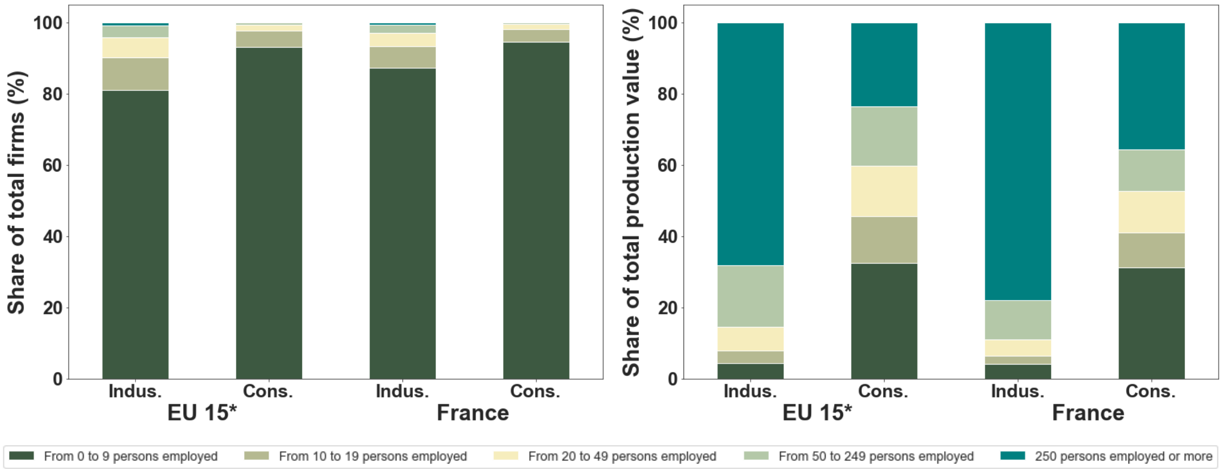
Those measures were further detailed in the 2018 *Plan de Rénovation Energétique des Bâtiments*[18] (PREB), which structured public action around four axes. First, energy retrofits were put forward as a national priority, involving all levels of government. Second, specific policies would have to be designed to end energy poverty. Third, in-depth renovations had to be undertaken for office buildings and the tertiary sector. Fourth, the development of skills and the diffusion of innovations among construction firms was set as a major challenge for the French state. A total budget of 14 billion euros was allocated for the following five years to achieve those goals, of which 1.2 billions went directly to energy poverty. At least 7 million severely unfit dwellings - formally defined as dwellings whose energy consumption exceed 330 kWh/m^2 - were set to be renovated by 2025. The total amount also included 30 000 million euros spent to develop professional training, aiming to generate 65 000 skilled workers by 2050, as well as 40 millions to support innovation. For the first time, both households and firms were included in the same policy proposal. Consequently, the housing sector has become the larger source of climate investment for the last decade, making up for 38% and 33% of investments in 2011 and 2020 respectively (Figure 2). The

18. "*Plan for the Energy Retrofit of Buildings*".

2020 Covid-19 recovery plan reaffirmed this dynamic, reassessing the central role of retrofits within the national energy plan.

1.3 Current-day construction and housing policies

The construction sector in Europe stands out with respect to other markets for two main reasons. First, it is extremely fragmented, with 60% of firms generating roughly 80% of the value added (CSTB 2017). Figure 3 displays the number of firms and the production value per firm size. The European construction market appears to be more concentrated than the manufacturing sector, but large firms are a minority in both. There is however a clear difference when looking at the share of the production value that small and medium firms account for. More than half the value in the construction sector is produced by firms with less than 50 employees - both at the European and French scale -, against roughly 15% for the industrial sector.



Source: Author's computations from Eurostat data.

Note: "EU 15*" refers to the EU 15 group minus the United Kingdom, "Industry" refers to manufacturing activities. The Y-axis provides shares of total values. For instance, 93% of French construction firms had 9 workers or less in 2019, against 81% in the manufacturing sector, and they accounted for 32% of the total production value in construction against 4% in manufacturing.

Figure 3 – Number of firms and production value per firm size (2019)

Second, it is a market with extensive information asymmetries. Most customers are not able to independently assess their needs, nor to remedy their issues on their own. They have to *trust* contractors and experts with the assessment of their problems and the implementation of a solution. Trust is hence a key factor when choosing a contractor, as even the *ex post* evaluation of the final product may be uncertain. In the case of insulation for instance, a homeowner will usually not know what type of material is appropriate given the technical characteristics of their dwelling and the nature of their surroundings. They also will not be able to assess if the materials they signed off on are the one being actually installed, nor if the installation was done properly, especially once drywall has been installed over it. Ultimately, it is also hard to quantitatively measure the increase in comfort or the energy savings, as they depend on other factors, such as the weather, energy prices, etc. Overall, it is hard for households to evaluate the quality and skill level of their contractors, be it before or after renovations are undertaken. Professionals have the upper hand in terms of information and each project comes with negotiation and search costs. As a result, market prices are dispersed and not always an appropriate signal for workers' skills (ADEME 2018c).

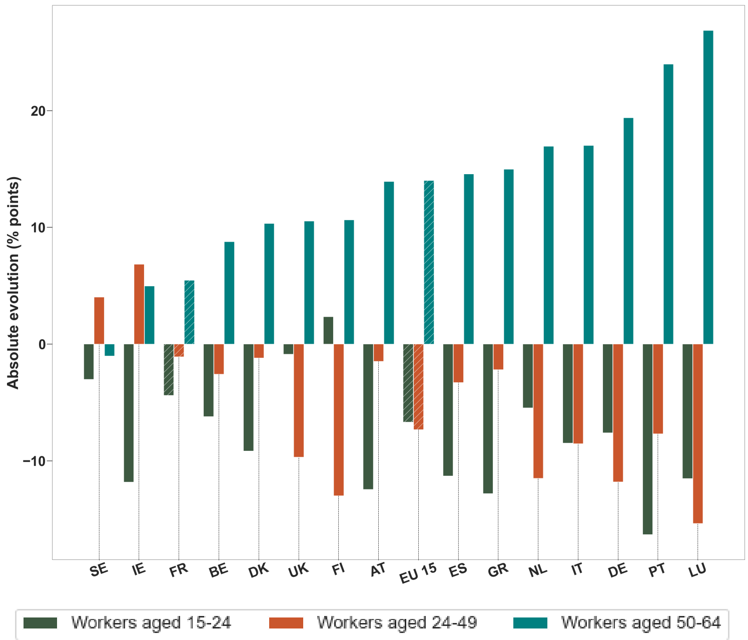
The housing and construction sector are thus currently at the crossroads of major policies regarding social issues, public health and environmental concerns. It is a significant market in size, with 34.5 million dwellings in 2018 - occupying over 2 billion square meters of the French metropolitan territory (Crépon and Charrue 2018). Yet public actors struggle to promote significant change to modernize the sector. One prominent strategy is retrofitting: however, its implementation is fraught with issues. Indeed, almost all EU countries have chosen to delegate the organization of energy retrofits to the market, meaning policies have aimed to incentivize rather than obligate homeowners to undertake them. Refurbishment has become the main activity in the European construction market. It represented 57% of added value in 2015, and follow an increasing trend (ADEME 2018c). Estimations based on the Euroconstruct database showed that energy retrofits accounted for 109 billion euros in terms of production, which is 15% of added value produced by refurbishment activities, as well as 882 900 jobs for the EU-28 group (CSTB 2017). In France, households spend on average 15 billion euros each year for refurbishments designed to improve the energy efficiency of their dwellings. Over the 2006-2013 period, roughly 2.8 million dwellings have been renovated in France, with only 200 000 deep retrofits (ADEME 2018c). This retrofitting strategy has thus made in-roads, but it also has two major problems: time and quality. Indeed, the number of retrofits increased, but not sufficiently. Further, growing concerns about fraud and defects, in particular, have created a tension between the need to increase the volume of retrofits and the necessity to ensure they reach a minimal quality standard. To summarize, the current European - and French - policy roadmap for the construction sector rests on three pillars: upskilling workers, boosting innovation and removing households' financial barriers. The present thesis focuses on these three aspects during the 2010-2020 period, with an emphasis on the French construction sector. This time period corresponds to the first implementation of practical measures specifically targeting retrofits, both for households and firms. Further, France was chosen as a case study, since its policy developments are a prime example of the direction taken by the European Union as a whole in terms of regulations to fight climate change. How does contractor's skill heterogeneity affect the quality of the retrofits? How do new technologies affect market outcomes? Are the current policy schemes adequate to generate sufficient energy savings through renovations?

The remainder of this introduction will provide an overview of how the sector has been historically structured in France, covering the main scientific contributions as well as presenting relevant market features. The following section will focus on skill improvement and present the theoretical approach taken in the first Chapter. Innovation diffusion challenges will then be discussed in Section 3, with an overview of the methodologies used in Chapters 2 and 3. The last section will focus on financial aid schemes targeting households, and detail the estimation method used in Chapter 4.

2 Skills, information asymmetries and retrofit outcomes

2.1 The few and far between: a growing skill mismatch

When it comes to the skills needed to assist the construction sector in meeting new energy targets, there is a growing skill mismatch on the European construction sector, due to the aging population and lack of enrollment of new generations of workers (ECSO 2020b). It is an important issue, considering the economic relevance of the sector in terms of employment and added value, but also the key role it is set to play in the energy transition. These skills include the management of large project and technical knowledge on complex solutions, especially regarding floor and roof insulation, as well as the installation of renewable energy systems. Reports following the 2019 European Green Deal estimated that roughly 120 thousand construction jobs will need to be upskilled over the next 5 years to meet the retrofit target. New jobs linked to energy efficiency will emerge, while traditional skills will be deeply transformed. The European Construction Sector Observatory (ESCO) estimated that 35% of workers have seen their day-to-day jobs change in fundamental ways in the last 5 years, due to new materials, techniques and machines. This trend is likely to continue: "*Skills needed in construction are likely to change to meet demands for "green" and energy efficient buildings that follow new designs and use new materials, as well as digitization trends. [...] Demand for people with high-level qualifications could double, to account for* *one third of all jobs in construction by 2025*"[19]. Europe's aging population, however, might hinder skill improvement. As displayed in Figure 4, the share of older workers in the construction has increased significantly since the 90s in the EU-15 group. These workers typically have significant skills and can take on intermediate management roles, but they are close to retirement. As shares of middle-aged and young workers has steeply decreased, it is unsure if those skills will be passed on in the future. Demand for continuous professional training is also relatively low compared to other sectors. This can be explained by the construction market being highly competitive and dominated by small construction firms, per ECSO (2020a): "*hours spent on training can be perceived especially by small and micro enterprises as a loss of working hours, with no guarantee of return on investments. The economic crisis has put many SMEs in "survival" mode, forcing them to prioritize short-term work over long-term investments*"[20].



Source: Author's computations from Eurostat data.

Note: Working-population is restricted to the 15-64 age group and the EU 15 group was taken as a reference for data continuity. The Y-axis provides the absolute change in the share each age-group represents in the working-age population employed in construction between 1998 and 2019, expressed in percentage points. In France for instance, workers aged 15 to 24 years old represented 10% of workers in 1998, against 6% in 2019, hence a 6 percentage point decrease.

Figure 4 – Change in employment per age group in national markets (1998-2019)

19. ECSO 2020b, p33.
20. ECSO 2020b, p51.

Problems specific to France compound with these shared concerns. The French construction market has been scarred by increasing difficulties to find skilled workers. These can be traced back to measures taken during major recessions experienced in the 1990s, which intended to boost activity and facilitate employment. Indeed, in order to boost demand, the French government lowered the VAT rate to 5.5% on all construction and refurbishment activities in 1999. This rebate bore a heavy weight on France's public finances, and to mitigate its impact, the VAT rate was increased to 7% in 2012 and to 10% in 2013. As the priorities shifted towards promoting energy efficiency, two rates were set in 2013: 5.5% for energy retrofits, while other activities remained subject to the 10% rate. In parallel, and of more importance here, a 1996 law relaxed regulations around construction firms, specifically the definition of an artisan firm. These companies were historically heavily regulated to safeguard traditional skills, a key element being that workers had to be trained and hold a degree in the firm's trade. This condition was loosened, by establishing that only the head of the firm needed to be trained in the trade for the company to be recognized as *artisanale*. In other words, the label used to ensure quality workmanship but has become increasingly misleading. Additionally, the law set an equivalence between professional training and three years of experience, either in France or in EU member states. This contributed to decrease the value of professional training, and might help explain why enrollment rates in those programs have consistently decreased ever since.

2.2 Haste makes waste: balancing quality and quantity with label schemes

As high-skill workers become increasingly hard to find, there was a need to create quality signals for final consumers to minimize the risk of "*cowboy builders*". In France, a variety of labels have been set in place over the years, historically starting with new construction. The *Label Haute Isolation*[21] was the first certification ensuring the energy efficiency of new buildings. It was meant to incentivize developers to go further than baseline regulation. New labels emerged over time, following regulation revisions. In 1982, several *Haute Performance Energétique*[22] (HPE) labels were introduced, rating dwellings on a four-star system depending on their insulation, heating systems, ventilation and hot water production. The two-star HPE standard, meaning the building's energy consumption was 25% below the mandatory level, became regulatory in 1998, with some freedom regarding the choice

21. "*High Insulation Label*".
22. "*High Energy Performance*".

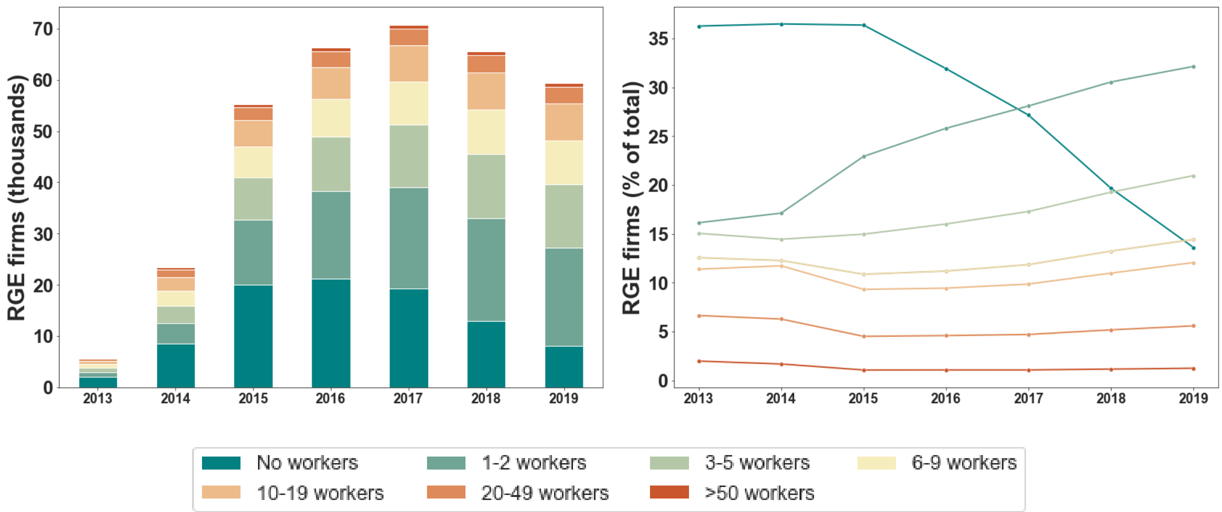
of materials. In 2005, the HPE labeling scheme was reinforced, with the introduction of the *Haute Performance Energétique énergies renouvelables*[23] (HPE EnR) label to signal buildings in which heating is powered with a renewable energy source. The *Bâtiment Basse Consommation*[24] (BBC) label was also created for new builds consuming less than 50 kWh/m² per year. It currently corresponds to the consumption of category-A buildings on the DPE scale in Figure 1.

Early labels only targeted finished buildings, not companies. The creation of the *Qualit'EnR* agency in 2006 was the first attempt in that direction. Its goal was to introduce labels rewarding highly trained professionals, in order to boost skill development on the market. The *Eco-Artisan* brand was launched two years later by the CAPEB, the main employers' federation for small construction firms. In the same vein, the French Building Federation (FFB) created the *Pros de la performance énergétique*[25] label. Both put the spotlight on contractors who were able to evaluate the energy efficiency of dwellings, provide precise retrofit advice for their clients and undertake the renovation work. The management of these labels was transferred to the certification agency Qualibat in 2010, in order to consolidate the sector's upskilling efforts into a single labelling scheme, designed to promote energy efficiency. The chart setting the current reference, the *Reconnu Garant de l'Environment*[26] (RGE) label, was signed the following year. The label's objective was twofold: first, it was designed to increase homeowners' trust in contractors. But second, it aimed to incentivize companies to train their employees in energy efficiency, as the label was set to become regulatory at some point. That became a reality in 2014, when some financial aid schemes for households became conditional on hiring a RGE company - following the implementation of the 2013 *Eco-conditionnalité des aides publiques*[27] law.

Overall, the RGE label is meant to increase retrofit quality by incentivizing contractors to develop the relevant skills, help households to find competent workers and better direct public investments through eco-conditionality. The number of RGE labelled firms has steadily increased over time until 2017, with a significant jump after 2014, before declining (Figure 2.4.7). There were 59 440 firms labelled in 2019, across the three certifying agencies (*Qualibat*, *Qualit'ENR* and *Qualifelec*), with on average 80% of labels delivered by Qualibat. Despite these successes, RGE has had severe limitations in its objective to transform the

23. "*High Energy Performance Renewable Energy*".
24. "*Low-Consumption Building*".
25. "*Energy Performance Professionals*".
26. "*Recognised Environmental Guarantor*".
27. "*Eco-conditionality of public aid*"

construction sector. First, small firms remain under-represented given their total share of the market. The total cost for a four-year certification, before tax, borne by a contractor is around 4 000€, which includes processing charges, training fees and forgone revenues (CGEDD 2017). The total cost of training has been estimated at 100 million euros for the 2014-2016 period, excluding renewable-specific formations (ECSO 2020c). These costs have professional collectives such as *RGE pas comme ça*[28], to vocally criticize the label, which they believe induces prohibitive expenses for small companies.



Sources: Author's computations from ADEME and Insee data.

Note: The Y-axes provide the number of RGE firms for each year, in thousands (left) and as a share of total RGE firms (right). For instance, there were 8 088 certified firms with no employees in 2019, which corresponds to 14% of the RGE population.

Figure 5 – Evolution of RGE firms over time per number of workers (2013-2019)

This is particularly problematic in light of the middling return on investment RGE can produce: contractors interviewed by the CGEDD overwhelmingly agreed that being certified allowed them to maintain their activity level, but not to expand. Second, despite this non-negligible public investment, too few deep renovations have been undertaken. This can be can be explained by their cost for individual households, varying between 20 000 and 30 000€, as well as relatively low energy prices over the period, deflating the perceived urgency or economic benefits of retrofitting. A third factor is that most RGE firms can usually not offer a global diagnostic, meaning they are only able to tackle partial renovations such as roof insulation, window replacement or changing the heating system. These

28. "*RGE not like this*".

improvements have limited impact on their own, and it would be more efficient to take them on at once. The labeling scheme is still very much comprised within the traditional trade categories, with few interconnections. These early evaluations provided a somewhat pessimistic description of the label, identifying many areas for improvement - clarification for households, more hands-on training, more frequent audits. Perhaps the best way to illustrate the design difficulty around RGE is to focus on the evolution of the conditions for firms to obtain it over the years. The first reform, implemented in 2015, aimed to simplify the procedure by lowering prerequisites in terms of initial training and diminishing the number of mandatory audits. As the number of fraud complaints rapidly increased, a counter-reform was set up in 2020 to reinstate more audits, especially on some key areas such as insulation, and raise the penalty charges for non-conforming firms.

2.3 Leading the blind: a credence good approach

Is labeling companies enough to ensure renovations will meet minimal quality standards? On one hand, customers do not have *ex ante* signals to properly evaluate the quality of the offer made by a contractor. On the other hand, firms may lack the skills to fix an issue, or use their informational advantage to increase resale prices without improving quality. As data on firms' abilities and fraud is very scarce and hard to obtain, I turned to a modeling approach to look into the effect of information asymmetry on market outcome. Following Nelson (1970), goods and services can be categorized depending on how easily customers can obtain information about them. Goods which have attributes that can be observed before purchase are referred to as "*search goods*". Customers can rely on information disclosed on labels, prior experience or public review to make the best purchase choice for them. It is typically the case for most ordinary commodities: clothing, basic food items, etc. By opposition, "*experience*" goods and services refer to instances where information on quality is only available to the consumer *ex post*. Purchasing a theater ticket or a book, for instance, does imply a certain level of uncertainty, as customers can only evaluate if the product met their expectations after consuming them. This level of information asymmetry is however not sufficient to describe the specific issues in the construction industry. When choosing a contractor for renovation work, most households do not have the necessary skills to evaluate what they precisely need. Contrary to the case of experience goods, they also cannot tell with certainty if the solution offered to them is appropriate, nor if it was actually implemented. The "*credence good*" category, as originally defined by Darby and Karni (1973), appeared as a better fit to approach these issues. Broadly speaking, it refers to every situation in which "*customers are not able to evaluate whether information provided by the expert is accurate or not - even after purchase*" [29]. The literature on credence goods is vast, as such information asymmetries apply to a variety of topics: medical treatments, car repairs, taxi rides, financial advice, etc.

	Customer's actual issue / type			
	$\overline{c}$		$\underline{c}$	
Price / Fix	$\overline{p}$	$\underline{p}$	$\overline{p}$	$\underline{p}$
$\overline{c}$	No Fraud	Undercharging	Overtreatment	Undercharging
$\underline{c}$	Overcharging	Under-treatment	Overcharging	No fraud

Assumptions: $\overline{p} \geq \underline{p}$ and $\overline{c} \geq \underline{c}$.

Table 1 – Characterization of fraud in a credence good set-up

Dulleck and Kerschbamer (2006) have provided a thorough literature review on the topic and developed a model which encompassed a large number of previous papers and scenarios. Using their notations, I assume customers can have either an easy-fix problem $\overline{c}$ or one that requires a sophisticated treatment $\underline{c}$. They do not know their own type, meaning they have to *trust* an expert diagnosis to fix it. The expert will diagnose either $\overline{c}$ or $\underline{c}$, and offer to solve each issue at price $\overline{p}$ and $\underline{p}$ respectively. Depending on the information structure and the nature of market institutions, fraud can arise in different forms (Table 1). Undertreatment refers to situations where the customer had a complex problem, which was met with a simple solution. In other words, their issue is not settled after the expert's intervention. On the other side of the spectrum, overtreatment refers to situations where a $\underline{c}$-type customer receives a $\overline{c}$-type fix - for instance a plumber changing an entire heating system when the issue was a leak in one pipe. The initial problem is thus solved, but using too many resources. Finally, undercharging and overcharging describe situations where the customer paid the

29. Gottschalk (2018), p2.

wrong price for the solution that was actually implemented. Paying $\overline{p}$ while receiving a $\underline{c}$ fix would be overcharging, and vice-versa. Undercharging is usually overlooked in a static setup, but can occur in dynamic models as a way to deter entry. Depending on what the consumer can observe before, during and after the expert's intervention, fraud is more or less likely and can take these different forms. Strategies can be strictly dominant due to timing: if the consumer does not know their type, overtreatment is likely. But if they cannot observe the implementation phase nor evaluate what solution was put in place *ex post*, and if solution $\overline{c}$ is more costly, overcharging will dominate.

The aim of credence good models is to determine which institutions or state interventions can restore efficiency on the market, i.e. prevent fraud. Within their framework, Dulleck and Kerschbamer (2006) have shown that the market equilibrium exhibits *ex post* efficiency under three conditions. First, if customers have homogeneous preferences, experts cannot perform price discrimination through tariffs. Second, large economies of scope between diagnosis and treatment prevent customers from obtaining a diagnosis with an expensive expert and going to a cheaper one for the implementation. In other words, customers have to commit to an expert. Third, verifiability is key to ensure that the expert's commitments are fulfilled, which prevents overcharging. In the absence of verifiability, liability can restore efficiency as well. They noted that "*verifiability is often secured indirectly through the provision of ex-post evidence*"[30], meaning that customers will ultimately understand the treatment they got through experience. If liability is ensured, they can then seek damages, which prevents undertreatment. Table 2 summarizes the main theoretical contributions to the credence goods literature. The scope is restricted to papers describing expert markets, and empirical applications are left out - see Gottschalk (2018) for a thorough literature review that includes recent empirical evidence. The main takeaways are that in most cases the unregulated market equilibrium is inefficient on credence good markets, and that the nature of fraud depends on how verifiability, liability, homogeneity and commitment are modeled.

The model presented in Chapter 1 relaxes the verifiability and liability hypotheses to match the specificities of the provision of construction and renovation services. In most cases, the outcome is not directly assessable by households. Take the case of insulation: a consumer would agree to a certain type of material, say glass wool, to be put on a certain number of walls. The consumer, however, would not witness the actual installation of glass-wool mats, meaning another material could be installed, or a different thickness, and some hard-to-reach places could be left out, creating thermal bridges. At the end of the project,

30. Dulleck and Kerschbamer (2006), p17.

ASSUMPTIONS DROPPED	EQUILIBRIUM CHARACTERIZATION	EQUILIBRIUM PRICES	LITERATURE
V	**Overcharging**: the $\underline{c}$-type good is sold at price $\overline{p}$. Labels can restore efficiency.	$p = \overline{p}$	Baksi and Bose (2007)
	Full efficiency: private information is truthfully revealed.	$\overline{p} = \underline{p}$	Emons (1997)
L; L and C		$\overline{p} - \overline{c} = \underline{p} - \underline{c}$	Bester and Dahm (2018); Taylor (1995)
H; H and L	**Price discrimination**: the expert can perform over and undertreatment at equilibrium.	$\overline{p} \neq \underline{p}$ in some cases	T. Liu (2011); Dulleck and Kerschbamer (2007)
C and V	**Specialization**: separation of the search- cum-diagnosis cost	$\underline{p} = \underline{c}$ and $\overline{p} = \infty$ or $\underline{p} < \overline{p} = \overline{c}$	Wolinsky (1993); Glazer and McGuire (1996)
	Overcharging: separation of the search-cum-diagnosis cost, and customers with low valuation (v) remain untreated in some cases.	$\overline{p} = c > \underline{p} > \overline{c}$	Pitchik and Schotter (1987); Wolinsky (1993); Sülzle and Wambach (2005)
		$\overline{p} = v > \underline{p}$	Fong (2005)
L and V	**Lemons**: some profitable transactions do not occur and there is undertreatment in equilibrium.	Constant price	Akerlof (1970); Emons (2001)
C	**Overtreatment**: If the penalty for fraud (f) and the frequency of controls are not high enough, all experts perform the major treatment.		Dulleck and Kerschbamer (2009); Alger and Salanie (2006)

Note: Assuming $\overline{p} \geq \underline{p}$ and $\overline{c} \geq \underline{c}$. This table is a modified and updated version of Table 3 in Dulleck and Kerschbamer (2006). Following their notations, four assumptions can be relaxed in the papers listed here: homogeneity of consumers (H), commitment (C), verifiability (V) and liability (L).

Table 2 – Main contributions to the credence good theoretical literature on expert markets

the consumer will not be able to assess these issues, as drywall will have been placed on top. Even if they experience a lower energy efficiency than expected after the fact, they could attribute it to a number of other factors (harsher weather, defective appliances, old windows, etc.). In practice, fraud is persistent in equilibrium on the sector. Consumer satisfaction has been persistently low on the construction market among OECD countries (OECD 2010). In France, a recent evaluation of white certificate spendings [31] measured that savings induced by energy retrofits amounted to only 59% of forecasted savings (ADEME 2019a). The loss came from overestimation of predicted savings (23%), poor policy design (14%), and wrongful installations (4%). Keeping in mind that these estimations come from renovations undertaken in a somewhat stricter setup - households have to apply to get white certificate funding -, malfunctions are a non-negligible issue on the market. The goal of the model in Chapter 1 was to answer two policy questions: why does fraud persist in equilibrium on such a competitive market and do label schemes help prevent it? More specifically, why do unskilled firms still survive in such highly competitive market?

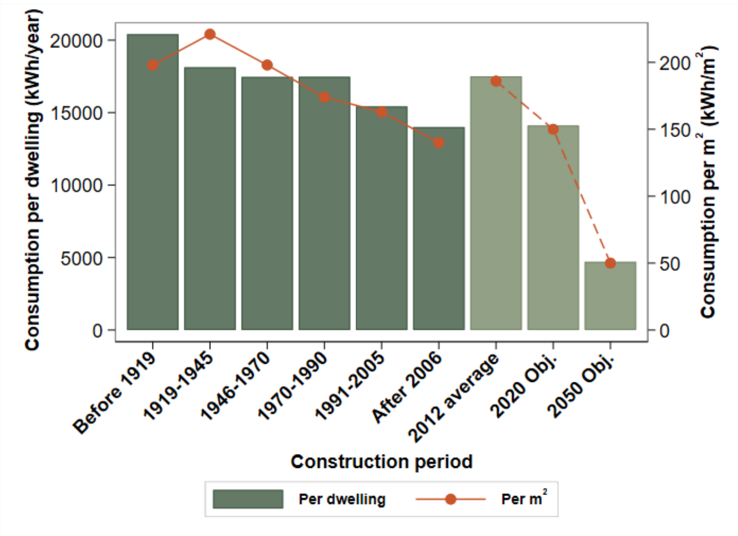
The impact of skill heterogeneity has been been approached by adapting standard credence good models with new assumptions: differences among experts in their choice of an unobservable diagnosis effort (Dulleck, Gong, and Li 2015; Pesendorfer and Wolinsky 2003) or their marginal costs (Alger and Salanie 2006). These contributions assumed that firms differ only in their level of effort, and that information asymmetries induce moral hazard on their part. They were however all assumed to have the same ability, meaning all experts could solve both complex and simple issues. Another strand of literature tackled the issue by setting explicit differences in firms' skills, but assuming their types were observable by the customer (Dulleck and Kerschbamer 2009; Bouckaert and Degryse 2000; Emons 2000; Glazer and McGuire 1996). These models found efficient and differentiating equilibria as consumers could choose their expert's type. In other words, they chose to take a risk or not depending on their preferences and valuations. It means that reliable quality signs can be found on the market, which is not the case for the construction sector. Unobservable firm types were thus introduced in Chapter 1 to study its impact on equilibrium over and undertreatment. Marginal costs are assumed to be homogeneous, in order to focus solely on the impact of skill shortage. Firms compete in a bid setup, making a take-it-or-leave-it offer to the customer that includes a diagnosis and a price. The resulting market equilibrium, which is characterized by both over and under-treatment, is close to reality as unskilled firms' entry is not deterred in most cases. Using it as a baseline, an extension explores scenarios in which a RGE-type label is introduced. Contrary to Bonroy and Constantatos (2008), the main focus is not firms' decision to get the label or not. The analysis is based

31. The white certificate policy is further detailed in Section 4.2 of this introduction.

on comparative statics, assuming only some skilled companies choose to get the label. It is consistent with the current state of diffusion of the RGE label, and with previous contributions on cost barriers preventing skilled companies from getting quality certifications. The analytical results show that such labeling schemes do not deter the entry of unskilled companies. Worse, as introducing a quality label increases the competition among skilled firms, their expected profits decrease. This result is also in line with previous results from Baksi, Bose, and Xiang (2017), who showed that high-end producers have lower profits due to label costs. Ultimately, increasing the number of skilled companies - though training programs for instance - is the only factor found to impact overall quality on the market.

3 Improving quality through innovations

3.1 Securing the perimeter: restricting professional practices and promoting new techniques

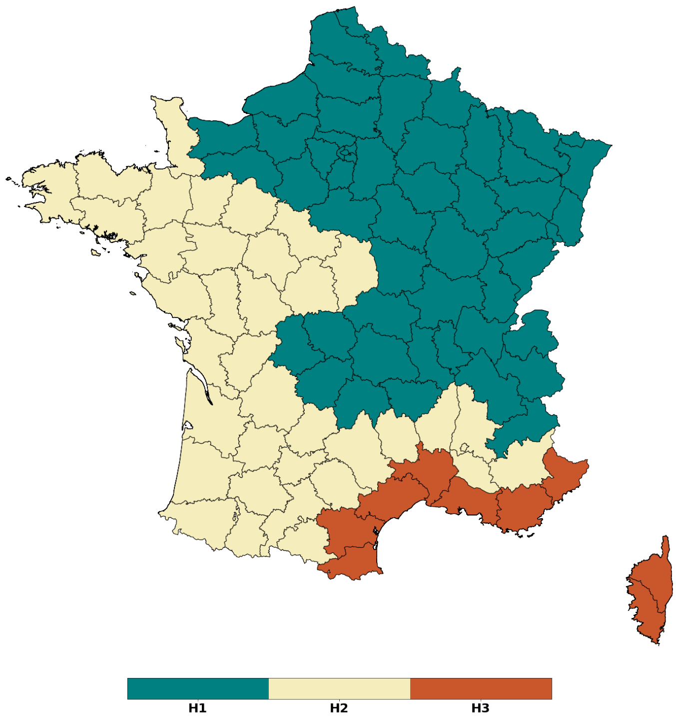


Sources: Author's computations from the Phebus survey (Cnis, 2013) and data found in ADEME (2018a).

Note: Energy consumption refers to residential consumption, all sources combined. For instance, households residing in dwellings built before 1919 have a total annual consumption of 20 thousand kWh on average, equivalent to 198kWh per m^2. The "2012 average" refers to the average consumption of all buildings that existed in 2012, independently of their construction period. Thermal regulation objectives are taken from ADEME (2018a).

Figure 6 – Residential energy consumption (2012)

Beyond skills and workmanship, buildings' energy efficiency relies heavily on the quality of the materials used. There were no general laws restricting construction in France prior to the first Thermal Regulation (RT), introduced in 1974. Even though it only applied to new builds, it set standards in terms of insulation and heating systems. It has been revised over the years to become more and more constraining (1982, 1988, 2000, 2005, 2012). Each revision of the regulation included standards set by quality labels created in between. One dwelling out of ten was however built before 1949, and only 40% of the housing stock was built after 1970 (Insee 2017). In other words, a large majority of the housing stock was built before any regulation was in place. Results from the 2013 "*Performance de l'Habitat, Équipements, Besoins et Usages de l'énergie*"[32] (Phébus) survey conducted by the *Conseil national de l'information statistique*[33] (CNIS) indicated that older buildings were much less energy efficient than their new counterparts (Figure 6). There are currently between 7 and 8 million energy-leaking homes, meaning with a F or G energy label.



Source: ADEME.

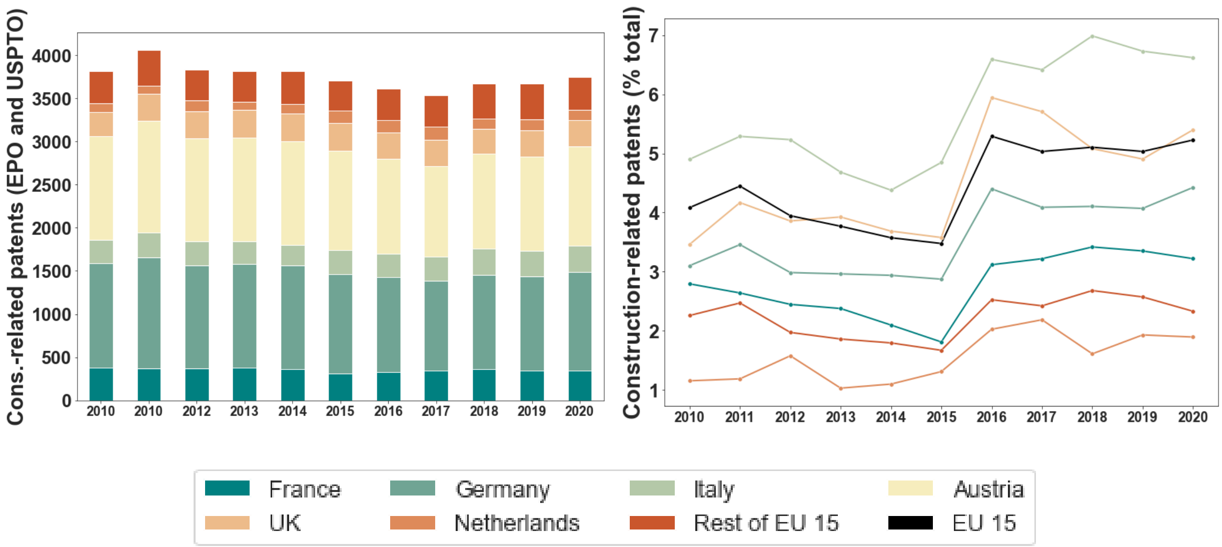
Note: Climate zones represented here were defined by the 2012 revision of the thermal regulation for existing buildings. They are still the reference as per the 2020 revision.

Figure 7 – Climate zones in metropolitan France

32. "*Habitat Performance, Equipment, Needs and Usage of Energy*".
33. "*National Counsel for Statistical information*".

Thermal regulation for *existing* buildings was only introduced in 2007. It notably included the definition of the minimal thermal resistance (R) threshold, which needs to be met after retrofits. To do so, the regulation relies on a material's insulation capacity, taking its thermal conductivity (λ) and its width into account. The standards vary depending on climate zones (Figure 7), which were attributed given winter temperatures in each French department. The minimal requirement is currently 2.2m^{2}K/W for a standard opaque side wall in the H3 zone, but rises to 2.9 in H1 departments (ADEME 2018b). Insulation has been mandatory since 2016 whenever major renovation work is undertaken, such as facade restorations. Improving the quality of materials and techniques used in renovation has become essential, if only to compensate the price increase induced by new thermal norms. Both thermal regulations have been replaced by the "*Environmental Regulation*", applicable since 2022. They introduced mandatory carbon audits and set new standards for insulation requirements and materials. Setting consumption reduction goals and constraints on materials encouraged contractors to look for new and better products to install, both for new construction and refurbishment projects.

Thermal regulations have allowed lawmakers to constrain professional practices, while promoting new ones through policies supporting innovation. In terms of construction-related patents, France is one of the driving forces in Europe, even though the number of applications to the European Patent Office (EPO) and US Patent and Trademark Office (USPTO) has declined by 10% over the 2010-2020 period (Figure 8, left). Four French construction firms ranked among the top 1 000 in the EU Industrial R&D Investment Scoreboard, namely Saint-Gobain, Bouygues, Tarkett and VICAT (ECSO 2022). Germany and Austria have however remained leaders in the sector, accounting for 60% of patents every year. On average, construction-related patents have represented 3.5% to 5.2% of all applications for EU-15 countries (Figure 8, right) - with the exception of Austria, where the share was close to 40-50%. Innovation in construction has been steady over time, but relatively low relative to the economic importance of the sector. For context, R&D spending accounted for only 0.1% of the annual added value in 2018 (Crépon and Charrue 2018). Additionally, innovation uptake is hindered by structural barriers. As firms usually obtain contracts in a bid-like manner, they tend to keep their costs as low as possible, which makes more expensive innovative technologies less attractive. Breakthrough product innovations, such as recycled rubber or cross-laminated timber, seem to have a hard time finding an audience, despite their environmental performance. From an insurance perspective, contractors are responsible for the proper functioning of the appliances they install in the long-run, and tend to favor materials with a proven track record. Further, new technologies sometimes require skills from different traditional trades, hence the need for updated professional training to boost their diffusion. Fostering innovation in the construction sector was thus an explicit goal in the 2018 French PREB regulation mentioned earlier. The estimated budget dedicated 40 billion euros to boost innovation. An additional 30 billion was planned to be directed towards professional training, which should benefit an estimated 65 000 workers over time.



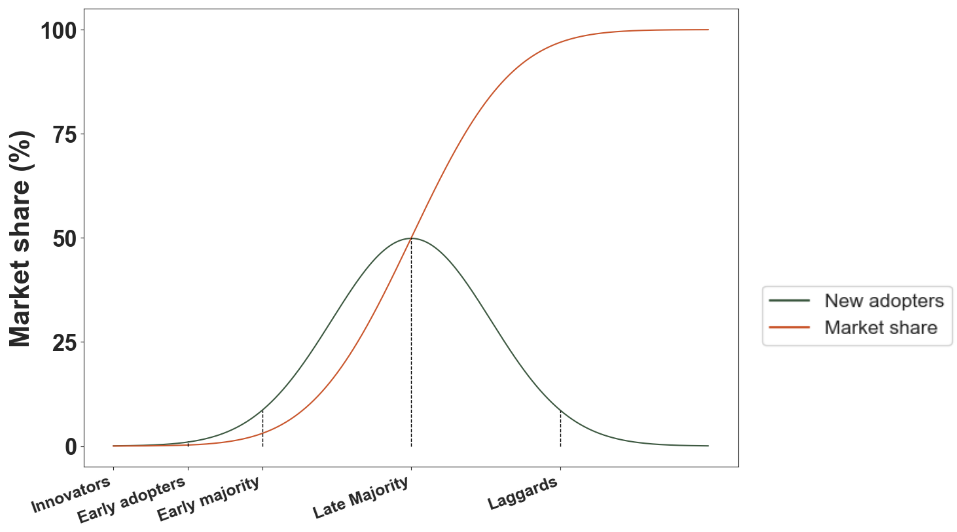
Sources: Author's computations from ECSO, Eurostat and USPTO data.

Note: Patents are presented by the country of origin of the applicants. The Y-axes provide the number of patents related to construction (left) and the share they represent within the total of applications from each country (right). For instance, 381 patents originated from France in 2010, which accounts for 2.8% of the patents filed by entities in France that year. Note that Austria is not depicted on the right-hand graph for visualization purposes: construction-related patents accounted for 40 to 50%of all patents submitted by applicants in Austria over the period.

Figure 8 – Construction-related patents from EU-15 countries (2010-2020)

3.2 From the lab to the market: the econometrics of new technology diffusion

What happens when an invention hits the market? So far, it has been established that construction and refurbishment activities are heavily regulated, with increasing standards on energy efficiency. More and more materials are becoming obsolete, yet patenting seems to lag behind compared to other markets. This makes it all the more important to understand what happens to these new products when they meet demand: "*Innovation is more* *than a new idea or an invention. An innovation requires implementation, either by being put into active use or by being made available for use by other parties, firms, individuals or organizations. The economic and social impacts of inventions and ideas depend on the diffusion and uptake of related innovations*"[34] (OECD 2018). In theory, a *good* innovation, say, one that increases every firm's expected profits, should immediately replace the technology that came before it. In practice, however, diffusion is far from an automatic and immediate process. New products represent a risk, as their actual performance remains unknown until customers have tried them out. Rogers (1962) first highlighted the importance of the diffusion process when studying the impact of innovations on our social and productive systems, depending on how fast information spreads and on customers' preferences. He built a typology characterizing adopters based on their time of adoption, going from "*early adopters*" to "*laggards*" (Figure 9). Assuming a normal distribution, it yields a S-shaped curve of cumulative adoption, which can be interpreted in terms of market share evolution. It is usually considered that an innovation is self-sustainable on a market once the late-majority point is passed, meaning more than 50% of agents have adopted.



Source: Adapted from Rogers (1962).

Note: It is assumed that new adoptions follow a normal distribution, hence the S-shaped cumulative distribution.

Figure 9 – Diffusion of innovations according to Rogers (1962)

This path of diffusion was observed in the data but lacked theoretical foundations until the contributions of Mansfield (1963) and Bass (1969). Mansfield's epidemic model relied on

34. OECD (2018), p44.

the assumption that firms adopt as soon as their expected profits after adoption become positive. Diffusion is driven by heterogeneous reserve prices and the idea that the cost of the innovation will decrease over time. The Bass model went further, as diffusion was approached as a self-contained process. Diffusion was assumed to be related to three parameters: the size of the market, the coefficient of innovation measuring the impact of external factors (eg. advertising) on the probability of adoption, and the coefficient of imitation measuring the word-of-mouth effect. The idea was that the probability of adoption increased over time as more and more information became available through past adopters. These early models have since been adapted in many different ways, in particular by Stoneman (1981) who developed a microeconomic approach with profit-maximizing firms and Bayesian learning. This profitability-based approach generates differences in adoption timing, and is used in Chapter 2 to derive the empirical results.

Empirical applications have showed that diffusion curves vary depending on technological characteristics, national contexts and market specificities. This literature review focuses on empirical papers and on adoption by firms, also leaving out macroeconomic contributions on international patterns - for reference, Stoneman and Battisti (2010) have put together an in-depth review of the main contributions to the field. I approached diffusion in two ways: "*inter-firm*" diffusion, measuring the number of new adopters over time, and "*intra-firm*" diffusion, describing the intensity of usage by adopters. The former is the most documented, in relation to firm characteristics (Zolas et al. 2021), benefits (DeCanio and Watkins 1998) and market parameters (Karaca-Mandic, Town, and Wilcock 2017; Allen, Clark, and Houde 2009) for instance. The latter has been linked to firm size (Astebro 2004), sometimes with differentiated effects on first adoption and on intensity of usage (Hollenstein 2004, Arvanitis and Ley 2013; Battisti, Canepa, and Stoneman 2009). It is often overlooked, yet low intensity of usage may hinder the overall diffusion of an innovation on a market (Battisti and Stoneman 2003). Table 3 sums up the main results from the firm diffusion literature, by methodology and data type. First, it should be noted that these papers focus on ICT technologies or on productive technologies, meaning innovations assumed to decrease firms' costs. A specificity of the construction sector is that most material innovations are designed to increase the comfort and safety of people residing in buildings. Adoption may be the best choice for occupiers, but contractors are the ones making the production decisions. There is very little evidence on construction firms' motivations to adopt, yet their intermediary role is central to the diffusion of new products on the housing market. Second, very few estimations actually rely on panel data and they seem to yield somewhat different results.

The approach taken in Chapter 2 relies on the simultaneous estimation of both inter and intra-firm diffusion using a panel double-hurdle model. This class of estimator originated

DIFFUSION TYPE	DATA	LITERATURE	MAIN VARIABLES
Inter-firm	Cross section	Zolas et al. (2021)	Firm size (+)
		Giotopoulos et al. (2017)	R&D spending (+), % skilled workers (+), decentralized management (+)
		Karaca-Mandic, Town, and Wilcock (2017)	Competition (+)
		Pontikakis, Y. Lin, and Demirbas (2006)	Experience with previous versions (+)
		DeCanio and Watkins (1998)	Firm size (+), yearly earnings (+), growth rate (+), insider control (-)
		Dunne (1994)	Firm size (+)
	Panel	J. Gómez and Vargas (2012)	Experience with previous versions (+), R&D spending (+), workers' education (+), firm size (+)
		Allen, Clark, and Houde (2009)	Competition (-)
Intra-firm	Cross-section	Stucki and Woerter (2016)	Carbon taxes (+), regulation (+), firm size (+), R&D activity (+)
	Panel	Bresnahan, Brynjolfsson, and Hitt (2002)	Workers skills (+) and education (+)
Inter & intra	Cross section	Battisti, Canepa, and Stoneman (2009)	**Intra**: Rank effects (+), firm size (-); **Inter**: Proportion of graduates employed (+), firm size (+), R&D indicator (+)
		Astebro (2004)	Sunk cost of learning (-), plant size (+)
		Hollenstein (2004)	**Intra**: Firm size (+), absorptive capacity (+), technology cost (-) anticipated benefits (+); **Inter**: Efficiency gains (+), epidemic effects (+)

Note: The (+) and (-) indications in the "Main variables" column refer to significantly positive and negative coefficients, respectively. "Firm size" refers to the number of employees; "Insider control" is computed as follows: $\frac{\text{Shares owned by directors}}{\text{Shares owned by directors+Total shares}}$.

Table 3 – Main empirical contributions to the literature on the diffusion of new technologies among firms

with Cragg (1971), as a generalization of the Tobit model. The idea is that the quantity purchased by a firm can be separated into two decisions: the decision to adopt, which is a binary variable, and the quantity maximizing their profits. In the Craggit setup, that quantity can be 0 in the second hurdle, which is not possible in a simple Tobit. To my knowledge, only two attempts have been made to adapt and estimate hurdle models to panel data. Dong, Chung, and Kaiser (2004) extended the standard Probit-Normal formalization of the two hurdles to estimate customer demand for milk, and Gillingham and Tsvetanov (2019) used a fixed effect Logit-Poisson approach on solar panel installations. Both papers however focused on customer choices, not firms. The hurdle model developed in Chapter 2 also assumes a Logit-Poisson distribution of the hurdles, but accounts for spatial effects in a way that was not done by Gillingham and Tsvetanov (2019). Specifically, the spatial adoption index developed by R. Dubin (1995) was extended to a panel setup and included in both hurdles. Each firm's adoption decision depends on past adoptions, with the impact of other firms' decisions decreasing as geographical distance between them increases. The model can thus capture evolutive word-of-mouth effects, allowing their intensity and effect to vary between the two hurdles. The model is run on scanner data containing information on French construction firms' drywall purchases from 2017 to 2020, merged with administrative information (experience, RGE, size, etc.) and local variables (household revenues, competition, etc.). Estimated parameters are obtained using a GMM procedure for the hurdle model combined with a step-wise method to identify the adoption index parameters. The results support that both firm characteristics and local market determinants drive the demand for the innovative product: adoption is driven by large companies in a competitive environment. There is also evidence of a positive word-of-mouth effect on intra-firm diffusion, but it disappears when controlling for the main store visited, suggesting that store-level loyalty is a key factor. Overall, these results suggest interesting directions for diffusion and industrial policy on the construction sector.

3.3 Back to the lab: insights from experimental economics

In Chapter 2, construction professionals' preferences are deduced from their purchase behaviors: their choice of material indicate how they rank different products. Further, the analysis is limited to one product, while innovation on materials can improve various characteristics. Further, innovation uptake has been found to be relatively slower on the construction market than in other sectors for any new material. It has been attributed to a certain conservatism of contractors when it comes to their technique and the materials they use (eg. Du et al. 2014), but is it because they do not value innovation or do other factors come into play? Experimental economics provide different tools to study individuals' decision making processes relying on stated preferences. Instead of observing real-world behaviors, these methods present the experiment's participants with hypothetical scenarios. They offer the possibility to predict future behaviors on innovations that may not exist yet and have the advantage of avoiding confounding factors such as price shocks. In other words, as the context is controlled, the information gathered on preferences is less noisy and can be more detailed. Among these methods, the Discrete Choice Experiment (DCE) approach was initially theorized by Louviere and Woodworth (1983) as an alternative to revealed preference models to study customer allocation. The core assumption is that consumption goods are indivisible bundles of characteristics. A class of goods can thus be seen as a list of potential attributes, each good being characterized by the level of these attributes. In practice, DCE respondents are presented with choice cards describing hypothetical situations and are asked to rank the different alternatives. Contrary to scaling methods for retrieving stated preferences, they are not asked to assign a particular value to any of these attributes. Instead, their valuation of the attributes and levels is derived using a random utility framework applied to the series of choices they made.

Following D. McFadden (1973), the random utility model describes an individual i's utility derived from choice j, denoted $U_{i,j}$, as a linear composition of the good's attributes $X_{i,j}$ and a stochastic element $\epsilon_{i,j}$. In the specification used in Chapter 3, a random-parameter approach was used for the estimations, meaning that the coefficients β_i can differ between individuals to reflect preference heterogeneity. Formally, the utility of an individual i choosing j is given by: $U_{i,j} = X_{i,j}\beta_i + \epsilon_{i,j}$. Alternative j is chosen if and only if $U_{i,j} > U_{i,k} \quad \forall k \neq j$. The probability that an individual chooses alternative j is then estimated using the mixed logit model (D. McFadden and K. Train 2000)- the mixed logit probability is computed taking the integral of the conditional logit probability $\mathbb{P}_{i,j}|\beta_i$ over all β_i.

The main challenge when designing a DCE is its dimensionality. Enough attributes and levels must be included in order to capture all the main aspects of the choices respondents have to make in real-world situations. However, the more attributes are included, the higher the number of iterations each respondent has to complete, which can lead to cognitive fatigue. The DCE method has been applied to a variety of topics and contexts, mainly in health economics (Soekhai et al. 2019) and to measure environmental valuations (Rakotonarivo, Schaafsma, and Hockley 2016; Carson and Czajkowski 2014). Innovation diffusion has been less extensively studied, and most papers have focused on customers rather than firms so far. Table 4 provides a summary of the existing DCEs on innovation uptake. Information was found to play a central role in agents' decisions, but the effect

FOCUS	LITERATURE	CONTEXT	DCE DIMENSIONALITY	MAIN RESULTS
Information	Van Rijnsoever, Van Mossel, and Broecks 2015	Sample of 1500 Dutch households, asked about the installation of energy technologies	3 attributes with 3 levels (long-term problems, security of supply, spatial impact), 1 binary attribute (private costs) and price as a continuous variable.	Introducting new information through labels shifts preferences away from nuclear and biomass-fueled energy technologies.
	Q. Chen, Anders, and An 2013	Sample of 99 consumers in Canada, each respondent received a $30 allowance to spend on meat with different innovative packaging.	3 attributes (price, ageing, shelf-life), with 3 levels each.	WTP to pay for vacuum-sealed products is increasing in all attributes but price, and their responsiveness to information.
Environmental regulation	Jones et al. 2013	Sample of 400 households in Vietnam asked about electric motorcycles.	9 attributes (price range, refuel time, operating cost, maintenance cost, acceleration, speed, license requirement, sales tax) with various levels (2 to 6).	Sales tax can efficiently push customers towards electric vehicles.
	Ewing and Sarigöllü 2000	Sample of 881 commuters in Québec asked about clean-fuel vehicles	8 attributes (purchase price, maintenance cost,cruising range, refueling time, acceleration, polluting emissions) with various levels (2 to 4).	New regulation (carbon tax on fuel, special lanes for electric vehicles) are not effective if hybrid vehicles' performance is not equivalent to fuel-powered ones.
Firms	Jourdain et al. 2020	Sample of 120 farmers in Laos asked about alternative cropping systems.	Five attributes (labor, cash outflow, maximum economic loss, soil fertility, income).	Evidence of preference heterogeneity towards their perception of risk and economic losses.

Note: "DCE" refers to Discrete Choice Experiment; "WTP" refers to Willingness To Pay.

Table 4 – Contributions to the literature on innovation uptake using a DCE

of the source of information has not been addressed. It may have a non-negligible impact on contractors, who can obtain product information form various sources (eg. material retailers, manufacturers, etc.) and not value them equally. Different types of regulations were also explored in these DCEs, and their effect on decisions seems to be context-specific. These DCEs also vary in terms of dimensionality and attributes, except for the price which is always included. Having a price in the regressors is useful to conduct cost-benefit analysis, as it allows the transformation of coefficients into monetary values. Assuming the price is a continuous variable and including a *status quo* level in all attributes, respondents' willingness to pay for each attribute level can be computed. It also applies to negative attributes, for which a perceived monetary cost can be deduced.

The experimental design in Chapter 3 characterizes hypothetical innovative materials using three attributes (green improvements, technical improvements and information source) with three levels, while the price variable has five levels. As contractors do not use the same materials in their day-to-day jobs depending on their trades, an additional challenge was to find a way to present these hypothetical materials that could be understandable by any respondent. It was addressed by first having respondent select a product they were familiar with within a list and report the average price they pay for it. The hypothetical materials were then described by comparison to this reference product, and the price was formalized as a price increase. Only strict improvements were considered, meaning respondents never had to sacrifice an attribute level to obtain an improvement on another dimension. Two questions were asked for each choice set: what is the better option out of the two hypothetical products and would they choose to spontaneously try it. The drivers of adoption were then determined by defining reference material as a choice with no improvements, no price increase and the information source being the respondent's own experience. Additional information was gathered on respondents to explore policy options, in particular about the labels their company has and their education level. The Technology Readiness Index (TRI) developed by Parasuraman and Colby (2015) was also included to cross-validate the DCE design. Mixed logit regression results suggest that there is heterogeneity among construction professionals. All improvements were found to have a positive valuation, but the willingness to pay for technical improvement was found to be higher than for green characteristics. Innovative characteristics are thus valued, but the cost associated to the risk of having to trust information coming from any source rather than their own experience was estimated to be greater. It could explain why innovation uptake is rather slow on the construction market and provides ground for policy design. Labels were also found to reflect biases in respondents' preferences, validating the quality of the signal they send to contractors' customers.

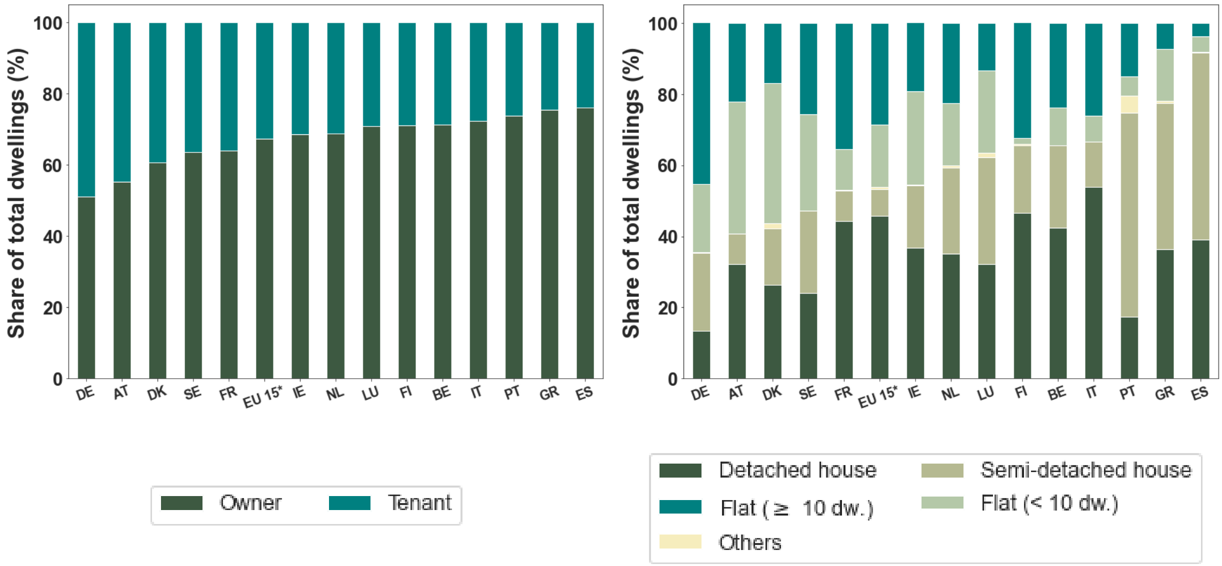
4 Household policies

4.1 No place like home: access to decent housing and ownership

In addition to housing supply regulations, policies have been implemented to alleviate households' financial burden and promote decent housing. In France, housing policy is usually traced back to the 1956 winter truce law, which is still active. It forbids the eviction of tenants between November 1^{1st} and March 31^{1st}. Housing benefits were introduced in 1977, with different rates indexed on applicant's revenues. Landlords have been targeted by regulations in terms of comfort and energy efficiency since 1989: "*Le bailleur est tenu de remettre au locataire un logement décent [...] répondant à un critère de performance énergétique minimale*" (89-462 , Article 6)[35]. This principle was reiterated, at least symbolically, in 1990 with the Besson law, which proclaimed a universal right to housing. Ten years later, the law on *Solidarité et Renouvellement Urbain*[36] (SRU) deeply reformed the housing code around two axes. First, it aimed to promote universal access to fit dwellings. Its fifth article wrote the definition of "*decent housing*" into law, which includes having a livable surface larger than $9m^2$ and a minimal ceiling height of 2.2m. Second, it set sustainable development regulations in place, discouraging further land artificialization for urban development. The state has also historically intervened to help low-income households access property, with various low-interest loan schemes introduced since the 1970s. The *Prêt aidé à l'accession à la propriété*[37] (PAP) and the *Prêt aidé à taux ajusté*[38] (PAJ) both worked on the same principle, that is, to facilitate access to property. They were indexed on revenue, localization and family size and were meant to cover a property purchase or renovation expenses if they exceeded 35% of the total cost of the operation. They set the ground for a long line of housing aid policies, especially after the suppression of revenue-based conditionality in 1991.

Access to property has been a priority for most West-European countries since the 1950s. The current European housing stock is composed of 70% of owner-occupiers and individual houses make up 60% of dwellings (Figure 10). Continuous state intervention has led to a drastic increase of comfort since the 50s. Data from the Insee's housing survey shows that only 25% of dwellings had indoor toilets after WWII, and a mere 10% had a tub or a

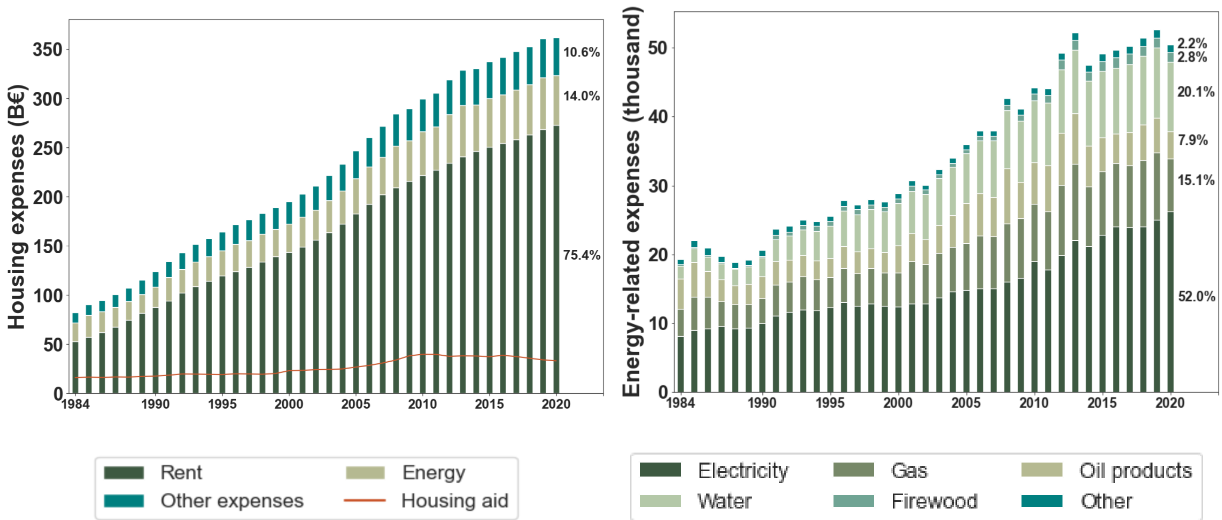
35. "*The landlord is required to provide a decent dwelling to their tenant [...] and it has to meet minimal energy efficiency standards*".
36. "*Solidarity and Urban Renewal*".
37. "*Assisted loan for home buyers*".
38. "*Assisted loan with an adjusted rate*".



Source: Author's computations from Eurostat data.

Note: "EU 15*" refers to the EU 15 group minus the United Kingdom. The Y-axis provides shares among the total number of occupied dwellings in 2019. For instance, 66% of occupied dwellings in France were houses and 64% of occupants were owners.

Figure 10 – Housing per tenure status and dwelling type (2019)



Source: Author's computations from Insee data.

Note: Rents refer to actual rents and imputed rents, meaning the rent owner-occupiers would pay if they did not already own their dwellings. The Y-axis provides the value for each graph, in thousands. For instance, the value of total non-rent expenses went from 19 to 51 thousands between 1984 and 2020.

Figure 11 – Total occupier expenses (1984-2020)

shower. Currently, only 1% of dwellings do not have basic sanitation, meaning an indoor restroom and shower (Insee 2017). Only 1.3% of dwellings were considered unfit per SRU standards in 2013, with 0.6% of households living in a flat or house deemed insalubrious or dangerous by the judicial system. This, however, does not mean that every dwelling is equipped to insulate the occupier from energy poverty and its downstream effects. Only 58.8% of dwellings had double glazing in 2001, against 83.6% in 2013. There is still room for improvement, especially for low-income households. Within the bottom 30%, which represented roughly 8.2 million households in 2013, 20% suffered from thermal discomfort, meaning they had to feel cold inside during at least 24 hours due to unpaid bills or malfunctioning appliances. A third of them were energy-poor, and 7.3% suffered from both issues. Energy consumption per capita has on average decreased since the 1970s, which is in large part due to better insulation in new dwellings (Dupont 2018). Total public expense in housing aid peaked in 2010 and has been decreasing ever since, which coincides with the introduction of retrofit funding schemes Figure 11). Still, when looking at the existing housing stock, energy remains the main expense for households outside of rent.

4.2 The carrot and the stick: aid and regulation for energy retrofits

Over the 2010-2020 decade, policymakers' objectives went from ensuring decent housing to promoting *efficient* dwellings, increasing energy-efficiency requirements on existing dwellings and implementing financial aid schemes for energy retrofits. Focusing first on homeowners' obligations, legislation was gradually introduced to make energy retrofits mandatory. In 2007, the *Réglementation Thermique des Bâtiments Existants* (RTE) *par Elément*[39] defined a baseline energy performance to achieve after a significant renovation, for every dwelling built after 1948 or that has a surface larger than 1000m^2. It targeted renovations that include major work on walls, roofs or floors, glass walls, heating, hot water production, ventilation, lighting and renewable energy appliances. A "*global RTE*" was adopted the following year, applicable to projects whose costs exceed 25% of the building's value. It established mandatory requirements in terms of heating efficiency for renovated dwellings, with a maximal yearly energy consumption of 195 kWh/m^2. In the longer run, energy-leaking dwellings will be deemed unfit for the rental market. By 2025, landlords will not be allowed to rent out dwellings with a consumption exceeding 420 kWh/m^2. This corresponds to categories F and G on the DPE scale, which account for 17% of the housing stock (CGEDD 2020).

39. "*Thermal Regulation of Existing Buildings by element*".

Higher requirements came with aid schemes to ease homeowners' financial burden. The 2005 *Programmation fixant les Orientations de la Politique Energétique*[40] (POPE) law introduced policy tools to improve the energy efficiency of the existing housing stock. It also created the *Certificats d'Economie d'Energie* (CEE), known as "*White Certificates*" in other European countries, mandating energy producers to invest in energy retrofits for their clients (households, firms, public agencies). White certificates allow suppliers to meet their target in a variety of ways, either by directly financing retrofits, buying certificates from their competitors, or paying a fine if they do not reach the target. This scheme was the first out of the current five financial schemes directed towards energy retrofits in France. The program has had four application periods to date, with increasing energy savings objectives attached to each of them. The first period went on from 2006 to 2008, with a combined objective of 54 TWh - they have ultimately saved 65 (ADEME 2019a). The second period (2011-2014) had a more ambitious cumulative objective of 345 TWh. The third period, from 2015 to 2017, saw the introduction of "*energy-poverty certificates*", meaning 150 TWh of savings have to be achieved for energy-poor households in addition to the 700 TWh target for the period. As energy savings measured at the end of each period exceeded the requirement by far, a much higher target of 1 200 TWh was set for the fourth period (2018-2021).

The POPE law also created the *Crédit d'Impôt pour le Développement Durable*[41] (CIDD), a tax credit in favor of energy retrofits. It covered a share of the cost of appliances and materials, up to 16 000€ for a couple. It was revised in 2012 to restrict beneficiaries to low-income households, and to incentivize homeowners to engage in large retrofits rather than repeated one-offs over time. The CIDD "*bouquet de travaux*"[42] offered a 25% tax credit if at least two retrofit actions were undertaken - insulation and double glazing for instance -, while the CIDD "*Action unique*"[43] was set at only 15%. A further reform was voted in 2014, as the CIDD was replaced by the *Crédit d'Impôt à la Transition énergétique*[44] (CITE). Differentiated rates were set depending on the presumed efficiency of the work. For instance, the tax credit for double glazing was lowered to 15%. The main drawback of that tax credit was that households still had to be able to cover the full cost before receiving the aid (CGDD 2018). The current version of the policy, following the 2020 *MaPrimRénov'*[45] reform, has turned the tax credit into a grant scheme and removed conditions on revenue.

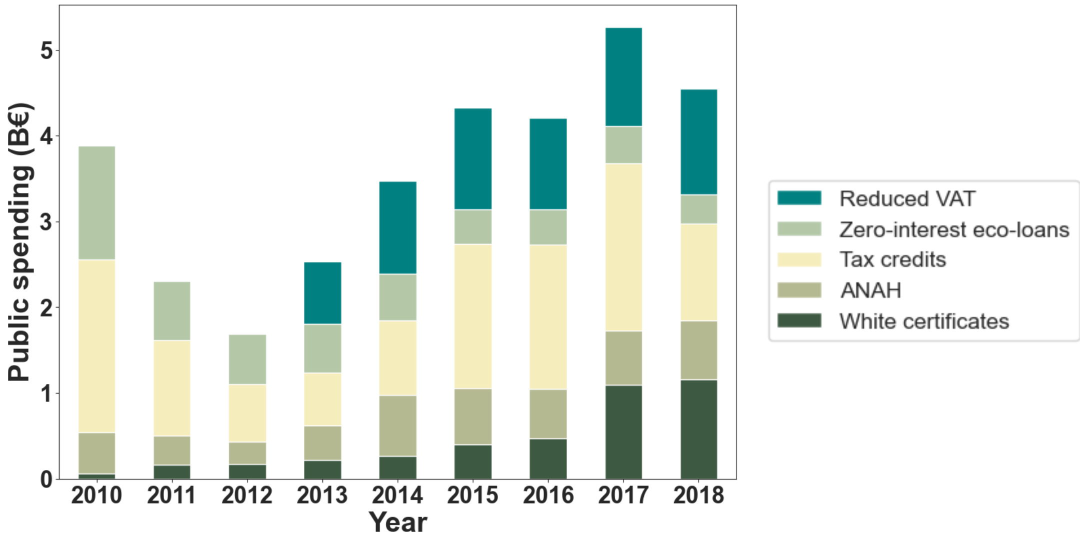
40. "*Plan setting the Goals of the Energy Policy*".
41. "*Tax Credit for Sustainable Development*".
42. "*Bundle of work*".
43. "*Singular action*".
44. "*Tax Credit for the Energy Transition*".
45. "*MyReno'Grant*".

The *Eco-prêts à taux zéro*[46] (EPTZ) were implemented in 2009 as another alternative. Similarly to white certificates, the state does not directly grant money to households. Instead, it relies on private banks to loan funds to households at a zero interest-rate. The loss in terms of interests is then paid back to the banks by the state. This policy is closer to the loan programs developed for first time buyers in the 1970s-1980s, which illustrates how housing aid and energy policies have been progressively blending in France since 2010. However, as of 2019, French households had contracted less than 40 000 EPTZ in total, which was much below initial objectives. The lack of attractiveness of the scheme can be related to a general context of low interest rates over the period and by the competition with the other financial aid opportunities (AN 2021). All three policies were subjected to the *Eco-conditionalité des politiques publiques*[47] law adopted in 2013. Households now have to hire an RGE company to benefit from financial aid through one of these schemes. This measure was taken to ensure a baseline quality of retrofits, given the significant cost of these policies for the state.

Two other policies are currently in place to make retrofits more accessible. Introduced in 2010, the *Fonds d'Aide à la Rénovation Thermique*[48] (FART), now known as the ANAH's *Habiter Mieux*[49] program, provides grants to energy-poor households. Additionally, reduced VAT rates are applicable for retrofit activity, which should lower the cost for firms and ultimately their upfront prices. Both policies do not require RGE contractors. These five policies induced a non-negligible cost for the state, reaching more than 4 billion euros in 2018 (Figure 12). Apart from these national policies, complementary smaller-scale schemes have been set up. For instance, the *Fondation Abbé Pierre* NGO launched the *Toits d'abord*[50] program, targeting people facing extreme hardship. With the help of departmental assemblies, they provide funds to build or renovate social housing. Using white certificates, the Effy group set their *Pacte Energie Solidarité*[51] in 2013, offering free retrofits to low-income households - for the symbolic price of 1€. A multitude of schemes have also been developed by local government institutions (regions, departments and cities) to provide additional retrofit funds, but they have not been properly identified to date. They vary in their funding, global budget and the type of households they target.

In practice, individual retrofits remain hard to track. Early evaluations of the PREB's objectives showed that the 500 000 annual retrofit goal was far from being reached

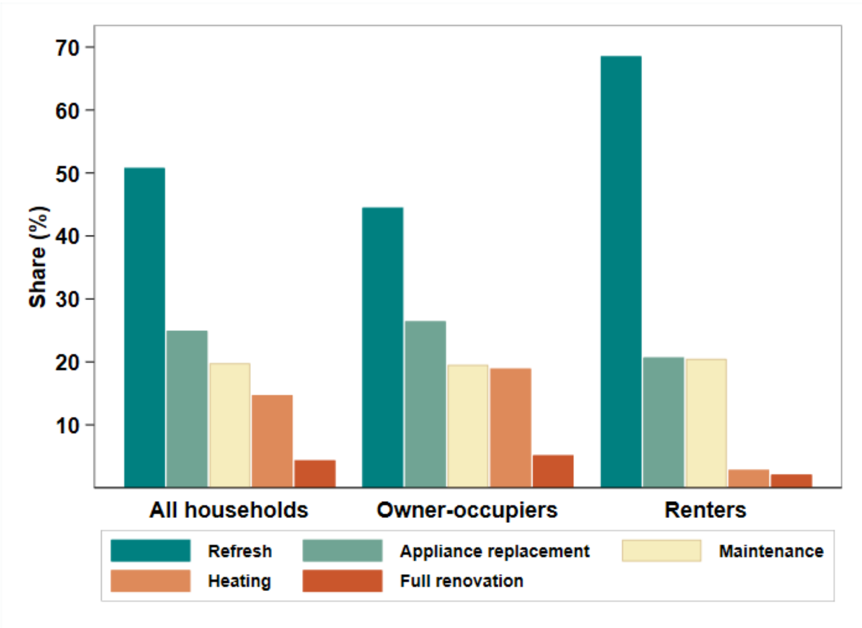
46. "*Zero-interest eco-loans*".
47. "*Eco-conditionality of policies*".
48. "*Assistance Funds for Thermal Renovation*".
49. "*Better Living*".
50. "*Roofs first*".
51. "*Energy Solidarity Pact*".



Source:Author's computations from various official sources (see Chapter 4 for details).

Note: Public spending refers to what households actually received during each given year. For instance, French households perceived 3.9 billion euros in 2010.

Figure 12 – Total spending on financial aid schemes (2010-2018)

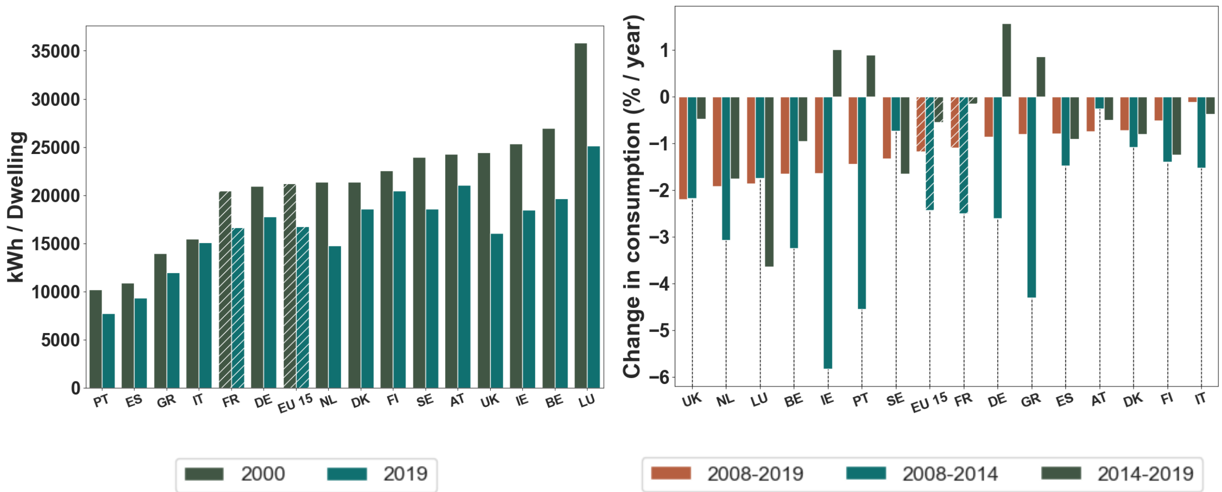


Source: Author's computations from the French Housing Survey (Insee, 2013).

Note: Households may report several motives, hence the sum of bars may not be equal to 100. For instance, among all households who reported renovations, 14.7% cited heating system replacement as a motivation. This rate reached 18.9% among owner-occupiers and fell to 1.8% among renters.

Figure 13 – Renovation motives per occupation status

(ADEME 2019b). Previous results from the 2013 Insee Housing Survey indicated that 30% of households had undertaken renovations in the twelve months preceding the survey (Insee 2017). Yet, 50% of those renovations were solely meant to refresh the look of the dwelling, 25% aimed to replace outdated and out-of-use equipment, and 20% were routine maintenance work. Owner-occupiers were almost the only respondents citing energy efficiency or heating system replacement as motivations (Figure 13). Among homeowners, only 12% received aid to found their retrofits. Crépon and Charrue (2018) more recently estimated that there were 8 million retrofits in 2018, which is 20 times more than the number of dwellings built that year. However, only 38% of these renovations were estimated to have an impact on energy efficiency. Similar figures were found in the ADEME's "*Enquête sur les travaux de rénovation énergétique dans les maisons individuelles*"[52] (TREMI) survey (ADEME 2018a). Using observations on retrofits conducted during the 2014-2016 period, they found that more than 5 million houses were renovated in 2015. Only 25% of these retrofits led to a significant change in energy efficiency - meaning the house's DPE label went up by at least one category.



Source: Author's computations from the Odyssée-Mure survey.

Note: The EU 15 group was taken as a reference for data continuity. The Y-axes provide the average consumption per dwelling (left) and its annual evolution considering different time periods (right). For instance, French households consumed on average 20.5 thousand kWh per dwellings in 2000, against 16.6 in 2019. The average decrease was 2.5% every year between 2008 and 2014, against 0.2% from 2014 to 2019.

Figure 14 – Consumption per dwelling (2000-2019)

Overall, residential energy consumption has decreased since 2000 in Europe (Figure 14). The decline was much faster during the 2008-2014 period than from 2014 to 2019, and

52. "*Survey on energy retrofits of individual houses*".

France appears to be close to the EU 15 average. Higher energy efficiency standards in new construction certainly drive part of this evolution, but the exact contribution of retrofits remains to be assessed.

4.3 Is the game worth the candle? Evaluating the impact of aid schemes

As such, French households currently have access to a variety of financial aid schemes, depending on their revenue and the type of work they are considering. Energy-poor households, who make up for roughly 14% of the population (I4CE 2018), are targeted by specific policies. Yet, more than a decade after their implementation, little is known about the *in situ* efficiency of such policies to decrease the residential demand for energy.

The determinants of household electricity consumption has been extensively studied empirically since J. A. Dubin and D. L. McFadden's (1984) work using US data. Their model has been refined, allowing for correlation between choices regarding electricity-using appliances and overall consumption (Bernard, Bolduc, and Belanger 1996), heteroscedasticity (R.-S. Lee and Singh 1994) or focusing on certain demographic groups (Liao and Chang 2002). Recent papers also extended the set of explanatory variable, including finer household characteristics (Vaage 2000), panel data (B. Halvorsen and Larsen 2001) or local temperatures (Mansur, Mendelsohn, and Morrison 2005). The most consistent factors driving households' energy consumption across all surveys are their dwellings' physical characteristics, such as their size or the neighborhood's density, their socioeconomic status and the price of energy (R. Halvorsen 1975; Hartman and Werth 1981; Reiss and White 2005). Rehdanz (2007) showed that among German households, renters were more responsive to price changes than owner-occupiers regarding residential space heating expenditures. Landlords seemed to have less incentives to invest in energy-efficient accommodations than owner-occupiers, as in most cases they could not compensate for the cost of the retrofit with a rent augmentation. Other factors found to significantly impact energy consumption include the age, ethnicity and number of household members (Poyer and Williams 1993; Poyer, Henderson, and Teotia 1997). In France, Risch and Salmon (2017) found little effect of household characteristics, while dwelling and climate-related variables explained most of the consumption per square meter. Larger families were however found to be more likely to be energy-poor, whereas households living in renovated dwellings had a lesser predisposition (Belaïd 2018). Households' behaviors and attitudes towards energy savings have also been established as a driver of their consumption in France. Bakaloglou and Charlier (2019) found that households with a preference for comfort had an over-consumption of 10%, reaching 18% for high-income households, and that poorer households were more likely to live in non-efficient dwellings. Women and non-single individuals were found to exhibit more favorable attitudes towards energy-savings (Belaïd and Joumni 2020), while age impacted behaviors following an inverted U-shape (Belaïd and Garcia 2016).

Beyond household and building characteristics, a growing body of work has delved into the negative impact of housing density on per-capita residential energy consumption (P. P. Combes and Gobillon 2015). This phenomenon is known as the "*urban heat island*": local temperatures are significantly higher in cities than in rural areas, mostly due to a more intense human activity. This negative relationship between energy consumption and housing density has been corroborated by various studies in Québec (Larivière and Lafrance 1999) France (Lampin 2013), China (Y. Liu, Song, and Arp 2012; H. Chen, Jia, and Lau 2008), Norway (Holden and Norland 2005) and the USA (Erwing and Rong 2008a), while Kaza (2010) found no significant effect. As temperatures tend to be higher in cities, urban households were found to have lower heating needs (Santamouris et al. 2001) but higher air conditioning needs (Wong et al. 2011). Controlling for dwelling characteristics, Belaïd (2016) found that French rural households consumed on average 4 to 17% more energy than their urban counterparts. Using the French national housing survey, Hache, Leboullenger, and Mignon (2017) further found that there were more energy-poor households in the North of France, which they attributed to the harsher weather conditions in winter.

Policies aiming to improve the energy-efficiency of buildings should thus take into account their occupants' characteristics, their technical specificities and their location. Financial aid to households aims to promote efficient energy retrofits by lowering the up-front cost borne by households, which has been identified as the key barrier to the investment (Aravena, Riquelme, and Denny 2016; Achtnicht and Madlener 2014; Alberini, Banfi, and Ramseier 2013; Caird, Roy, and Herring 2008). Early evaluations of financial aid schemes for households focused on cost-efficiency, exploring the rebound effect [53] or free riding - which here refers to households using state subsidies to finance a retrofit project they would have taken on either way using their private founds. In France, there is evidence of both a rebound effect, which was found to be larger among energy-poor households (Belaïd, Ben Youssef, and Lazaric 2020) and in the long-run (Belaïd, Bakaloglou, and Roubaud 2018), and of substantial free riding, especially among richer households (Nauleau 2014). These estimations of policies' cost-effectiveness however *assumed* savings would be achieved through the policy. A more recent strand of literature explored whether fiscal

53. See Greening, D. L. Greene, and Difiglio (2000) for a literature review on different methods to characterize the rebound effect.

ENERGY SOURCE	ESTIMATION METHOD	LITERATURE	CONTEXT	MAIN RESULTS (MEAN)
Tax credits and subsidies				
Electricity	FE regression	Liang et al. 2018	Energize Phoenix program in the US (2008-2013)	8% reduction of monthly energy saving (30-50% less than predicted savings)
	Matching	Alberini and Towe 2015	Rebates on heat pump purchases in the US (2008-2012)	5% reduction
	DID	Davis, Fuchs, and Gertler 2014	Appliance replacement program in Mexico (2009-2012)	8% reduction for fridge replacement (25% of predicted savings); 2% increase for AC replacement
Gas and electricity	RCT and DID	Fowlie, Greenstone, and Wolfram 2018	Weatherization assistance program in the US (2011-2012)	10 to 20% reduction (33% of predicted savings)
	FE regression	Allcott and Greenstone 2017	Various grant and subsidy programs in the US (2011-2014)	8.5% reduction in expenditure (58% of predicted savings)
	Matching	Webber, Gouldson, and Kerr 2015	Kirklees Warm Zone scheme in the UK (2007–2010) providing free insulation to suitable households	38% of predicted savings acutally achieved.
Gas	Matching	Scheer, Clancy, and Ní Hógáin 2013	Home Energy Saving program in Ireland (2008-2010)	21 % reduction (36% less than predicted savings)
Policies targeting low-income households				
Electricity	FE regression	Graff Zivin and Novan 2016	Energy Savings Assistance Program providing free energy efficiency upgrades to low-income households in the US (2011-2012)	7% reduction (79% of predicted savings)
Gas and electricity	Machine learning	Christensen et al. 2021	Weatherization Assistance Program for low-income households in the US (2009-2016)	51% of predicted reduction

Multi-policy approach				
All energy sources	FE regression	Blaise and Glachant 2019	French national aid scheme (2010-2013)	8.39€ annual reduction of household expense for each 1000€ invested (8 times less than predicted predicted savings)

Note: "AC" refers to Air Conditioning; "DID" refers to Difference In Difference; "FE" refers to Fixed Effects; RCT refers to Randomized Controlled Trial.

Table 5 – Evaluations of energy efficiency policies using *ex post* data

aid programs actually induced these energy savings in practice. Table 5 sums up the main recent contributions to this literature, focusing on policies targeting retrofits of private housing - information policies and energy electricity rebates are left out, as well as behavioral programs[54]. Estimated savings from *ex post* data are systematically below projected savings, but there is not consensus on the magnitude of the difference. There has also been a heavy focus on tax rebates and grants, leaving-out other types of policies such as low-interest loans.

Previous contributions to the literature focused on the rebound effect on consumption to explain the differences between projected and effective savings: *ex ante* savings were lower because households changed their behaviors. The approach presented in Chapter 4 aims to cover a blind spot of the literature: the impact of workmanship quality on the efficiency of the retrofits, while controlling for several policy spending, household and dwelling characteristics, and local determinants. Different aid programs are tackled to further assess their relative efficiency, and their effect is estimated on both gas and electricity consumption. The data covers the five French national aid schemes from 2011 to 2018, taking advantage of the eco-conditionality law after 2014. The estimation relies on the spatial panel approach developed by Kapoor, Kelejian, and Prucha (2007). Regression results suggest that (1) higher local policy spending led to higher access to certified professionals, which in turn led to higher savings, (2) achieved savings varied depending on the policy channel and (3) part of the savings on electricity may have been offset by switching to gas heating. These findings highlight the importance of including supply-side quality in policy design. They also suggest that a comprehensive evaluation of retrofit funding policies must include various energy sources, as households can switch from one to the other.

54. For more details, Gillingham, Keyes, and Palmer (2018) have established a thorough literature review on the efficiency of information and behavioral programs, while Kerr and Winskel (2020) looked into papers on the leverage effect on private investments and supply-side policies

* * *

«Il faut toujours connaître les limites du possible. Pas pour s'arrêter, mais pour tenter l'impossible dans les meilleures conditions.»

Romain Gary – *Charge d'âme.*

* * *

Chapter 1

Why labels fail: Fraud on a market for credence goods with unobservable skill heterogeneity among experts

* * *

Asymmetries of information and uncertainty about product quality are often a central issue for customers. It is particularly the case in the construction market, where firms act as experts providing both the diagnosis and technical solutions to their clients, who are usually unable to assess them. As this sector is becoming more and more prevalent in the conversation on global warming and energy efficiency, it is important to understand how unique characteristics impact policy design. This article presents a credence-good model with skill heterogeneity among experts meant to replicate key features of the sector, focusing on maintenance and retrofit services. In particular, the equilibrium is characterized by a low and unique market price, and skilled firms cannot distinguish themselves from their unskilled competitors. This setup is then used to contrast the efficiency of two public policy tools intended to make construction markets more efficient: human capital development investments and quality labels. Analytical results indicate that the latter may impact over-treatment, but does not affect the level of under-treatment in equilibrium, while increasing the number of skilled firms is always efficient to increase customer satisfaction. Under this model's assumptions, if the goal is to ensure the proper renovation of the building stock, labels miss the mark.

* * *

1.1 Introduction

The procurement of goods and services in a context of information asymmetry is a well-studied problem in economics. The way imperfect information affects market outcomes, welfare and equilibrium behaviors has been largely studied in the case of public good provision, healthcare and labor (Laffont and Tirole 1993). The procurement of services by private consumers has been less extensively studied, yet there are some specific aspects deserving more attention. Credence good problems arise whenever consumers cannot evaluate the information given to them with certainty: they have to *trust* the agent or institution providing them with it. Contrary to experience goods, this is usually still true *ex post*, as customers cannot distinguish between an expert who provided the wrong solution and a product failure despite the expert's best efforts (Gottschalk 2018). Fraud arises whenever an expert seller has incentives to misrepresents the consumer's needs to increase their profits. It is a well-documented and frequent problem in real-world credence markets, whether it be detours taken by taxi drivers (Tang 2020), unnecessary car repairs (Rasch and Waibel 2018) or superfluous prescription drugs (Gottschalk, Mimra, and Waibel 2020). These case studies raise two connected questions: what drives experts' dishonesty and how can public policies be implemented to prevent it?

This paper attempts to replicate the dynamics observed on European countries' construction sectors, which are highly atomistic and competitive, yet customers are often unhappy with the quality of service they get (OECD 2010). It aims to understand why these inefficiencies persist in equilibrium in such a competitive environment, despite important regulation efforts. In particular, European states have turned to two main policy tools: investing in workers' skill development or setting up certifications to signal high-quality firms to consumers. The UK and several Eastern European governments have focused on human capital development, through apprenticeship founding or increased educational resources (ECSO 2020a). Labels are the main tool used in countries like France, where many certifications are implemented and offered by the state, unions (eg. the Qualirecycle BTP label offered by the FFB union) or independent organizations like Effinergie or Qualibat, which specialize in certifying the quality of different aspects of the construction process. We focus on the labeling of quality products, even though labeling could also be used as a way to reveal low-quality ones (Baksi and Bose 2007).These different certifications have been around for years, but many firms do not see the point in getting them - and customer satisfaction has not drastically increased (ECSO 2018b). This model aims to contrast these two policy objectives in a simple manner, through the analysis of comparative statics and alternative specifications. As the energy retrofit of the building stock has become a central objective of the post-Covid European economic recovery plan, it is more important than ever to gain more insight into the nature and drivers of fraudulent behavior, and on the conditions under which labels may or may not be effective.

The core assumption of the model presented in this paper is that consumers do not have the practical skills to assess their maintenance and renovation needs, nor to address them. It is also impossible to distinguish between skilled and unskilled firms prior to interacting with them. As they limit their search, it gives unskilled firms the opportunity to be active on the market with a positive profit. The model is then extended to include labeled firms - that is, skilled firms whose type is known with certainty by the customer. Not all skilled firms get labeled, which matches real-world behaviors. Indeed, they do not necessarily have an incentive to get the label: some of them may already have a well-established reputation and do not have enough a reason to get the label, others may have arrived on the market too recently to know labels exist (ECSO 2018b). The main results are that (1) at the equilibrium, firms offer their services at their reserve prices and customers cannot distinguish unskilled and skilled contractors (2) maximum overtreatment and undertreatment coexist in this market equilibrium, and (3) labels are in most cases inefficient to push unskilled firms out of the market. Comparative statics are used to discuss the different outcomes and the effect of some key variables. A literature review is presented in section 1.2, followed by a simple version of the model in section 1.3 and the general setup in section 1.4. Finally, different label specifications are reviewed in section 1.5 and section 2.6 concludes.

1.2 Literature review

The procurement of construction and maintenance services poses problems because households are not experts. Contractors are usually in charge of both the diagnosis of the problem and the implementation of a solution, as they are supposed to know what works best given the current characteristics of the dwellings – to maximize energy efficiency improvements for instance. Renovations are thus typical credence goods, as defined by Darby and Karni (1973). The consumer acts as a principal relying on the expertise of agents to determine what they need. This literature review highlights previous contributions related to producer heterogeneity, starting with empirical findings supporting its importance before reviewing the different ways theoretical contributions have accounted for it. Models estimating the impact of labels will also be briefly discussed, even though they are based on a different set of assumptions. A more general review of past credence good models can be found in Balafoutas and Kerschbamer (2020).

Recent papers in econometrics and behavioral economics provided evidence on factors driving firms to defraud their customers, exposing how heterogeneity among experts can drastically influence market outcomes [1]. The first large-scale lab experiment was carried out by Dulleck, Kerschbamer, and Sutter (2011), who tested some of the main theoretical results on credence goods. Their findings particularly highlighted how unobservable supplier heterogeneity could have a significant impact on the market's efficiency, despite being greatly overlooked in the literature. Drawing from a field study on auto repair shops, Rasch and Waibel (2018) found that financial pressure and lack of reputational concerns were strong drivers of fraudulent behaviors, which is also consistent with the theory. Interestingly, they showed that overcharging becomes more likely in a more competitive environment, and that high-skill firms were less prone to overcharge. Agarwal, C.-W. Liu, and Prasad (2019) conducted an experiment focusing on unobservable diagnosis effort, and found that market efficiency did not increase when consumers could obtain another expert's opinion, but that further information acquired through personal research made the equilibrium level of fraud drop [2]. These results provided interesting insights for many credence goods markets where experts operate with little or no diagnosis fee, but fraud still occurs in equilibrium - which is typically the case for the construction industry. They however contradicted those of Mimra, Rasch, and Waibel (2016), who found that the availability of a costly second opinion induced a 40% fall in the equilibrium level of overtreatment if search costs were sufficiently low. A key difference between the two papers is that diagnosis is not costly for experts in Mimra, Rasch, and Waibel (2016), providing them with fewer incentives to defraud customers. Tang (2020) is one of few contributions relying on real-world data to study overtreatment, in the form of detours taken by taxi divers. His results suggested significant disparities in taxi drivers' propensity to cheat depending on their cultural background, and that these behaviors persisted over time. These findings provided empirical support to the idea that there are types of firms that are more or less likely to defraud consumers, but this dimension has not yet been detailed in past theoretical contributions.

The first theoretical papers focused on sequential search principal-agent setups, in which the service provided can be of two types (high or low cost), which cannot be observed by the principal interacting with homogeneous agents (Pitchik and Schotter 1987). Fraud usually comes in the form of overcharging, meaning an expert charging the high-cost service but actually implementing the low-cost solution. In most models, introducing competition

1. Kerschbamer and Sutter (2017) provided a good overview of the related literature relying on lab experiments or field studies.

2. Their experimental design is based on augmented version of the sequential model found in Pesendorfer and Wolinsky (2003) that allows consumers to either seek a secondary opinion from another expert *ex post* or to look for information themselves *ex ante* after the diagnosis.

restores Bertrand efficiency despite the information asymmetries, and there is no fraud in equilibrium. For instance, Wolinsky (1993) detailed how separating equilibria could emerge depending on the search-cum-diagnosis cost and showed that competition could lead to efficiency in this case. Another way to look at this issue is to focus on diagnosis, in the spirit of Darby and Karni (1973): consumers know what kind of service is provided, but they ignore whether they needed that level of service in the first place, as the diagnosis phase lies with the firm. Competition might also lead to efficient outcomes when there are large economies of scope between diagnosis and repair, as price signals can successfully reveal firm incentives to consumers (Emons 1997). Despite being the most extensively studied case, overcharging is not the only form of fraud on credence good markets, as Dulleck and Kerschbamer (2006) pointed out. Using a synthetic model to compare various inefficiencies and types of fraudulent behaviors, they summarized previous models' outcomes and highlighted the relative importance of the assumptions made on firms' liability or the *ex post* verifiability of the goods' type. They derived two main results. First, under liability or verifiability undertreatment cannot be an equilibrium behavior since the customer will notice their utility of zero. Equilibrium overtreatment is however possible, since a consumer with a minor problem derives the same utility when it is fixed, whatever solution the firm used. Second, overtreatment strictly dominates overcharging from the firm's perspective when the solutions have increasing costs. They further discussed the potential implications of producer heterogeneity, while stressing that it remained a missing dimension in previous contributions to the literature. These models indeed differed in the nature of the information asymmetry, but they all relied on identical firms facing consumers of different types, while in reality experts do not have the same competence, nor the same propensity to defraud customers.

Very few papers focus explicitly on producer heterogeneity. There have been some attempts to introduce differences among experts in their choice of diagnosis effort, which is assumed to be unobservable by consumers. In the model developed by Pesendorfer and Wolinsky (2003), consumers do not know their own type, which can only be observed by firms conditionally on a costly design effort. The main focus of their model was to take into account customers' efforts to gather several opinions. Contrary to the problem studied in this paper, the information asymmetry emerged because firms privately chose their level of effort, but they were otherwise assumed to be homogeneous. Customers discovered their own type by sequentially sampling firms until their diagnoses matched. Dulleck, Gong, and Li (2015) extended the model with sequential bidding by contractors: consumers would shortlist a finite number of firms, which then individually chose their effort levels and bid on the price and on the design in an auction. Consumers would then choose the firm offering the right design at the lowest price and compensated the others at a fixed design fee. Sampling two firms was found to be enough to restore Bertrand competition and to incentivize contractors to provide a high effort level - or at least to do so with a positive probability. Non-degenerate fixed price equilibria existed only under certain conditions on the cost of effort and the search cost, which had to remain small relative to the value customers give to the project. A crucial aspect remaining overlooked was that firms may be heterogeneous in their skills, namely their design and implementation costs. Using a similar setup but allowing for an endogenous diagnosis price, Alger and Salanie (2006) generated an equilibrium with overtreatment, as the fee could be set below cost. All firms still optimally adopted the same pricing behavior in equilibrium and were assumed to have the same ability to solve the issue, meaning inefficiencies only stemmed moral hazard. In other words, firms' lack of actual skill did not come into play - they *chose* to defraud their customers, despite being able to fix their issue.

Another class of credence good models introduced firm heterogeneity by assuming experts can be of two types, skilled or unskilled, which were observable by customers. Glazer and McGuire (1996) made the first contribution to this line of work, comparing safe sellers who can always solve the issue, and cheaper but risky sellers who may solve it depending on its seriousness - which customers could not appreciate. They found that price competition was enough to ensure that risky sellers would not serve customers whose problems they could not fix. Similarly, Emons (2000) focused on the price and quality choice of sellers who could only imperfectly diagnose the issue when they entered a market on which safe experts operate. He showed that product differentiation could be used by risky sellers to loosen price competition on the market, but that it was not their most profitable option in equilibrium. Complementary results can be found in Bouckaert and Degryse (2000), whose model included experts who were able to fix the issue and non-experts fixing it only with a positive probability. An equilibrium with price differentiation arised only when the probability of successful repair using the non-expert's technology was small enough. Dulleck and Kerschbamer (2009) also developed a framework with experts who would perform a costly diagnosis, and discounters who could offer the same quality at a lower price but could not tell the consumer if their problem was severe or simple. In this setting, experts were able to defraud consumers by over-treating them, but consumers could also defraud experts by going to a discounter in order to obtain the quality recommended by the expert. This could result in equilibrium undertreatment, as experts could cheat with a positive probability to keep consumers imperfectly informed. Overall, these models all found efficient equilibria since consumers could discriminate firms *ex ante*, hence they optimally chose to the risk they took.

Up to this point, skill heterogeneity has hence been introduced either by assuming homogeneous firms could decide on their unobservable effort level, or by having observable firm types regarding their skill level. The main novelty of this paper is to introduce unobservable firm types and to focus on equilibrium undertreatment. To do so, the verifiability and liability assumptions are lifted. The customer may have an easy or complex issue, which they cannot observe, and some of the firms they face are not able to produce the correct diagnosis. It is a bid setup, in which firms compete in prices and diagnosis to execute a task for a consumer. This model focuses explicitly on firm heterogeneity and goes further than previous work specifying firm types in that consumers are not able to discriminate firms *ex ante*. It is an appropriate setup to discuss the conditions under which labels may be effective. A similar approach was developed by Bonroy and Constantatos (2008), with a firm producing a high-end product at a higher marginal cost than a low-quality producer, but they focused on customers' beliefs, which is not the main subject matter here. They showed that as labels increased cost, they could reduce the quality producers' market share. There are also conditions under which they proved the existence of adverse effects, as labels increased competition in prices. These findings are in line with our partial labeling assumption, as there are many barriers preventing skilled firms from getting certifications on the quality of their production. Also relying on consumers' heterogeneous beliefs and preferences, Baksi, Bose, and Xiang (2017) found that even if labeling can sometimes improve social welfare, it always leads to a decrease in high-end producers' profits if customers over-estimate the quality of intermediate products. This is again in line with our results and provides more ground for the assumption that some skilled firms will refuse to get a costly quality certification.

1.3 Simple setup

1.3.1 One consumer facing two firms

Let us first examine a very simple setup in order to introduce the main variables used in the general model. Consider a market with one consumer and two heterogeneous firms *vis-à-vis* their skill levels. They have a hard-fix issue $\overline{c}$ with probability $\mu \in [0,1]$ - meaning they have an easy-fix issue with probability $1-\mu$. Firm with skill $\overline{\beta}$ can solve both types of issue, while firm with skill $\underline{\beta}$ can only solve easy problems. The consumer derives utility V net of the price if the problem is fixed; they can never observe firms' skills, nor can they diagnose their own issue. Firms observe their own skill level and can diagnose the consumer's issue before setting up their selling price.

Firm $\underline{\beta}$ will always state that the problem is an easy-fix ($\underline{c}$) and offer a price p, while firm $\overline{\beta}$ can offer the correct diagnosis and propose prices $\overline{p}$ or $\underline{p}$ accordingly. For simplicity, assume firms can solve the issues at no cost: the skill difference stems solely from the fact that the $\underline{\beta}$ firm cannot properly diagnose the customer's needs. Overtreatment is not ruled out, as the $\overline{\beta}$ firm can choose to misreport a $\underline{c}$ issue as a $\overline{c}$ issue with probability $\eta \in [0,1]$. It may be profitable to do so if $\overline{p} \geq \underline{p}$, hence the value of η is set by the skilled firm before setting their price. Figure 1.1 displays the game in its extensive form, with the resulting diagnosis and payoffs for the two firms and the consumer - dotted lines represent information asymmetry.

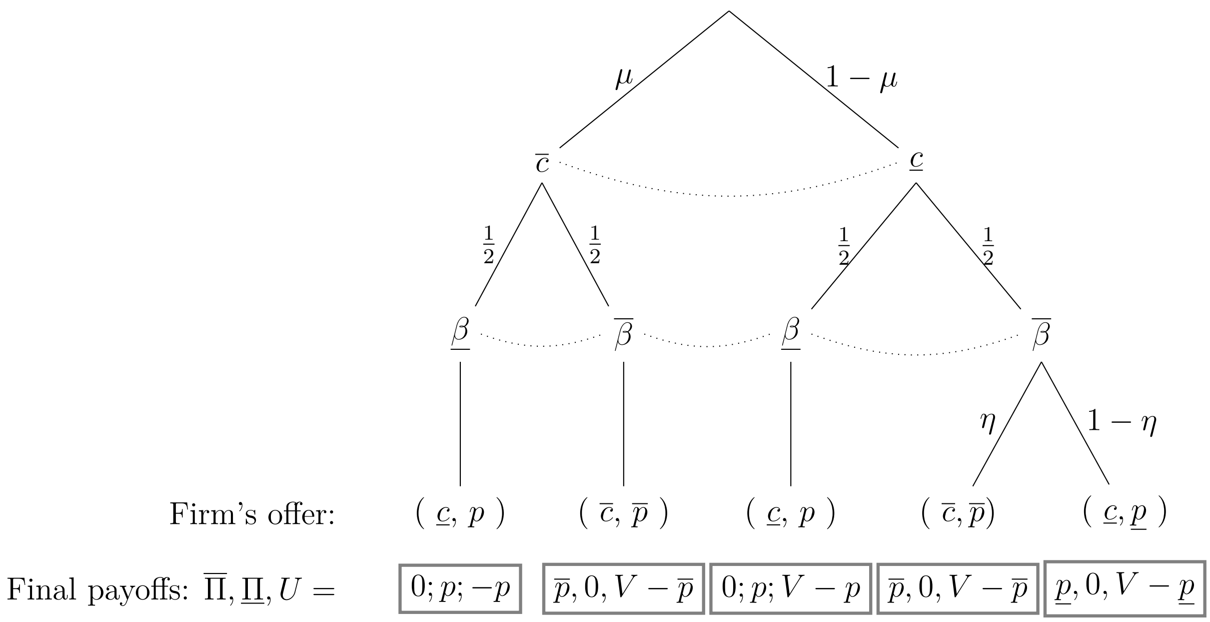


Figure 1.1 – One-shot game

Proposition 1.1. *In equilibrium the skilled firm optimally sets* $\eta^* = 1$ *and only charge* $\overline{p}^* = V$*, and the unskilled firm's optimal price is* $p^* = (1-\mu)V$*.*

Proof. Assume $\eta < 1$. The consumer gets a $\overline{c}$ or a $\underline{c}$ diagnosis with probabilities $\mathbb{P}(c = \overline{c}) = \frac{\mu+\eta(1-\mu)}{2}$ and $\mathbb{P}(c = \underline{c}) = \frac{1+(1-\eta)(1-\mu)}{2}$ respectively. If the diagnosis is $\overline{c}$, they know they are facing the skilled firm and will get V with certainty, even if they had a $\underline{c}$ issue. Hence $U(\overline{c}) = V - \overline{p}$. They agree to pay price $\overline{p}$ if and only if their utility is positive, that is if $\overline{p} \leq V$. The skilled firm maximizes its profits by setting $\overline{p}^* = V$.

Facing a $\underline{c}$ diagnosis, the consumer has the following expected utility depending on the type of firm and their actual problem [3]:

3. See Appendix 1.A.1 for the derivation of these probabilities.

$$\mathbb{E}(U|c=\underline{c},\eta<1)=\frac{1}{2}\Big(V-\overline{p}\Big)+\frac{1}{2}\Big(\mu(0-p)+(1-\mu)(V-p)\Big)=\frac{2-\mu}{2}V-\frac{1}{2}\overline{p}-\frac{1}{2}p$$

As they don't know what firm they are facing, they cannot distinguish $\underline{p}$ from p. Let $\tilde{p}\in\{\overline{p},p\}$ be the price as perceived by the consumer when choosing to accept a $\underline{c}$ diagnosis or not. Their expected utility becomes $\mathbb{E}(U|c=\underline{c},\eta<1)=\frac{2-\mu}{2}V-\tilde{p}$, thus the maximum prices firms can set are $\underline{p}=p=\frac{2-\mu}{2}V$.

It is straightforward that $\overline{p}^*\geq\underline{p}\quad\forall\mu\in[0,1]$, which implies that the skilled firm's optimal lying strategy is $\eta^*=1$, meaning the $\overline{\beta}$ firm always offer the $\overline{c}$ diagnosis. As a result, $\mathbb{P}(c=\overline{c})=\mathbb{P}(c=\underline{c})=\frac{1}{2}$. It does not affect the $\overline{c}$ diagnosis case, but if the customer receives a $\underline{c}$ diagnosis they now have the following expected utility:

$$\mathbb{E}(U|c=\underline{c},\eta=1)=\mu(0-p)+(1-\mu)(V-p)=(1-\mu)V-p$$

To maximize its profits while keeping the customer's utility non-negative, the unskilled firm has to set $p^*=(1-\mu)V$. □

As the skilled firm specializes in equilibrium, the maximum price the unskilled firm can set is lower than what they could charge if the customer had some uncertainty on the firm's type when getting a $\underline{c}$ diagnosis. It is a rather intuitive result, as the diagnosis carries more information when firms specialize - and the customer is less willing to pay for an unskilled firm's services. One can also note that if $\mu=0$, they know they cannot have a hard-fix issue and do not take any risk accepting a $\underline{c}$ diagnosis. As a consequence, all firms could set their selling price at V. It is also worth mentioning that as long as the customer's valuation is positive, all firms have an incentive to be active on the market because their expected profits will be positive as well, as equilibrium payoffs are given by:

$$\begin{aligned}\mathbb{E}(U)&=\tfrac{1}{2}(V-\overline{p}^*)+\tfrac{1}{2}(\mu(0-p^*)+(1-\mu)(V-p^*))=0\\ \mathbb{E}(\overline{\Pi}^*)&=\tfrac{1}{2}\overline{p}^*=\tfrac{1}{2}V\\ \mathbb{E}(\underline{\Pi}^*)&=\tfrac{1}{2}p^*=\tfrac{1-\mu}{2}V\end{aligned}$$

Both firms are active on the market as long as $\mu<1$ and $V>0$. The skilled firm's profits are higher than that of their unskilled counterpart, which is driven by the fact that they can sell at a higher retail price along with the $\overline{c}$ diagnosis. In particular, if $\mu=0$, meaning the consumer always has and easy-fix problem, both firms have the same expected profits as prices equalize. In this equilibrium, the customer has to deal with both potential overtreatment and undertreatment, which are due respectively to the skilled firm misreporting and the unskilled firm's inability to diagnose a $\overline{c}$ issue. There is no *ex-post* uncertainty about the drawn firm's type in equilibrium as each type specializes in one treatment, but the consumer only learns their own type if they dealt with the $\underline{\beta}$ firm: either the issue is fixed and they deduce it was a $\underline{c}$ one, or it is not fixed and they learn it was a $\overline{c}$ one. The persistence of some uncertainty is a realistic result, as renovation and maintenance services are typically very hard for the customer to evaluate. The persistence of the issue can be noticed, but it is impossible to tell if the solution was appropriate once the problem is fixed. Taking a very concrete example, if your boiler stops working and a plumber comes to change it, you will be able to tell that you have hot water or not afterwards, but you cannot really know if a full replacement was necessary: perhaps a less complex repair of some parts could have sufficed. It is typically quite difficult to assess the overall quality of a renovation outcome as a non-expert.

1.3.2 Extending to J firms

Before turning to the general model, let us review the impact of having more than two firms on the equilibrium outcomes. Assume now that the consumer faces $J > 2$ firms on the market. Denote $\delta \in [0, 1]$ the share of $\overline{\beta}$-type firms among them. Let the consumer draw one firm at random and decides to buy or not from the (c,$\tilde{p}$) offer they face.

Proposition 1.2. *The equilibrium behaviors are unchanged : skilled firms' optimal lying strategy is $\eta^* = 1$ and they only charge $\overline{p}^* = V$. Unskilled firms' optimal price remains $p^* = (1 - \mu)V$.*

Proof. Let $\eta < 1$. We now have $\mathbb{P}(c = \overline{c}) = \delta\Big(\mu + \eta(1 - \mu)\Big)$ and $\mathbb{P}(c = \underline{c}) = 1 - \delta + \delta(1 - \eta)(1 - \mu)$. Facing a $\overline{c}$ diagnosis, the customer still gets $U(\overline{c}) = V - \overline{p}$ with certainty so the firm's optimal price remains $\overline{p}^* = V$.

If the customer receives a $\underline{c}$ diagnosis, their expected utility depends on their probability of having a hard-fix issue and on the share of skilled firms:

$$\begin{aligned}\mathbb{E}(U|c = \underline{c}, \eta < 1) &= \delta(V - \underline{p}) + (1 - \delta)\Big(\mu(0 - p) + (1 - \mu)(V - p)\Big) \\ &= \Big(1 - \mu(1 - \delta)\Big)V - \delta\underline{p} - (1 - \delta)p\end{aligned}$$

Following the same reasoning as in proposition 1.1, let $\tilde{p} \in \{\underline{p}, p\}$, which means the customer's utility becomes $\mathbb{E}(U|c = \underline{c}, \eta < 1) = \Big(1 - \mu(1 - \delta)\Big)V - \tilde{p}$. The maximum prices firms can set are thus $\underline{p} = p = \Big(1 - \mu(1 - \delta)\Big)V$.

As $\overline{p}^* \geq \underline{p} \quad \forall \mu, \delta \in [0,1]$, skilled firms' optimal strategy remains $\eta^* = 1$. As a consequence, the diagnoses' probabilities become $\mathbb{P}(c = \overline{c}) = \delta$ and $\mathbb{P}(c = \underline{c}) = 1 - \delta$, but the consumer's utility is only affected in case of a $\underline{c}$ diagnosis:

$$\mathbb{E}(U|c = \underline{c}, \eta = 1) = \mu(0 - p) + (1 - \mu)(V - p)$$

The maximum price unskilled firms can set while maintaining non-negative utility is $p^* = (1 - \mu)V$ □

Consequently, equilibrium payoffs for the consumers and each type of firm are:

$$\begin{aligned}
\mathbb{E}(U) &= \delta(V - \overline{p}^*) + (1 - \delta)(\mu(0 - p^*) + (1 - \mu)(V - p^*)) \quad = 0 \\
\mathbb{E}(\overline{\Pi}^*) &= \tfrac{1}{J}\overline{p}^* = \tfrac{1}{J}V \\
\mathbb{E}(\underline{\Pi}^*) &= \tfrac{1}{J}p^* = \tfrac{1-\mu}{J}V
\end{aligned}$$

Increasing the number of firms on the market does not increase the customer's utility if they interact with only one firm: it remains 0 in equilibrium. Firms' individual profits are lower since $J > 2$, but it is only due to a lower probability of being drawn by the consumer. The share of same-type firm does not affect any of the payoffs and this equilibrium remains characterized by maximum over-treatment and under-treatment. The main takeaway here is that whatever the number and types of firms on the market, if the since samples only one, prices will remain set at their highest level because firms do not feel any competitive pressure. It seems more relevant to assume that the customer meets several firms, as it is both a way to reduce uncertainty and to increase their equilibrium expected utility, as shown in the following section.

1.4 General model

1.4.1 Setup

Assume now that the consumer simultaneously draws two firms, and then compares their prices and diagnoses before making a buy-or not decision. Firms set their prices above a threshold $k > 0$ without knowing what kind of firm they are competing against. This threshold is set for computational reasons, but it could be interpreted as a minimum resale price to cover fixed costs - capital investments for instance. Each skilled firm j has a lying policy, meaning they choose to over-treat their client with probability η_j. Whatever offers they are facing, the customer always goes for the lowest price when the two firms offer the same diagnosis. When facing a conflicting diagnosis, they go for the $(\bar{c}, \bar{p})$ one.

Figure 1.2 displays the game in its extensive form. Denote $\mathbb{1}_j$ the indicator function equal to 1 if the customer chooses firm j and 0 otherwise, and let H_j be the linear combination $\eta_j \bar{p}_j + (1-\eta_j)\underline{p}_j$. The computation of total probabilities is detailed in figure 1.B.1 in the Appendix.

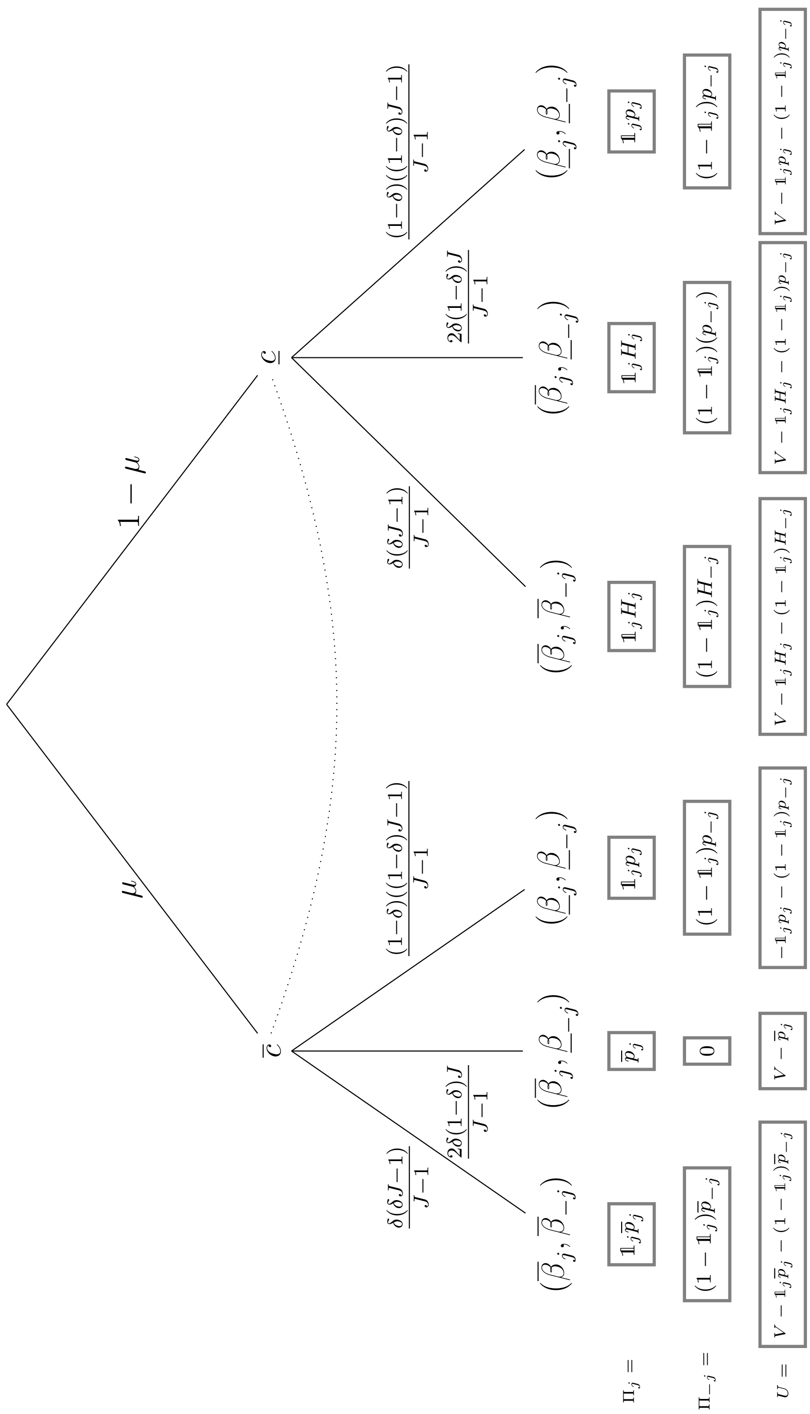


Figure 1.2 – One-shot game with two firms drawn

1.4.2 Equilibrium lying strategy and prices

Assume for now that all firms are active on the market, in order to determine the equilibrium prices and lying policy before reviewing their participation conditions.

Proposition 1.3. *In equilibrium, skilled firms' optimal choice is to set* $\eta^* = 1$ *and* $\underline{p^*} = \overline{p^*} = k$.

Proof. From a skilled firm's perspective, let us first consider a customer with a $\overline{c}$ issue. In this case, a skilled firm's expected profits are:

$$\mathbb{E}(\overline{\Pi}_j|c = \overline{c}) = \frac{\delta J - 1}{J-1}\mathbb{1}_j\overline{p}_j + \frac{(1-\delta)}{J-1}\overline{p_j}$$

They get the deal with certainty if they are matched with an unskilled firm (with probability $\frac{(1-\delta)J}{J-1}$), but if they are matched with another skilled firm they only win over the customer if they price is lower than their competitor's (which occurs with probability $\frac{\delta J-1}{J-1}$). Hence for any $\overline{p}_j, \overline{p}_{-j} \in [k, +\infty[$ such that $\overline{p}_j \geq \overline{p}_{-j}$, there is a small $\epsilon > 0$ such that setting $\overline{p}_j - \epsilon < \overline{p}_{-j}$ would yield higher profits for firm j. This Bertrand mechanism drives skilled firms' prices to k, as undercutting becomes impossible. The customer would in this case randomize, which means that skilled firms' profits become:

$$\mathbb{E}(\overline{\Pi}_j|c = \overline{c}) = \frac{\delta J - 1}{J-1} \times \frac{k}{2} + \frac{(1-\delta)J}{J-1}k = \frac{J(2-\delta)-1}{J-1}\frac{k}{2}$$

Figure 1.3 illustrates this mechanism for $J = 1000$, $\delta = 0.5$ and $k = 50$, drawing firm$j$'s isoprofit lines in the (p_{-j}, p_j) referential. The top left graph depicts situation where initially $\overline{p}_j > \overline{p}_{-j}$, the top right graph the case where both prices are equal and strictly above k initially and the bottom one displays the equilibrium situation. It is clear in the two top graphs that setting a price slightly below their competitor's is always optimal when prices are set strictly above k.

If the customer has a $\underline{c}$ issue, a skilled firm j simultaneously chooses its lying strategy η_j and its resale prices $\overline{p}_j$ and $\underline{p}_j$. Depending on their competitor's type, their expected profits are:

$$\begin{cases} \mathbb{E}(\overline{\Pi}_j|c = \underline{c}, \beta_{-j} = \overline{\beta}) & = & \eta_j\Big(\eta_{-j}\mathbb{1}_j\overline{p}_j + (1-\eta_{-j})\overline{p}_j\Big) + (1-\eta_j)\Big(\eta_{-j} \times 0 + (1-\eta_{-j})\mathbb{1}_j\underline{p}_j\Big) \\ \mathbb{E}(\overline{\Pi}_j|c = \underline{c}, \beta_{-j} = \underline{\beta}) & = & \eta_j\overline{p}_j + (1-\eta_j)\mathbb{1}_j\underline{p}_j \end{cases}$$

If a skilled firm j is matched with an unskilled firm and chooses not to misreport with a positive probability (meaning $\eta_j < 1$), the Bertrand mechanism described previously drives $\underline{p}_j$ and p_{-j} down to k, which means the customer randomizes. Hence their expected profits become:

$$\mathbb{E}(\overline{\Pi}_j | c = \underline{c}, \beta_{-j} = \underline{\beta}) = \eta_j \overline{p}_j + (1 - \eta_j)\frac{k}{2}$$

As $\frac{\partial \mathbb{E}(\overline{\Pi}_j | \underline{c}, \underline{\beta}_{-j})}{\partial \eta_j} = \overline{p}_j - \frac{k}{2}$ and $\overline{p}_j \geq k$, it is straightforward that their expected profits conditional on the customer having a $\overline{c}$ issue and being drawn with an unskilled firm are an increasing function of η_j, whatever the value of $\overline{p}_j$. Their optimal choice is to set $\eta_j(\underline{\beta}_{-j}) = 1$.

Turning to the case where they are matched with another skilled firm, if both firm may misreport with a positive probability the Bertrand mechanism described beforehand implies that $\underline{p}_j = \overline{p}_j = k$ for all skilled firms. Their expected profits in that case become:

$$\mathbb{E}(\overline{\Pi}_j | c = \underline{c}, \beta_{-j} = \overline{\beta}) = \eta_j \Big(\eta_{-j}\frac{k}{2} + (1 - \eta_{-j})k\Big) + (1 - \eta_j)(1 - \eta_{-j})\frac{k}{2}$$

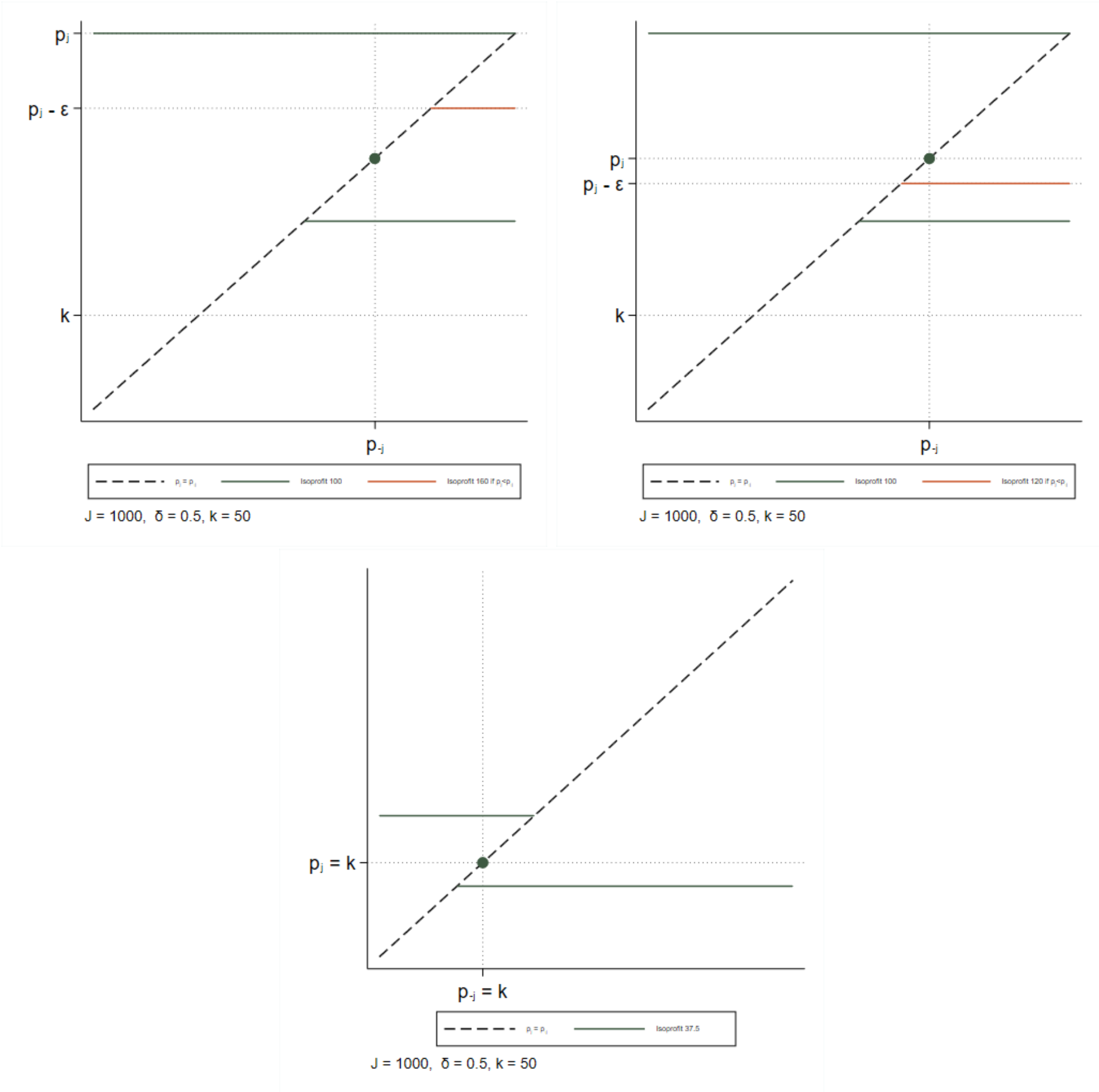
Hence $\frac{\partial \mathbb{E}(\underline{\Pi}_j | \underline{c}, \underline{\beta}_{-j})}{\partial \eta_j} = \frac{k}{2}$, which is always positive. It implies that their optimal choice is to set $\eta_j(\overline{\beta}_{-j}) = 1$, which further means that $\eta^* = 1$ is their equilibrium lying policy.

Finally, let us show that $\overline{p}_j^* = k \quad \forall j$ when the customer has a $\overline{c}$ issue. Whatever their competitor's type, a skilled firm's expected profits under their optimal lying strategy are given by:

$$\mathbb{E}(\overline{\Pi}_j | c = \overline{c}) = \frac{\delta J - 1}{J - 1}\mathbb{1}_j \overline{p}_j + \frac{(1 - \delta)J}{J - 1}\overline{p}_j$$

This is equivalent to their expected profits when the customer has a $\underline{c}$ issue, so following the same steps their optimal choice is $\overline{p}_j^* = k$. □

Sampling two firms is enough to restore competitive pressure on skilled firms, which leads to lower prices but has no effect on overtreatment. As prices are at their lowest, and increasing them would only decrease expected profits, over-treatment is the only dimension they can play on to differentiate themselves from their unskilled competitors in the eye of the customer. Low and non-separating prices are in line with the reality of construction markets. Further, skilled firms' failure to include a skill premium in their resale prices matches common complaints made by professional organizations. Turning to unskilled firms, they also lower their resale price in reaction to potential competitors.



Source: Author's computations.

Note: Simulated results assuming $J = 1000$, $\delta = 0.5$ and $k = 50$.

Figure 1.3 – Skilled firms' isoprofit lines when facing a $\bar{c}$ customer.

Proposition 1.4. *In equilibrium, unskilled firms' optimal choice is to set $p^* = k$.*

Proof. Since skilled firms set $\eta^* = 1$, unskilled firms' expected profits are given by:

$$\mathbb{E}(\underline{\Pi}) = \frac{2}{J}\frac{(1-\delta)J-1}{J-1}\mathbb{1}_j p_j$$

As their profits are 0 whenever they set $p_j > p_{-j}$, the Bertrand mechanism previously described implies directly that $p_j^* = k$. □

Unskilled firms set the lowest price possible, not to align with skilled firms, but because of the competition with same-type firms. Contrary to previous work on credence goods, they do not try to pass as skilled firms - they can't -, yet competition drives all prices to their minimum level. Both kinds of firms are fully specialized in equilibrium, so the customer can derive their types based on the diagnosis received. It does not however lift all the uncertainty, especially if the share of unskilled firms is high, as further discussed thereafter.

1.4.3 Equilibrium payoffs and participation conditions

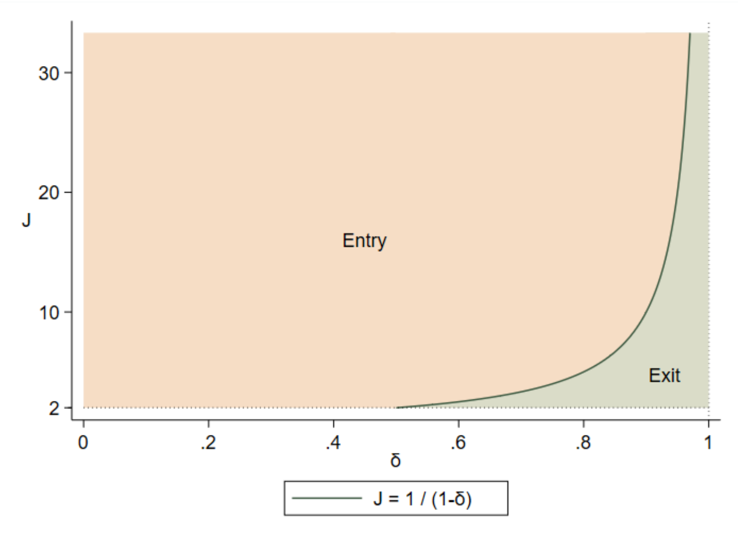
The consumer's expected utility depends on the number of firms (J), the price k set by all firms, the share of $\overline{\beta}$ firms (δ) and their probability to have a $\overline{c}$ issue (μ).

$$\begin{aligned}\mathbb{E}(U^*) &= \left(1-\tfrac{(1-\delta)((1-\delta)J-1)}{J-1}\right)(V-k)+\tfrac{(1-\delta)((1-\delta)J-1)}{J-1}\left(\mu(0-k)+(1-\mu)(V-k)\right)\\ &= V\left(1-\tfrac{(1-\delta)((1-\delta)J-1)}{J-1}+(1-\mu)\tfrac{(1-\delta)((1-\delta)J-1)}{J-1}\right)-k\\ &= V\left(1-\mu\tfrac{(1-\delta)((1-\delta)J-1)}{J-1}\right)-k\end{aligned}$$

Their participation condition is hence $k \leq V\left(1-\mu\frac{(1-\delta)((1-\delta)J-1)}{J-1}\right)$, meaning they only enter the market if k is low enough to compensate for the risk they take when accepting a $\underline{c}$ offer. Analyzing this result from another angle, it is consistent with the fact that housing renovations can be postponed but become more and more necessary over time (meaning V would tend to increase). Discomfort due to bad insulation might be tolerable the first years after buying and moving into a new dwelling, but will eventually have to be addressed. Households typically take some time before turning a renovation idea into a reality because of a multitude of decision barriers (see for instance, Azizi, Nair, and Olofsson 2019), which would be consistent with an increasing valuation as time passes. This model does not allow to study this time dimension, but it would be an interesting development. Turning to firms' expected payoffs:

$$\begin{aligned}
\mathbb{E}(\underline{\Pi}^*) &= \tfrac{2}{J}\tfrac{(1-\delta)J-1}{J-1}\tfrac{1}{2}k \\
&= \tfrac{(1-\delta)J-1}{J(J-1)}k \\
\mathbb{E}(\overline{\Pi}^*) &= \tfrac{2}{J}\Big(\tfrac{\delta J-1}{J-1}\tfrac{1}{2} + \tfrac{(1-\delta)J}{J-1}\Big)k \\
&= \tfrac{1}{J(J-1)}\Big(\delta J - 1 + 2(1-\delta)J\Big)k \\
&= \tfrac{1}{J(J-1)}\Big(J(2-\delta) - 1\Big)k
\end{aligned}$$

As firms always offer the same diagnosis independently of the customer's actual problem, μ does not impact their profits. The only parameters affecting their payoffs in equilibrium are the total number of firms and the share of same-type firms, which is given by δ. For a strictly positive k, the participation conditions of skilled and unskilled firms are respectively $J \geq \frac{1}{1-2\delta}$ and $J \geq \frac{1}{1-\delta}$. As $J > 2$, skilled firms always have an incentive to be active on the market and unskilled firms always make a positive profit if $\delta \leq \frac{1}{2}$. If less than half the firms are skilled, the unskilled are always active (Figure 1.4). Unskilled firms may thus not enter the market if more than half the active firms are skilled, depending on the value of J. Interestingly, a higher overall number of firms makes it easier for them to make a positive profit in equilibrium, as it increases their chance to be drawn with another $\underline{\beta}$-type firm.



Source: Author's computations.

Figure 1.4 – Unskilled firms' entry condition

1.4.4 Comparative statics

The model does not allow the study of dynamic changes, but comparative statics provide insights on the impact of the market parameters on final outcomes. Unsurprisingly, equilibrium profits of both types of firms are increasing in the market price k. More interestingly, they both decrease, and in the same magnitude, as δ increases. From a skilled firm's perspective, an increase in δ means an increase in competition, as it becomes more probable to be drawn with another skilled firm and only make the sale with a 50% chance. Similarly, as unskilled firms can only win over the customer when they are matched with another unskilled firm, increasing the share of skilled firms implies a drop in their equilibrium profits.

$$\frac{\partial \mathbb{E}(\overline{\Pi}^*)}{\partial \delta} \quad = \quad \frac{\partial \mathbb{E}(\underline{\Pi}^*)}{\partial \delta} \quad = \quad \frac{-1}{J-1}k$$

The derivatives of equilibrium profits with respect to J are given by:

$$\begin{aligned}
\frac{\partial \mathbb{E}(\overline{\Pi}^*)}{\partial J} &= \frac{1}{J^2(1-J)^2}\Big(-(2-\delta)J^2 + 2J - 1\Big)k \\
\frac{\partial \mathbb{E}(\underline{\Pi}^*)}{\partial J} &= \frac{1}{J^2(J-1)^2}\Big(-(1-\delta)J^2 + 2J - 1\Big)k
\end{aligned}$$

Skilled firms' equilibrium profits are strictly decreasing function of J, as $-(2-\delta)J^2+2J-1 \leq 0 \quad \forall\, \delta \in [0,1]$. It is strictly decreasing for all $\delta < 1$, and the magnitude of the effect decreases as δ gets closer to 0. A higher number of skilled firms on the market increases their chance of being drawn with another skilled firm and decreases their individual chance of being drawn, both impacting their profits negatively. The effect of J on unskilled firm's profits is more ambiguous, as more firms on the market decreases their individual probability of being drawn but also increases their chance of being matched with another unskilled firm depending on the value of δ.

Proposition 1.5. *An increase in J is beneficial for unskilled firms' profits in equilibrium if and only if $J \leq \frac{1+\sqrt{\delta}}{1-\delta}$ and $\delta \geq \frac{1}{4}$.*

Proof. From the previous equation, $\frac{\partial \mathbb{E}(\underline{\Pi}^*)}{\partial J} \geq 0 \iff -(1-\delta)J^2 + 2J - 1 \geq 0$.

Denote f the function defined on $]2, +\infty[$ by $f(x) = -(1-\delta)x^2 + 2x - 1$, with $\delta \in [0,1]$. Its determinant is given by:

$$\Delta = 4 - 4(1-\delta) = 4\delta$$

If $\delta = 0$ then $\Delta = 0$ and $f(x) > 0 \forall x > 2$, as the polynomial has a single root in $x = 1$. If $\delta > 0$, f has two roots, denoted x_1 and x_2, defined as functions of $\delta \in [0,1[$:

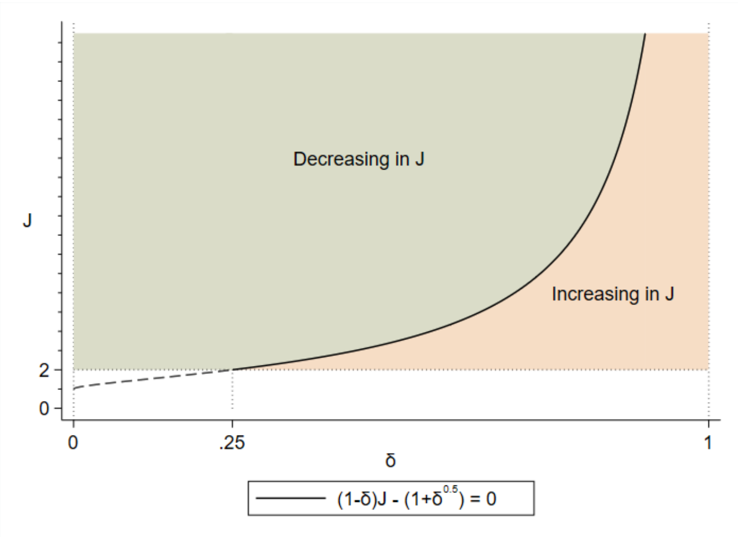
$$\begin{cases} x_1 &= \frac{-2-\sqrt{\delta}}{-2(1-\delta)} &= \frac{1+\sqrt{\delta}}{1-\delta} \\ x_2 &= \frac{-2+\sqrt{\delta}}{-2(1-\delta)} &= \frac{1-\sqrt{\delta}}{1-\delta} \end{cases}$$

As x_2 is a strictly decreasing function of δ and is equal to 1 when $\delta = 0$, $f(x) > x_2 \quad \forall x > 2$. It follows that $f(x)$ is positive when $x_1 > 2$ and $x \in]2, x_1]$ and negative otherwise. It can also be noted that x_1 is a strictly increasing function of δ and that $x_1 = 2 \iff \delta = \frac{1}{4}$, meaning that for $\delta \leq \frac{1}{4}$, f(x) is always negative.

Overall, the sign of the derivative of $\mathbb{E}(\underline{\Pi}^*)$ with respect to J is either positive of negative depending on the value of J and δ:

— If $\delta \leq \frac{1}{4}$ or $J \geq \frac{1+\sqrt{\delta}}{1-\delta}$, then $\mathbb{E}(\underline{\Pi}^*) \leq 0$.
— If $\delta \geq \frac{1}{4}$ and $J \leq \frac{1+\sqrt{\delta}}{1-\delta}$, then $\mathbb{E}(\underline{\Pi}^*) \geq 0$.

□



Source: Author's computations.

Figure 1.5 – Sign of $\frac{\partial \mathbb{E}(\underline{\Pi}^*)}{\partial J}$ depending on the value of J and δ

Figure 1.5 displays these two cases. When there are a lot of skilled firms and a few firms overall, the negative impact of an increase in J on the probability of being drawn, $\frac{2}{J}$, is more than compensated by the increase in the probability of being drawn with another unskilled firm. This result suggests that if a substantial number of firms operate on the market, focusing on the development of competence could be an effective way to make unskilled firms less profitable - and in turn increase customer's satisfaction and overall effectiveness of housing retrofit measures. This idea has been long prevalent among European policy makers, for instance with the emphasis on apprenticeships during François Hollande's presidency in France. The objective was to train young aspiring workers by making them work directly with experienced professionals for long periods of time, to ensure skill transmission beyond theoretical courses. However, our findings can suggest that skilled professionals have an incentive to keep δ low as it affects their expected profits negatively. This reinforces the need for a provision of quality professional training that do not depend on apprenticeship programs

The customer's expected utility in equilibrium is composed of two terms: their instant utility if they always got V when they paid k, minus an extra cost $\lambda = \mu V(1-\delta)\frac{(1-\delta)J-1}{J-1}$, which stems from the uncertainty linked to the information asymmetry. It is straightforward that $\mathbb{E}(U)$ is a decreasing function of k and λ. The value of λ tends towards 0 when δ is close to 1: in the extreme case where there are only $\overline{\beta}$ firms on the market, there is no extra cost due to information asymmetries. Conversely, if $\delta = 0$ then $\lambda = \mu V$, meaning that if there are no skilled firms on the market the net loss to consumer is their valuation V of getting the issue fixed times the probability of having a $\overline{c}$ issue. It is also notable that $\lim_{\mu \to 0} \lambda = 0$ since firm types do not matter if the customer cannot have a $\overline{c}$ issue. There are however some non-linearities in the sign of λ depending on the model parameters μ, δ and J.

$$\begin{aligned}
\frac{\partial \mathbb{E}(U)}{\partial \mu} &= -\frac{V(1-\delta)}{J-1}\Big((1-\delta)J - 1\Big) \\
\frac{\partial \mathbb{E}(U)}{\partial \delta} &= -\frac{\mu V}{J-1}\Big(1 - 2(1-\delta)J\Big)
\end{aligned}$$

These imply that $\frac{\partial \mathbb{E}(U)}{\partial \mu} \leq 0 \iff \delta \leq \frac{J-1}{J}$ and $\frac{\partial \mathbb{E}(U)}{\partial \delta} \geq 0 \iff \delta \leq \frac{2J-1}{2J}$. In other words, if δ is low enough, an increase in the share of skilled firms always leads to an increase in utility, and an increase in the probability of having a $\overline{c}$ issue has a detrimental effect. Let $\delta_\mu = \frac{J-1}{J}$ and $\delta_\delta = \frac{2J-1}{2J}$. They both tend towards 1 when J tends towards $+\infty$, meaning that these effects are always true whatever the value of δ when there are an infinity of firms of the market. They are both increasing functions of J, and as $J > 2$, it is straightforward that:

$$\begin{cases}
\delta_\mu & > & \frac{1}{2} \\
\delta_\delta & > & \frac{3}{4}
\end{cases}$$

The following graph sums up how λ evolves with respect to μ and δ, depending on these two thresholds. For simplicity, assume that $\delta \leq \frac{J-1}{J}$ henceforth.

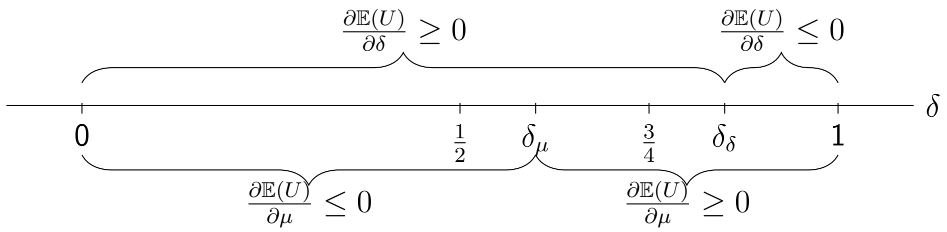


Figure 1.6 – Sign of the change in expected utility following a change in μ or δ

As $\frac{\partial \mathbb{E}(U)}{\partial J} = -\frac{\mu\delta(1-\delta)}{(J-1)^2}V$, an increase in J implies a strict decrease in the customer's utility in equilibrium as long as $\delta \in]0,1[$. It has no impact if there is only one type of firm on the market, in other words if either $\delta = 0$ or $\delta = 1$, or if the customer cannot have a serious issue, ie. $\mu = 0$. The higher the original number of firms J, the lesser the negative impact of an extra firm on the market on their utility, and the effect tends towards zero when there are infinitely many firms on the market. This is a somewhat counterintuitive result: consumers do not benefit from having too many different suppliers. This is a direct implication of the fact that they limit their search instead of investigating a large number of firms. It is a restrictive assumption, but it is consistent with reported customer behavior on the market. Having an expert assess a renovation need takes time, and a lot of consumers will choose to consult only a few firms.

The main takeaways from this model are that in the market equilibrium prices are low and that skilled firms do not have an incentive to be truthful, as they compete with one another. The unique price result directly stems from the assumption that all firms have the same reserve prices. Introducing firm-specific reservation prices does not alter the main results, nor does it change the comparative statics analysis for the most part, as shown in Appendix 1.C. If the model were extended to N consumers as a repeated game, this could however be useful to reproduce the price dispersion observed in real-world markets (Grandclément et al. 2018). Equilibrium fraud comes both in the form of overtreatment and undertreatment, the latter being more worrisome in the context of energy-efficiency renovations. Overtreatment is a misallocation of resources but does not hinder the final objective, which is to reduce the energy consumption of the residential sector. On the contrary, undertreatment undermines this goal and has been the main target of regulators.

1.5 Extensions

1.5.1 Introducing partial labeling of skilled firms

Labels seem like a natural solution to the undertreatment issue, as they are meant to restore information on firm types. As previously discussed, quality labels have been implemented in the construction sector to reassure customers on either the process, the materials used, the skills of the workers, etc. Despite this profusion of options, it is noticeable that they are not widespread among firms - the energy-efficiency certification "*Reconnu garant de l'environnement*" (RGE) [4] for instance accounts for roughly 15% of firms in France. Another key aspect of these labels is that they can be relatively unknown to the general public. In order to assess the efficiency of these labels, the previous model is extended, first assuming the customer would always choose a labeled firm over any other, and then in the more realistic hypothesis that they would be indifferent between a labeled firm and another one offering the same diagnosis at the same price.

Keeping the same framework, let a certain share of skilled firms decide to get a label, which reveals their type to the consumer. This is equivalent to introducing a third type in the previous game, denoted $\overline{\beta}^l$. Assume these firms are known to be always truthful in their diagnosis, so if the consumer faces an offer by a labeled firm against an offer by any other type, they buy from the labeled firm. If they draw two labeled firms, they buy from the cheapest one. Let $\delta = \delta^l + \delta^u$, where δ^l is the share of labeled skilled firms and δ^u is the share of unlabeled skilled firms. Figure 1.7 displays the game in its extensive form and Figure 1.D.1 in the Appendix provides details on the computation of total probabilities.

Proposition 1.6. *In equilibrium, there a unique market price set at k, and all unlabeled skilled firms set $\eta^* = 1$.*

Proof. This proof essentially follows that of Proposition 1.3 and 1.4. Nothing changes for unlabeled skilled firms and unskilled firms, except that unlabeled skilled firms cannot win over the customer if they are drawn with a labeled firm, hence in equilibrium they all set their prices to k and $\eta^* = 1$ remains an optimal strategy. Facing a $\underline{c}$ customer, a labeled skilled firm's profits are given by:

$$\mathbb{E}(\overline{\Pi}_j^l | c = \underline{c}) = \frac{\delta^l J - 1}{J-1} \times \mathbb{1}_j \times \underline{p}_j^l + \frac{(1-\delta^l)J}{J-1} \times \underline{p}_j^l$$

4. It can be translated to "*Recognised Environmental Guarantor*".

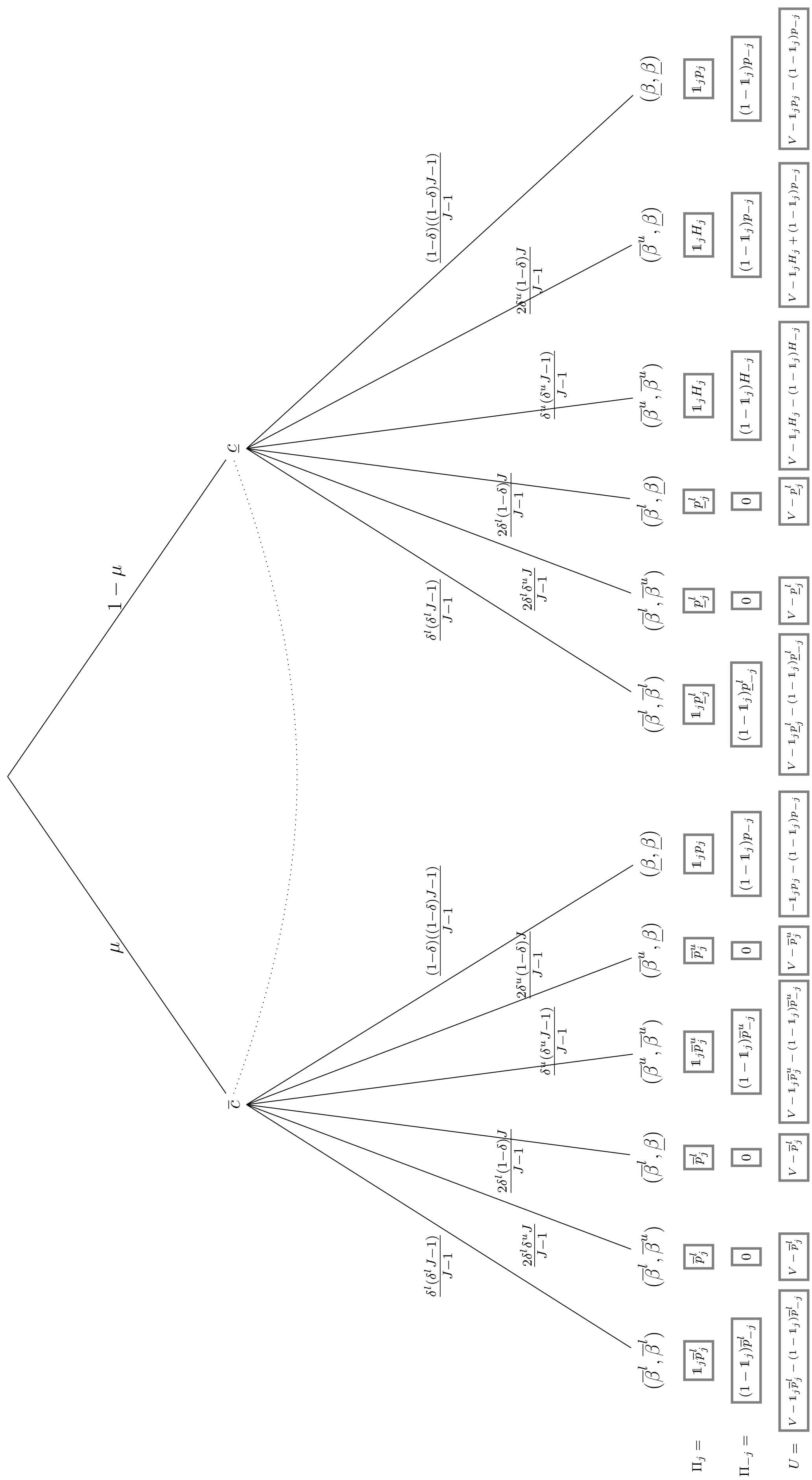


Figure 1.7 – Game with labeled skilled firms

The Bertrand mechanism described previously applies: for any price set by an opposite labeled firm such that $k < \underline{p}^l_{-j} \leq \underline{p}^l_j$, there is a strictly positive ϵ such that setting $\underline{p}^l_j = \underline{p}^l_j - \epsilon$ generates a strictly higher profit. As it pushes prices down, in equilibrium all labeled firms set $\underline{p}^l = k$. If the customer has a $\overline{c}$ issue, their profits take the same form as in the $\underline{c}$ case, except they set a price $\overline{p}^l$. Following the same reasoning, it is straightforward that $\overline{p}^l = k$ in equilibrium. □

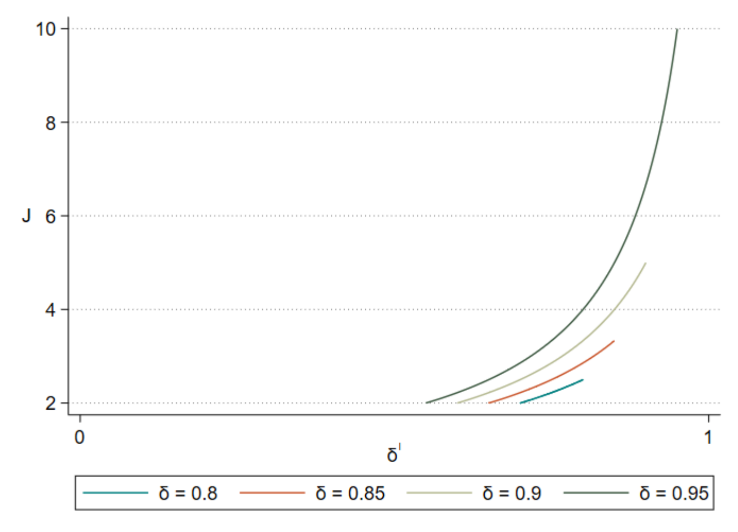
Equilibrium payoffs are given by:

$$\begin{aligned}
\mathbb{E}(\underline{\Pi}^*) &= \frac{2}{J}\left(\frac{(1-\delta)J-1}{J-1}\frac{k}{2} + \left(1 - \frac{(1-\delta)J-1}{J-1}\right)\times 0\right) &&= \frac{(1-\delta)J-1}{J(J-1)}k \\
\mathbb{E}(\overline{\Pi}^{u*}) &= \frac{2}{J}\left(\frac{\delta^l J}{J-1}\times 0 + \frac{\delta^u J-1}{J-1}\frac{1}{2}k + \frac{(1-\delta)J}{J-1}k\right) &&= \frac{k}{J(J-1)}\left(J\left(2-\delta-\delta^l\right) - 1\right) \\
\mathbb{E}(\overline{\Pi}^{l*}) &= \frac{2}{J}\left(\frac{\delta^l J-1}{J-1}\frac{k}{2} + \left(1 - \frac{\delta^l J-1}{J-1}\right)k\right) &&= \frac{k}{J(J-1)}\left(J(2-\delta^l) - 1\right) \\
\mathbb{E}(U^*) &= \frac{(1-\delta)((1-\delta)J-1)}{J-1}(V(1-\mu)-k) && \\
&\quad + \left(1 - \frac{(1-\delta)((1-\delta)J-1)}{J-1}\right)(V-k) &&= V\left(1 - \mu(1-\delta)\frac{(1-\delta)J-1}{J-1}\right) - k
\end{aligned}$$

Because of the competition among them, labeled skilled firms cannot set higher prices, even if the customer always favor them against any other unlabeled firm. It could be one of the causes undermining the appeal of certifications for skilled firms, providing ground for the assumption that only some of them would go through this process. Labeling is also inefficient to prevent overtreatment and to push unskilled firms out of the market, since their profits only depend on the overall share of skilled firms. Hence, if the share of skilled firms δ remains the same, it does not increase the consumer's equilibrium utility. There is less uncertainty for the consumer, who will learn their own type whenever drawing an unskilled firms or at least one labeled firm, but it does not translate into a higher utility level on average.

In fine, on a market where unskilled firms would be otherwise active, introducing a type-revealing label will not push them out but it will affect unlabeled skilled firms' profits. They are strictly lower in this setup if $\delta^l > 0$, and they do not always have an incentive to enter the market. Their expected equilibrium profits are positive if and only if $J \geq \frac{1}{2(1-\delta^l)-\delta^u}$. As $\delta \leq \frac{3}{4} \implies \frac{1}{2(1-\delta^l)-\delta^u} \leq 2$, their equilibrium expected profits are positive as long as $\delta \leq \frac{3}{4}$ or $J \geq \frac{1}{2(1-\delta^l)-\delta^u}$. They are negative if and only if $\delta > \frac{3}{4}$ and $J \leq \frac{1}{2(1-\delta^l)-\delta^u}$. Figure 1.8 displays unlabeled skilled firms' entry condition, plotting J as a function of δ^l for given levels of δ. It can be noted that everything else equal, the higher δ is, the more firms need to be on the market for unlabeled firms to expect positive profits in equilibrium. Similarly, given any $\delta > \frac{3}{4}$, an increase in δ^l implies a more constraining entry condition.

The main effect of labels is hence to increase the competitive pressure on skilled firms, by reducing their chances to win the customer over. If the share of labeled firms remains quite low, however, it won't be enough of a reason to push them out of the market.



<u>Source:</u> Author's computations.

Figure 1.8 – Unlabeled skilled firms' entry condition

1.5.2 Partial labeling with a label-indifferent consumer

As labels are not always well known outside of the professional spheres, it could be unrealistic to assume that customers would systematically choose a certified firm. Consider the same setup with labels, except that consumers do not always go for the labeled firm if they are facing a $(\overline{\beta}^l, \overline{\beta}^u)$ pair or a $(\overline{\beta}^l, \underline{\beta})$ one offering the same diagnosis. As shown thereafter, there is still one market price set at k, as this result is driven by the perspective of being drawn with same-type firms, but the equilibrium profits of labeled and unlabeled skilled firms will be affected.

Proposition 1.7. *In equilibrium, unlabeled skilled firms always set* $\overline{p}^{u*} = \underline{p}^{u*} = k$.

Proof. In this setup, an unlabeled skilled firm's expected profits when facing a $\overline{c}$ customer are the same as in the proof of Proposition 1.3:

$$\mathbb{E}(\overline{\Pi}^u | c = \overline{c}) = \frac{\delta^l J}{J-1}\mathbb{1}_j\overline{p}_j^u + \frac{\delta^u J - 1}{J-1}\mathbb{1}_j\overline{p}_j^u + \frac{(1-\delta)J}{J-1}\overline{p}_j^u = \frac{\delta J - 1}{J-1}\mathbb{1}_j\overline{p}_j^u + \frac{(1-\delta)J}{J-1}\overline{p}_j^u$$

When facing a $\underline{c}$ customer, their expected profits are also unchanged when they are matched with a same-type firm or an unskilled firm:

$$\begin{cases} \mathbb{E}(\overline{\Pi}^u|c=\underline{c},\beta_{-j}=\overline{\beta}^u) &= \eta_j\Big(\eta_{-j}\mathbb{1}_j\overline{p}_j^u+(1-\eta_{-j})\overline{p}_j^u\Big)+(1-\eta_j)\Big(\eta_{-j}\times 0+(1-\eta_{-j})\mathbb{1}_j\underline{p}_j\Big) \\ \mathbb{E}(\overline{\Pi}^u|c=\underline{c},\beta_{-j}=\underline{\beta}) &= \eta_j\overline{p}_j^u+(1-\eta_j)\mathbb{1}_j\underline{p}_j^u \end{cases}$$

The optimal strategy in these cases does not change: all prices drop to k and $\eta^*(\overline{\beta}^u)=\eta^*(\underline{\beta})=1$. If they deal with a $\underline{c}$ customer and are drawn with a labeled firm however, their profits are given by:

$$\mathbb{E}(\overline{\Pi}^u|c=\underline{c},\beta_{-j}=\overline{\beta}^l)=\eta_j\times 0+(1-\eta_j)\mathbb{1}_j\underline{p}_j^u$$

It is straightforward that in this situation it is optimal to set $\underline{p}_j^u=k$ (and $\underline{p}_{-j}^l=k$). Their profits become $\mathbb{E}(\overline{\Pi}^u|c=\underline{c},\beta_{-j}=\overline{\beta}^l)=(1-\eta_j)\frac{k}{2}$, implying $\frac{\partial\mathbb{E}(\overline{\Pi}^u|c=\underline{c},\beta_{-j}=\overline{\beta}^l)}{\partial\eta_j}=-\frac{k}{2}$. As $\mathbb{E}(\overline{\Pi}^u|\underline{c},\overline{\beta}^l)$ is a decreasing function of η_j, firms j's optimal lying strategy is $\eta_j^*(\overline{\beta}^l)=0$. Unlabeled skilled firms' equilibrium prices are always $\overline{p}^{u*}=\underline{p}^{u*}=k$, independently of their choice regarding their individual lying strategy η_j. □

It is not a surprising result, as prices are pushed down solely by the fact that the customer consults more than one firm, and by the uncertainty on the competitor's type. The robustness of this result is central, as intense competitive pressure on prices is a key feature of the construction market this model attempts to replicate. The optimal lying policy may however become truth-telling in this extension, depending on the share of labeled firms.

Proposition 1.8. *If $\delta^l>\frac{1}{2}$ or $J<\frac{1}{1-2\delta^l}$, $\eta^*=0$ is the equilibrium strategy for labeled skilled firms. If $\delta^l<\frac{1}{2}$ and $J>\frac{1}{1-2\delta^l}$, their equilibrium strategy is $\eta^*=1$. If $\delta^l\in[\frac{1}{4},\frac{1}{2}]$ and $J=\frac{1}{1-2\delta^l}$, their equilibrium strategy is $\eta^*=\frac{1}{2}$.*

Proof. As firms do not know their competitor's type, they set the value of η depending on their overall profits:

$$\begin{aligned} \mathbb{E}(\overline{\Pi}^{u*}|\eta=1) &= \frac{2}{J}\Bigg(\frac{(1-\delta)J}{J-1}k+\frac{\delta^u J-1}{J-1}\frac{k}{2}+\frac{\delta^l J-1}{J-1}\Big(\mu\frac{k}{2}+(1-\mu)\times 0\Big)\Bigg) \\ &= \frac{k}{J(J-1)}\Big(J(2-\delta-(1-\mu)\delta^l)-1\Big) \\ \mathbb{E}(\overline{\Pi}^{u*}|\eta=0) &= \frac{2}{J}\Bigg(\frac{(1-\delta)J}{J-1}(\mu k+(1-\mu)\frac{k}{2})+\frac{\delta J-1}{J-1}\frac{k}{2}\Bigg) \\ &= \frac{k}{J(J-1)}\Big(J(1+\mu(1-\delta))-1\Big) \end{aligned}$$

As $\mathbb{E}(\overline{\Pi}^{u*}|\eta = 1) - \mathbb{E}(\overline{\Pi}^{u*}|\eta = 0) = \frac{(1-\mu)k}{J-1}\Big(1 - \delta - \delta^l\Big)$, lying is a dominant strategy if and only if $1 - \delta \geq \delta^l$. Furthermore, $\delta \leq \frac{1}{2} \implies 1 - \delta \geq \frac{1}{2}$, meaning $1 - \delta \geq \delta \geq \delta^l$. Consequently, truth-telling is a dominant strategy if and only if $\delta \geq \frac{1}{2}$ and $\delta^l \geq 1 - \delta$. It is strictly dominant if these inequalities are strict. In case of equality, the firm randomizes, setting $\eta = \frac{1}{2}$.

Let us review these three cases to determine the equilibria. First, let $1-\delta > \delta^l$ and assume all unlabeled skilled firms adopt the strategy $\eta^* = 1$ and set their prices to k. If one firm j were to deviate in this equilibrium by setting $\eta_j = \eta < 1$, their deviation profits would be:

$$\begin{aligned}
\mathbb{E}(\overline{\Pi}_j^{u*}|\eta_j^* = \eta, \eta_{-j}^* = 1) &= \tfrac{2}{J}\bigg(\tfrac{\delta^l J}{J-1}\Big(\mu\tfrac{k}{2} + (1-\mu)\eta \times 0 + (2-\mu)(1-\eta)\tfrac{k}{2}\Big) \\
&\quad + \tfrac{\delta^u J - 1}{J-1}\Big(\mu\tfrac{k}{2} + (1-\mu)\eta\tfrac{k}{2} + (1-\mu)(1-\eta) \times 0\Big) \\
&\quad + \tfrac{(1-\delta)J}{J-1}(\mu k + (1-\mu)\eta k + (1-\mu)(1-\eta)\tfrac{k}{2})\bigg) \\
&= \tfrac{k}{J(J-1)}\bigg(J\Big(1 + \mu + \eta(1-\mu) + \delta^l(1-\mu)(1-2\eta) - \delta\Big) \\
&\quad -\mu - \eta(1-\mu)\bigg)
\end{aligned}$$

Let $\Delta\overline{\Pi}^u_{\eta^*=1} = \mathbb{E}(\overline{\Pi}_j^{u*}|\eta_j^* = \eta, \eta_{-j}^* = 1) - \mathbb{E}(\overline{\Pi}^{u*}|\eta_j^* = 1\forall j)$, which simplifies to:

$$\begin{aligned}
\Delta\overline{\Pi}^u_{\eta^*=1} &= \tfrac{k}{J(J-1)}\bigg(J\Big(1 + \mu + \eta(1-\mu) + \delta^l(1-\mu)(1-2\eta) - \delta - 2 + \delta + (1-\mu)\delta^l\Big) \\
&\quad -\mu - \eta(1-\mu) + 1\bigg) \\
&= \tfrac{(1-\mu)(1-\eta)k}{J(J-1)}\Big(1 - J(1-2\delta^l)\Big)
\end{aligned}$$

As $1-\delta > \delta^l$ and $\delta > \delta^l$, it is straightforward that $\delta^l < \frac{1}{2}$, which implies that $1 - 2\,\delta^l \in]0,1[$. Furthermore, as $\eta < 1$, $\Delta\overline{\Pi}^u_{\eta^*=1} > 0 \iff 1 - J(1-2\delta^l) > 0$, which is equivalent to $J < \frac{1}{1-2\delta^l}$. In that case as the deviation profit is a decreasing function of η since $\frac{\partial\mathbb{E}(\overline{\Pi}_j^{u*}|\eta_j^*=\eta,\eta_{-j}^*=1)}{\partial\eta} = -\frac{(1-\mu)k}{J(J-1)}(1 - J(1-2\delta^l)) < 0$, the optimal deviation strategy is to set $\eta_j^* = 0$.

Turning to the $1-\delta < \delta^l$ case, assume all unlabeled skilled firms adopt the strategy $\eta^* = 0$ and set their prices to k. If one firm j were to deviate in this equilibrium by setting $\eta_j = \eta > 0$, their deviation profits would be:

$$\begin{aligned}
\mathbb{E}(\overline{\Pi}_j^{u*}|\eta_j^*=\eta,\eta_{-j}^*=0) &= \tfrac{2}{J}\Big(\tfrac{\delta^l J}{J-1}\Big(\mu\tfrac{k}{2}+(1-\mu)\eta\times 0+(1-\mu)(1-\eta)\tfrac{k}{2}\Big)\\
&\quad+\tfrac{\delta^u J-1}{J-1}\Big(\mu\tfrac{k}{2}+(1-\mu)\eta k+(1-\mu)(1-\eta)\tfrac{k}{2}\Big)\\
&\quad+\tfrac{(1-\delta)J}{J-1}\Big(\mu k+(1-\mu)\eta k+(1-\mu)(1-\eta)\tfrac{k}{2}\Big)\Big)\\
&= \tfrac{k}{J(J-1)}\Big(J\Big(1+\mu+\eta(1-\mu)-2\eta\delta^l(1-\mu)-\mu\delta\Big)-1-(1-\mu)\eta\Big)
\end{aligned}$$

It yields the following net deviation gain:

$$\begin{aligned}
\Delta\overline{\Pi}^u_{\eta^*=0} &= \tfrac{k}{J(J-1)}\Big(J\Big(1+\mu+\eta(1-\mu)-2\eta\delta^l(1-\mu)-\mu\delta-1-\mu(1-\delta)\Big)\\
&\quad-1-(1-\mu)\eta+1\Big)\\
&= \tfrac{\eta(1-\mu)k}{J-1}\Big(J(1-2\delta^l)-1\Big)
\end{aligned}$$

As $\eta>0$, $\Delta\overline{\Pi}^u_{\eta^*=0}$ is always negative if $1-2\delta^l\leq 0$, which is equivalent to $\delta^l\leq\frac{1}{2}$.

Alternatively, if $\delta^l<\frac{1}{2}$, the difference is strictly positive if and only if $J\,(\,1-2\,\delta^l\,)-1\;>\;0$, that is, $J>\frac{1}{1-2\delta^l}$. In that case, there are profitable deviations from the equilibrium, and as $\frac{\partial\mathbb{E}(\overline{\Pi}_j^{u*}|\eta_j^*=\eta,\eta_{-j}^*=0)}{\partial\eta}=\frac{(1-\mu)k}{J-1}(J(1-2\delta^l)-1)>0$, the optimal deviation strategy is to set $\eta_j^*=1$.

Finally if $1-\delta=\delta^l$ and all unlabeled skilled firms randomize, meaning $\eta^*=\frac{1}{2}$ and set their prices to k, their expected profits in equilibrium are given by:

$$\begin{aligned}
\mathbb{E}(\overline{\Pi}^{u*}|\eta^*=\tfrac{1}{2}) &= \tfrac{2}{J}\Big(\tfrac{\delta^l J}{J-1}\Big(\mu\tfrac{k}{2}+\tfrac{1-\mu}{2}\times 0+\tfrac{1-\mu}{2}\tfrac{k}{2}\Big)+\tfrac{\delta^l J-1}{J-1}\Big(\mu\tfrac{k}{2}+\tfrac{1-\mu}{2}(\tfrac{1}{2}\tfrac{k}{2}+\tfrac{1}{2}k)\\
&\quad+\tfrac{1-\mu}{2}(\tfrac{1}{2}\times 0+\tfrac{1}{2}\tfrac{k}{2})\Big)+\tfrac{(1-\delta)J}{J-1}\Big(\mu k+\tfrac{1-\mu}{2}k+\tfrac{1-\mu}{2}\tfrac{k}{2}\Big)\Big)\\
&= \tfrac{k}{2J(J-1)}\Big(J\Big(3+\mu-\delta(1+\mu)-(1-\mu)\delta^l\Big)-2\Big)
\end{aligned}$$

If one firm j were to deviate in this equilibrium by setting $\eta_j=\eta\neq\frac{1}{2}$, their deviation profits would be:

$$\begin{aligned}
\mathbb{E}(\overline{\Pi}_j^{u*}|\eta_j^*=\eta,\eta_{-j}^*=\tfrac{1}{2}) &= \tfrac{2}{J}\Big(\tfrac{\delta^l J}{J-1}\Big(\mu\tfrac{k}{2}+(1-\mu)\eta\times 0+(1-\mu)(1-\eta)\tfrac{k}{2}\Big)+\tfrac{\delta^u J-1}{J-1}\Big(\mu\tfrac{k}{2}\\
&\quad+(1-\mu)\eta(\tfrac{1}{2}\tfrac{k}{2}+\tfrac{1}{2}k)+(1-\mu)(1-\eta)(\tfrac{1}{2}\times 0+\tfrac{1}{2}\tfrac{k}{2})\Big)\Big)\\
&= \tfrac{k}{2J(J-1)}\Big(J\Big(2\eta(1-\mu)+2(1+\mu)+\delta^l(1-\mu)(1-4\eta)\\
&\quad-\delta(1+\mu)\Big)\quad-1-\mu-2\eta(1-\mu)\Big)
\end{aligned}$$

The difference between these two expected profits is given by:

$$\begin{aligned}
\Delta\overline{\Pi}^u_{\eta^*=\frac{1}{2}} &= \tfrac{k}{2J(J-1)}\Big(J\Big(2\eta(1-\mu)+2(1+\mu)+\delta^l(1-\mu)(1-4\eta)-\delta(1+\mu)-3-\mu \\
&\quad +\delta(1+\mu)+(1-\mu)\delta^l\Big)-1-\mu-2\eta(1-\mu)+2\Big) \\
&= \tfrac{(1-2\eta)(1-\mu)k}{2J(J-1)}\Big(1-(1-2\delta^l)J\Big)
\end{aligned}$$

As $\delta^l = 1-\delta$ and $\delta^l < \delta$, it is straightforward that $\delta > \frac{1}{2}$ which implies that both δ^l and $1-\delta$ are inferior to $\frac{1}{2}$. It implies that $1-2\delta^l \in]0,1[$.

If $\eta > \frac{1}{2}$, then $\Delta\overline{\Pi}^u_{\eta^*=\frac{1}{2}} > 0 \iff 1-(1-2\delta^l)J < 0$, which is equivalent to $J > \frac{1}{1-2\delta^l}$.
Conversely, if $\eta < \frac{1}{2}$, then $\Delta\overline{\Pi}^u_{\eta^*=\frac{1}{2}} > 0 \iff 1-(1-2\delta^l)J > 0$, meaning $J < \frac{1}{1-2\delta^l}$.
In both cases, profitable deviations are possible. The derivative of the deviation profits is given by :

$$\frac{\partial \mathbb{E}(\overline{\Pi}^{u*}_j|\eta^*_j=\eta,\eta^*_{-j}=\frac{1}{2})}{\partial\eta} = \frac{(1-\mu)k}{J(J-1)}\Big(J(1-2\delta^l)-1\Big)$$

Hence : $\begin{cases} \frac{\partial \mathbb{E}(\overline{\Pi}^{u*}_j|\eta^*_j=\eta,\eta^*_{-j}=\frac{1}{2})}{\partial\eta} > 0 \iff J > \frac{1}{1-2\delta^l} \\ \frac{\partial \mathbb{E}(\overline{\Pi}^{u*}_j|\eta^*_j=\eta,\eta^*_{-j}=\frac{1}{2})}{\partial\eta} < 0 \iff J < \frac{1}{1-2\delta^l} \end{cases}$

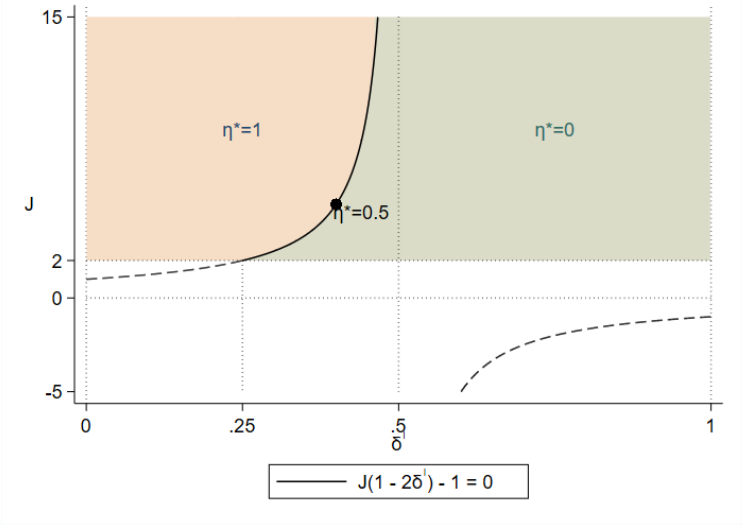
The $(\eta^*, \overline{p}^{u*}, \underline{p}^{u*}) = (\frac{1}{2}, k, k)$ is thus an equilibrium strategy for unlabeled skilled firms if and only if $J = \frac{1}{1-2\delta^l}$, which is possible only if $\delta \geq \frac{1}{4}$ since $J > 2$. The various equilibria depend on the values of δ^l and J:

— If $\delta^l > \frac{1}{2}$, unlabeled skilled firms' equilibrium lying strategy is $\eta^* = 0$
— If $\delta^l < \frac{1}{2}$, unlabeled skilled firms' equilibrium lying strategy is :

$$\begin{cases} \eta^* = 1 \iff J > \frac{1}{1-2\delta^l} \\ \eta^* = \frac{1}{2} \iff J = \frac{1}{1-2\delta^l} \quad \text{and} \quad \delta^l \geq \frac{1}{4} \\ \eta^* = 0 \iff J < \frac{1}{1-2\delta^l} \end{cases}$$

□

Labeling can thus prevent equilibrium overtreatment, but only if the consumer does not always pick labeled firms. Figure 1.9 sums up how the value of J and δ^l may affect the equilibrium lying strategy of unlabeled firms. If δ is small, lying is always optimal even if a lot of skilled firms are labeled, as the chance of matching with them does not represent



Source: Author's computations.

Figure 1.9 – Unlabeled skilled firms' optimal lying strategy given J and δ^l

enough of a risk to outweigh the certainty of winning over the customer if matched with an unskilled firm. The condition on J can also be rewritten as follows:

$$\begin{aligned} J(1-2\delta^l)-1 \lesseqgtr 0 &\iff J(1-\delta^l-(\delta-\delta^u))-1 \lesseqgtr 0 \\ &\iff (1-\delta)J+\delta^u J-1 \lesseqgtr \delta^l J \\ &\iff \tfrac{(1-\delta)J}{J-1}+\tfrac{\delta^u J-1}{J-1} \lesseqgtr \tfrac{\delta^l J}{J-1} \end{aligned}$$

The turning point for unlabeled skilled firms is ultimately whether it is more likely to be drawn with a labeled firm or with any other type of firm. If the former is more probable, truth-telling is optimal. Otherwise, either lying yields higher profits or truth-telling is not sustainable in equilibrium. In other words, if labeling is not sufficiently widespread and if there are not enough skilled firms overall, overtreatment will prevail. It is clearly not yet achieved in the European case, yet there have been efforts to generalize certifications and labels. The consumer's utility remains unchanged, since overtreatment does not lower their equilibrium payoffs. If the general goal is to ensure more efficient renovations, labels seem to miss the mark. Regarding the effects of unlabeled skilled firms' reporting strategy on other firms, $\eta = 0$ even raises unskilled firms' expected profits:

$$\begin{aligned}
\mathbb{E}(\underline{\Pi}^*|\eta=1) &= \tfrac{2}{J}\Big(\tfrac{(1-\delta)J-1}{J-1}\tfrac{k}{2}+\tfrac{\delta^u J}{J-1}\times 0+\tfrac{\delta^l J}{J-1}\Big(\mu\times 0+(1-\mu)\tfrac{k}{2}\Big)\Big)\\
&= \tfrac{k}{J(J-1)}\Big(J(1-\delta+(1-\mu)\delta^l)-1\Big)\\
\mathbb{E}(\underline{\Pi}^*|\eta=0) &= \tfrac{2}{J}\Big(\tfrac{(1-\delta)J-1}{J-1}\tfrac{k}{2}+\tfrac{\delta J}{J-1}\Big(\mu\times 0+(1-\mu)\tfrac{k}{2}\Big)\Big)\\
&= \tfrac{k}{J(J-1)}\Big(J(1-\delta\mu)-1\Big)
\end{aligned}$$

As $\mathbb{E}(\underline{\Pi}^*|\eta=1)-\mathbb{E}(\underline{\Pi}^*|\eta=0)=\frac{(1-\mu)k}{J-1}\Big(\delta^l-\delta\Big)$ and $\delta^l\leq\delta$, it is always better for them when unlabeled skilled firms are truthful. Their equilibrium profits are also strictly higher than in the previous label setup in both cases. Conversely, $\eta=0$ decreases the equilibrium profits of labeled firms, making the certification less attractive:

$$\begin{aligned}
\mathbb{E}(\overline{\Pi}^{l*}|\eta=1) &= \tfrac{2}{J}\Big(\tfrac{\delta^l J-1}{J-1}\tfrac{k}{2}+\tfrac{\delta^u J}{J-1}\Big(\mu\tfrac{k}{2}+(1-\mu)k\Big)+\tfrac{(1-\delta)J}{J-1}\Big(\mu k+(1-\mu)\tfrac{k}{2}\Big)\Big)\\
&= \tfrac{k}{J(J-1)}\Big(J\Big(1+\mu+\delta(1-2\mu)-\delta^l(1-\mu)\Big)-1\Big)\\
\mathbb{E}(\overline{\Pi}^{l*}|\eta=0) &= \tfrac{2}{J}\Big(\tfrac{\delta J-1}{J-1}\tfrac{k}{2}+\tfrac{(1-\delta)J}{J-1}\Big(\mu k+(1-\mu)\tfrac{k}{2}\Big)\Big)\\
&= \tfrac{k}{J(J-1)}\Big(J\Big(1+\mu(1-\delta)\Big)-1\Big)
\end{aligned}$$

As $\mathbb{E}(\overline{\Pi}^{l*}|\eta=1)-\mathbb{E}(\overline{\Pi}^{l*}|\eta=0)=\frac{(1-\mu)k}{J-1}\Big(\delta-\delta^l\Big)$ and $\delta^l\leq\delta$, it is always better for them when unlabeled skilled firms choose to be dishonest. These results establish that (1) the customer has to be somewhat indifferent to labels in order to effectively prevent equilibrium overtreatment and (2) that overtreatment is more efficient than labels to deter the entry of unskilled firms. When overtreatment is not an equilibrium behavior, the profits of labeled firms are lower and those of unskilled firms are higher. These results provide some insights as to why why fraud persists despite the existence of numerous certifications on the market. They have also not yet been largely adopted, which could reflect either that skilled firms do not see what could be gain from getting them, or that there is not a large share of skilled firms on the market.

1.6 Conclusion

The equilibria described in this paper successfully replicate key features of many European countries' construction sectors, that is: low and non-discriminating resale prices and the persistence of fraud in equilibrium despite intense competitive pressure. In particular, unskilled firms can make positive profits in most cases, and this would be especially true when considering a larger number of consumers - which would consist in independent repetitions of the described games. Labels are not an appropriate policy tool to push them out of the market, and may even increase their profits if they successfully prevent overtreatment.

These theoretical results can provide some explanations as to why such public policies have not been successful in undermining fraud and boost the energy gains that are supposedly achievable in the residential sector. They also provide arguments against current policies like direct funding for energy retrofits - the French *MaPrimeRénov'* for instance. As they lower the actual cost of these renovations, they may make household less mindful when choosing contractors. Finally, the variable that seems to play the most important role in deterring fraud is the share of skilled firms, which gives ground to policies aiming to directly upskill construction professionals. Their impact may not be as immediate as labels', but they would have a more decisive effect on undertreatment. Using French insurance data, the NGO *Agence Qualité Bâtiment*[5] found that the total compensation paid to households amounted to approximately 847 million euros in 2020 (AQC 2022). It has increased every year by 5.9% on average since 2011, which was when the RGE label was introduced. The same year, the state spent 5.4 billion euros to found 629 635 apprenticeship contracts, 11% of which were in the construction sector (CDC 2022). Using the mean cost, it adds up to 594 million euros spent on apprenticeships in the sector - 70% of the cost of defects and malfunctions. From a social welfare perspective, improving professional training for contractors could be a better allocation of resources.

This model is yet limited in some dimensions. It would be interesting to further develop a dynamic setup to see how an increase of skills would actually impact equilibrium payoffs. Overtreatment would also be a more serious issue if $\underline{p}$ and $\overline{p}$ were not equal, as the direct funding of energy retrofit has become a widespread policy in Europe. For instance, the French state has a projected budget of 368.9 million euros dedicated to energy retrofits for 2023 (PLF 2023), hence generalized overtreatment could lead to a drastic misallocation of public resources.

5. "*Construction Quality Agency*".

Appendices of Chapter 1

1.A Simple setup : customer utility

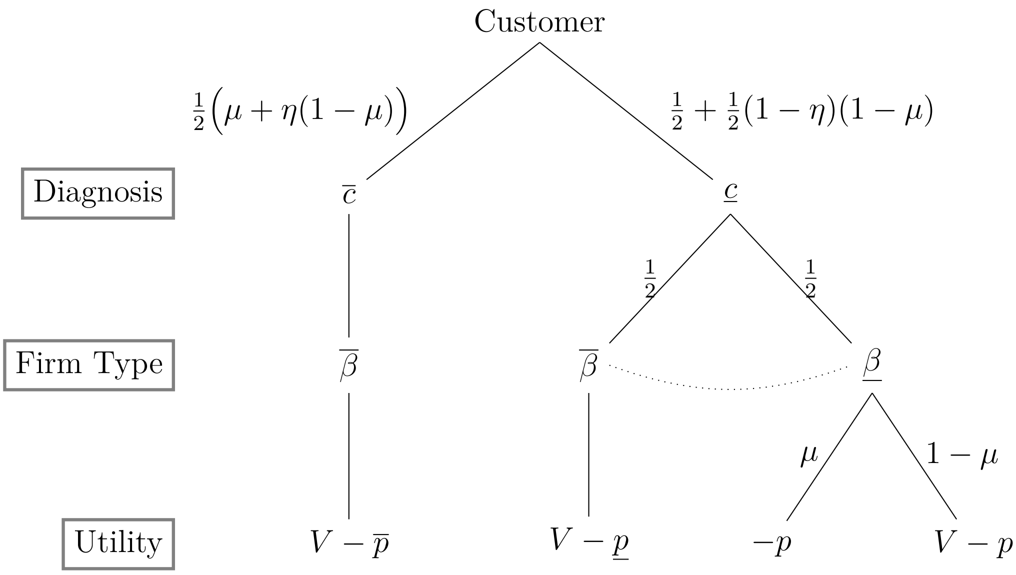


Figure 1.A.1 – Customer's expected utility depending on the diagnosis received if $\eta < 1$

1.B Obtaining total probabilities in the one-shot game with J firms and 2 firms drawn

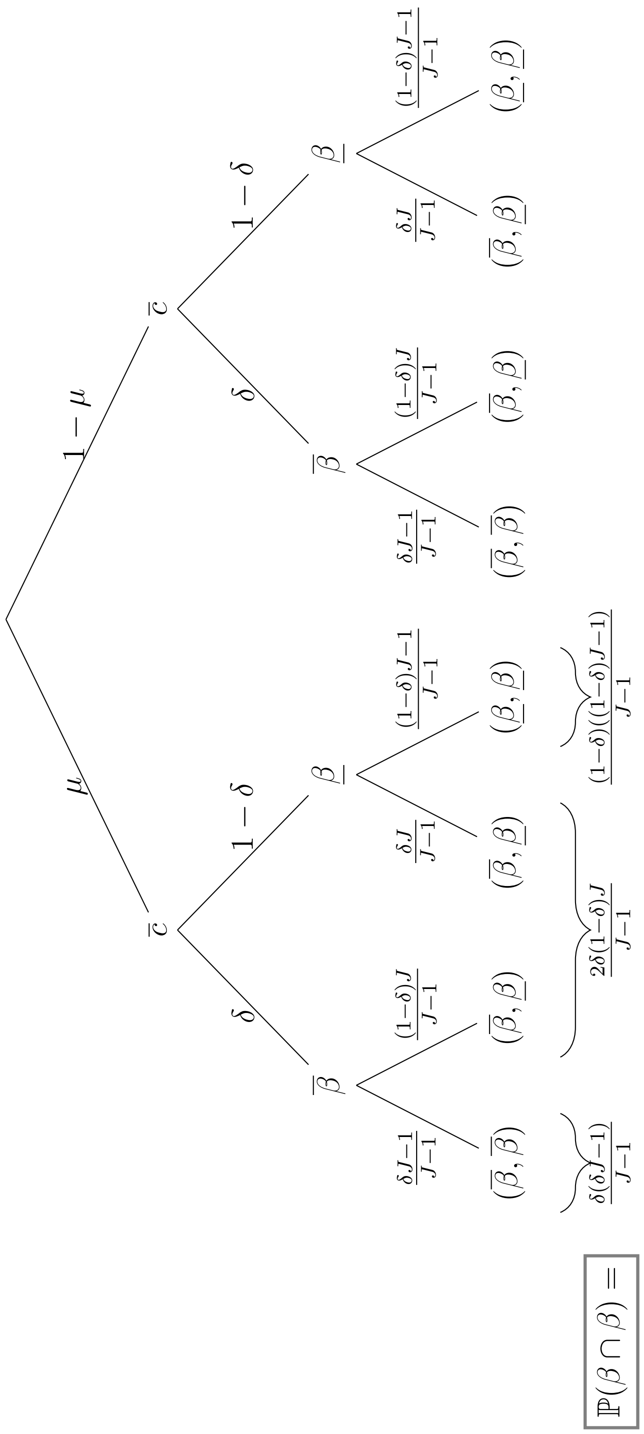


Figure 1.B.1 – Probability of drawing each pair of firms

1.C Introducing heterogeneous reserve prices in the general model

Given the same setup as in section 1.4, assume firms now have individual reserve prices. Formally, each firm j is randomly assigned a reserve price $k_j \in \mathbb{R}_+^*$ following a continuous cumulative distribution function F that is common knowledge. The main results from propositions 1.3 and 1.4 still hold, meaning in equilibrium $\eta_j^* = 1$, $\overline{p}^* = k_j$ and $p* = k_j$ for all firms j depending on their types.

Regarding skilled firms the potential competition still pushes them to post their minimal price k_j in all cases. As they do not know their competitor's type, if they offer a higher resale price there will always be a profitable deviation $\overline{p}_j - \epsilon$ or $\underline{p}_j - \epsilon$, where $\epsilon \in \mathbb{R}_+^*$. As both prices are equal, $\eta_j = 1$ is optimal to maximize their chances of winning over the customer. Their expected equilibrium payoffs are hence:

$$\begin{aligned}
\mathbb{E}(\overline{\Pi}_j^*) &= \tfrac{2}{J}\Big(\tfrac{\delta J-1}{J-1}\Big(1-F(k_j)\Big)k_j + \tfrac{(1-\delta)J}{J-1}k_j\Big) \\
&= \tfrac{2k_j}{J}\Big(1-\tfrac{\delta J-1}{J-1}F(k_j)\Big)
\end{aligned}$$

Unskilled firms will also post their minimal price, following the reasoning of Proposition 1.4. Their equilibrium expected profits are hence:

$$\mathbb{E}(\underline{\Pi}_j^*) = k_j\Big(1-F(k_j)\Big) \times \frac{2}{J} \times \frac{(1-\delta)J-1}{J-1}$$

The sign of the derivatives of expected profits with respect to J and δ remain unchanged. In particular, Proposition 1.5 still holds as $\frac{\partial \mathbb{E}(\underline{\Pi}_j^*)}{\partial J} = -\frac{k_j\big(1-F(k_j)\big)}{J^2(1-J)^2}\Big(2(1-\delta)J^2 - 4J + 2\Big)$. This derivative is positive if and only if $-(1-\delta)J^2 + 4J - 2 \geq 0$. The derivatives of expected profits with respect tot k_j are given by:

$$\begin{aligned}
\frac{\partial \mathbb{E}(\overline{\Pi}_j^*)}{\partial k_j} &= \tfrac{2}{J}\Big(1-\tfrac{\delta J-1}{J-1}\Big(F(k_j)+k_j f(k_j)\Big)\Big) \\
\frac{\partial \mathbb{E}(\underline{\Pi}_j^*)}{\partial k_j} &= \tfrac{2(1-\delta)J-2}{J(J-1)}\Big(1-F(k_j)-k_j f(k_j)\Big)
\end{aligned}$$

The expected profits of a skilled firm are an increasing function of its reserve price k_j if and only if $\frac{J-1}{\delta J-1} \geq F(k_j) + k_j f(k_j)$. Using partial integration, we find the following:

$$\begin{aligned}
&\int_0^{k_j} \tfrac{J-1}{\delta J-1}\partial t \geq \int_0^{k_j} F(t)\partial t + \int_0^{k_j} tf(t)\partial t \\
\iff\quad &\tfrac{J-1}{\delta J-1}k_j \geq \Big[tF(t)\Big]_0^{k_j} - \int_0^{k_j} tf(t)\partial t + \int_0^{k_j} tf(t)\partial t \\
\iff\quad &\tfrac{J-1}{\delta J-1}k_j \geq k_jF(k_j) \\
\iff\quad &\tfrac{J-1}{\delta J-1} \geq F(k_j)
\end{aligned}$$

Since $\frac{J-1}{\delta J-1} \geq 1\forall\delta \in [0,1]$, we find that $\frac{\partial\mathbb{E}(\overline{\Pi}_j^*)}{\partial k_j} \geq 0\forall k_j$. It is easy to show that $\frac{\partial\mathbb{E}(\underline{\Pi}_j^*)}{\partial k_j} \geq 0\forall k_j$ by following the same steps. This result implies that the negative effect of a marginally higher k_j on the probability that firm j sets a lower price than its competitor is completely offset by the direct gain if it wins over the customer.

The analysis of the customer's expected utility is identical to the one carried out in sections 1.4.3 and 1.4.4, assuming k is now defined by:

$$k = \begin{cases} \min(k_j, k_{-j}) & \text{if } \beta_j = \beta_{-j} \\ k_j & \text{if } (\beta_j, \beta_{-j}) = (\overline{\beta}, \underline{\beta}) \end{cases}$$

1.D Obtaining total probabilities in the game with labeled firms

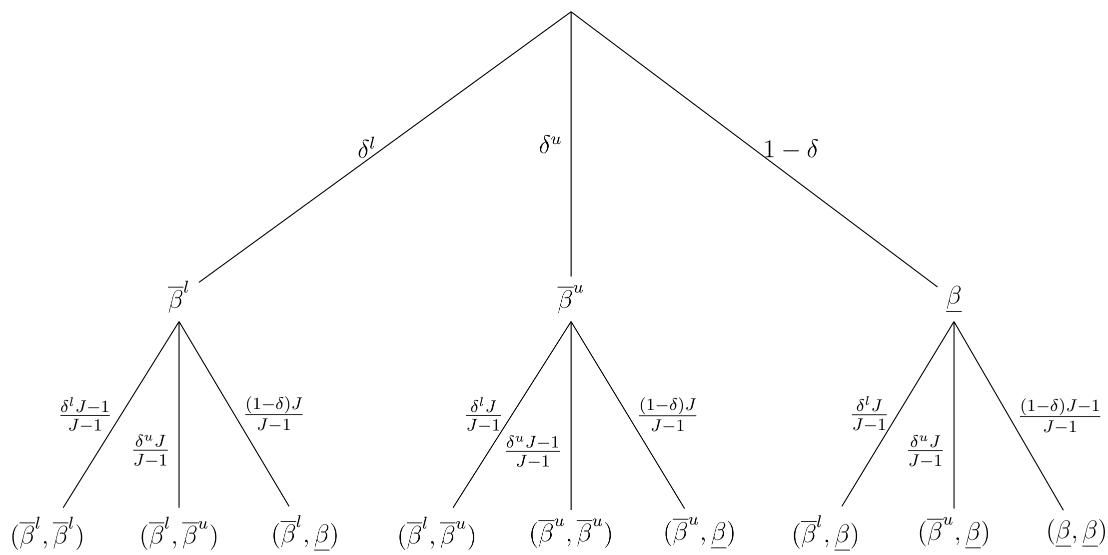


Figure 1.D.1 – Probability of drawing each pair of firms in the setup with labeled firms

* * *

«L'analyse mythique apparaît donc comme une tâche de Pénélope. Chaque progrès donne un nouvel espoir, suspendu à la solution d'une nouvelle difficulté. Le dossier n'est jamais clos.»

Claude Lévi-Strauss – *Le Cru et le Cuit.*

* * *

Chapter 2

If Drywall Could Talk: A Panel Data Double Hurdle Model to Assess New Technology Adoption in the French Construction Sector

* * *

Widespread adoption of new technologies can take time, depending on agents' perception of risk and the information they receive. It is especially true in the construction sector, yet high-performance materials are essential to ensure the efficiency and durability of the renovation and construction of dwellings. The depth of adoption is usually approached in one of two ways, either with inter-firm diffusion, which corresponds to new adoptions by firms over through time, or intra-firm diffusion, which measures the intensity of use by adopters. This paper presents an empirical procedure to estimate both dimensions simultaneously and account for geographical diffusion hubs. The estimator combines a panel data double-hurdle model and a spatial adoption index meant to capture word-of-mouth effects. A comprehensive dataset was built using scanner data and geolocalized census data. The model was run using this French data on an innovative gypsum board launched in 2017. Controls include both local and firm-specific features, as well as information regarding their general purchase behaviors. Results suggest that inter and intra firm adoption are not driven by the same determinants, and that word-of-mouth is not the sole factor explaining the emergence of geographical clusters of adoption.

* * *

2.1 Introduction

There is a general consensus in the economic literature that technological progress is a key driving force of economic development. Less attention has however been given to the actual diffusion of innovations, that is, how production processes evolve in reaction to new technologies. Widespread adoption can take time - or even never be reached - due to the risk new means of production represent. The initial contributions by Griliches (1957) and Mansfield (1968) established that this process was far from straightforward, the latter providing theoretical ground for the S-shaped path of technology diffusion observed over time. Various papers have refined and updated these frameworks, focusing on different aspects of the process. Here, innovation diffusion is understood in two ways: inter-firm diffusion, meaning the evolution of the number of adopters over time, and intra-firm diffusion, that is, the intensity of use by adopters over time. They both contribute to the overall adoption of a new technology but are in most cases studied separately. Intra-firm adoption in particular has remained overlooked, mostly due to the lack of appropriate data. This paper aims to assess these two dimensions of technology diffusion simultaneously, as they both contribute to the success or failure of an innovation.

Understanding the determinants behind the adoption of new technologies is particularly relevant in the context of the energy transition. Green technologies allow producers and consumers to maintain their level of production or consumption while decreasing their energy use - and ultimately, their carbon footprint. This paper focuses on technical innovations impacting the housing and construction market. The residential sector accounts for a non-negligible and growing part of the energy use worldwide, reaching 26% of total final consumption among European Union countries (Eurostat 2020) and 17% in the USA (EIA 2020). Part of this consumption is due to the obsolete state of many old dwellings and could be reduced with retrofit adjustments. This is known as the "energy efficiency gap", which measures the difference between the achievable and actual energy efficiency levels. Reducing the energy use in this sector has become a key objective of current low-carbon transition plans in many developed countries. Policymakers have implemented a mix of push and pull policies, which can vary depending on national contexts, but usually take the form of subsidizing retrofits while regulating practices and materials. Construction firms' choices in terms of materials are thus central to the energy efficiency of retrofitted homes and new constructions alike. Retrofits in particular will be more effective as new and better-performing products are developed and put on the market, such as less consuming boilers, compact insulation materials, smart glass, and so on.

This paper's objective is twofold. First, it aims to provide new insights on factors of diffusion both at the inter and intra-firm levels. Second, the estimation procedure is designed to take potential word-of-mouth effects into account. In practice, it combines a panel double-hurdle model and an explicit spatial adoption index. A comprehensive dataset was built using scanner data and geolocalized census data. Controls include both local and firm-specific features, as well as information regarding firms' purchase behaviors. Estimation results can thus shine a line on the most appropriate tools for policymakers. The relative importance of firm characteristics and local market features can provide ground for national sectoral policies (eg. financial support for firms, training) or localized programs (eg. financial support for households, awareness campaings). Contrary to past contributions, this paper focuses on an innovation that is not meant to alter firms' means of production. Contractors are not the direct beneficiaries of this new product, but rather act as intermediaries: the dwelling's occupiers will ultimately be the ones deriving utility from it. As firms often guide households in their choices in terms of design and technical solutions, it is important to understand which ones are more likely to try out these new products and / or use them more than once. This is especially true in the case of renovation projects, as new building are usually constructed following a precise blueprint - firms carrying on the work do not have the leeway to choose the materials.

The following section presents a selective literature review on the adoption of new technologies by firms. The theoretical grounds for the empirical estimation are detailed in section 2.3 and section 2.4 provides insights on the dataset along with descriptive statistics. The model was run using French data on an innovative gypsum board launched in 2017. Estimation results are discussed in section 2.5 and Section 2.6 concludes.

2.2 Literature review

The standard theory on new technology adoption relies on two main assumptions: firms are heterogeneous in their reservation prices and economies of scale lead to a price decrease of the innovation over time. These assumptions provide ground for the diffusion path observed over time, where a simple competitive framework would lead to instantaneous widespread adoption if the innovation generates higher profits. Higher reservation prices usually stem from buyers having different risk aversion levels, as adopting new technologies come with uncertainty regarding their profitability. Firms adopt whenever it becomes profitable for them to do so, in a static or inter-temporal approach. As the price falls, an increasing number of firms expect positive profits if they adopt[1]. The initial epidemic model of diffusion developed by Mansfield (1963) predicted that firm diffusion, both inter and intra, would follow a S-shaped path. His results relied solely on the assumption that the risk associated with an innovation would decrease over time. Stoneman (1981) established a more compelling specification, using a microeconomic approach based on profit-maximizing firms and Bayesian learning to explain different adoption timings. A profitability-based approach is used in this paper to derive the empirical results, as it proved to be a better fit when estimated with real-world data (Battisti and Stoneman, 2005).

A growing body of empirical work has put these models to the test. Most papers concluded that inter-firm adoption was positively associated to firm size, either because size is assumed to be correlated to efficiency, or because bigger firms may have more leeway to try new technologies (e.g. DeCanio and Watkins 1998; Dunne 1994). Experience, usually measured by the number of years a firm has remained active on the market, was also found to increase the probability of first adoption (Zolas et al. 2021). There is no consensus on the impact of market concentration and competitive pressure: more horizontal competition increased the speed of diffusion in Karaca-Mandic, Town, and Wilcock (2017) but not in Allen, Clark, and Houde (2009) for instance. Employees' skills and R&D spending were found to have a positive effect on firms' adoption probability (Giotopoulos et al. 2017; J. Gómez and Vargas 2012), as well as experience with a past version of the technology (Pontikakis, Y. Lin, and Demirbas 2006). The factors behind intra-firm diffusion have been less extensively studied, mainly due to the lack of data. Astebro (2004) focused on sunk costs, with the idea that small firms may have a harder time adjusting to a new technology. His results did support the existence of learning effects, and further implied that the choice to adopt was less plant-specific than the depth of adoption. Only plant size had an impact on the intensity of use over time, while the overall firm size had no significant effect. This result was used in this paper to define the relevant observation unit: multi-site firms are tackled at the productive unit level. The quality of human capital was also found to increase firm-level demand in the case of IT technologies (Bresnahan, Brynjolfsson, and Hitt 2002). Exploring the relationship between intra-firm and inter-firm diffusion, Hollenstein (2004) found that firm size only had a significant positive effect on Internet adoption among Swiss firm up to a certain threshold. Medium-sized firms were the most likely to have an intensive usage, especially if they had had a previous experience with an older version of the technology. Likewise, Battisti, Canepa, and Stoneman (2009) showed that firm size increased the probability to adopt an e-Business technology, but had a negative impact on the intensification of usage. Intra-firm

1. A thorough literature review on technology diffusion theory can be found in Stoneman and Battisti (2010).

and inter-firm adoption decisions are in all cases found to be independent, and high levels of overall adoption did not lead to higher intensity of use by individual firms. For instance, Battisti and Stoneman (2003) found that limited intra-firm diffusion 30 years after the launch of a new metalworking technology was hindering the overall output produced using that technology, even though the majority of firms had adopted it.

While ICTs have been well studied in the empirical literature on the diffusion of innovation, other technologies have gotten less attention. Regarding housing more specifically, homeowners' incentives to invest in energy retrofits were found to follow the standard cost-benefits arbitrage (eg. Metcalf and Hassett 1999) and to be stronger when energy prices increased (eg. Alberini, Khymych, and Scasny 2020), but firms' motivations are less clear-cut. Yearly earnings and the size of their workforce have been associated to higher probabilities to adopt greener means of production (Gillingham, Newell, and Palmer 2009; DeCanio and Watkins 1998). Using a Swiss multi-industry firm-level survey, Arvanitis and Ley (2013) further found that competitive pressure was the strongest driver of adoption for such technologies, particularly in high energy-consuming sectors, along with factor endowment and compatibility with existing means of production. Intra-firm diffusion remained quite limited, suggesting that adopting energy-saving technologies was more likely the result of one-time investments rather than part of a wider strategy. Taxes and regulations have been found to be efficient to boost intra-firm diffusion of green technologies (Stucki and Woerter 2016). Energy-saving innovations in the construction sector also tend to target the operation stage of buildings and not their production. New products are often designed to improve the comfort of people living in buildings, not firms' profitability. As architects and contractors are the ones making the technology choices, an incentives compatibility issue can arise: the products that will maximize the occupier's utility in the long run may not be the ones maximizing contractors' profits in the short run. It may explain why new products are usually not met with a high demand right away, even those for which benefits should quickly exceed the initial cost, but there is currently little evidence on innovation diffusion among construction firms. Du et al. (2014) provided some insights using survey data on Chinese firms', finding that barriers to adoption were stronger for smaller firms, which tended to only meet the regulatory requirements. Whether these results apply to real-world product diffusion and to other contexts has yet to be determined.

Finally, this paper contributes to the growing, yet sparse, literature on the spatial component of technology diffusion. Adoption by local competitors could either deter adoption or encourage it, depending on whether firms' activity is facilitated by imitation or differentiation. Distance has been found to mitigate the overall stock effect in the diffusion process, meaning that individuals or firms will be more strongly impacted by the decision of others closer to them. The concept of distance can be understood in various ways: the actual geographical distance between firms, their closeness in terms of employee education, background, area of expertise, etc. This paper uses the distance in kilometers between two firms to build a composite index, which will be discussed in Section 2.3. Analyses using similar methods have mainly been conducted at the international scale, and countries closer to adoption leaders were found more likely to adopt sooner and in larger proportions (Comin, Dmitriev, and Rossi-Hansberg 2012). Within-country estimations are mostly found in agricultural economics, following Case's 1992 results on the impact of adoption by neighbors to determine farmers' own propensity to adopt. This spatial effect has since been corroborated by various papers reviewing the agricultural sector in different countries (eg. Laepple et al. 2017; Ward and Pede 2015). Building on the logit estimation model with spatial dependence developed by R. Dubin (1995), Sarmiento and W. W. Wilson (2005) also found that spatial competition was a key driver of shuttle train elevator adoption in Nothern America. Specifically, adoption by a farmer triggered the adoption of others, but this effect decreased sharply with distance. More generally, geographical clusters of diffusion tend to appear in places where information circulates faster. ICT technologies were found to diffuse faster in regions where a lot of patents were granted (Bonaccorsi, Piscitello, and Rossi 2007) and in economically thriving areas, especially for smaller firms (Kelley and Helper 1999). Regarding intensity of usage, the overall diffusion process was estimated to be more limited in the countryside, where information spread at a slower pace (Galliano and Roux 2008). Most of the research on the construction and housing sector focused on homeowners. Their preferences were found to have a strong spatial dimension, in the sense that dwellings in socially homogeneous districts tend to display similar characteristics (Mohammadian, Haider, and Kanaroglou 2008). Energy-efficiency retrofits were undertaken more often in areas where families were younger and more educated (Morton, C. Wilson, and Anable 2018), which could lead to a faster and greater diffusion of innovative materials. The concentration of young people also seemed to stimulate the adoption of residential photovoltaic panels, with a strong impact of the adoption by close neighbors on the probability to adopt (Kim and Gim 2021). Local-level household characteristics was used in this paper to capture these potential demand-side effects on contractors' behaviors.

This paper contributes to the literature on inter and intra firm diffusion, and to the literature on the spatial component of new technology adoption. The estimation results are not fully in line with previous work, which did not account for space and time simultaneously, or only focused on one dimension of technology adoption. The estimation procedure relies on an augmented version of Cragg's double hurdle model, applied to panel data and count variables. A previous paper by Dong, Chung, and Kaiser (2004) used a similar methodology, but using a probit-normal specification while a logit-Poisson is needed here. It is also, as of writing, the first extension of R. Dubin's adoption index to an inter-temporal setup.

2.3 Model

2.3.1 Inter-firm diffusion

The specification of the first adoption decision takes after R. Dubin (1995), but has been adapted to a dynamic setup. When a new technology is introduced, firms are faced with the choice to either adopt it or keep using already existing competing products. Their decision will depend on their expected profits in case of adoption compared to their profits in case of non-adoption, denoted $\mathbb{E}(\Pi^A)$ and $\mathbb{E}(\Pi^N)$ respectively. These profits depend on a set of local building characteristics, like local temperatures and dwelling types, a set of demand-side variables such as median household revenues and dwelling prices, and a set of firm characteristics such as the number of employees and experience, all included in a matrix X. If its decisions were made independently from its rivals, a firm i located in a local market j would adopt for the first time at time t if and only if:

$$\begin{cases} \mathbb{E}_t(\Pi^A_{i,t+1}) - \mathbb{E}_t(\Pi^N_{i,t+1}) > 0 \\ \mathbb{E}_t(\Pi^A_{i,l+1}) - \mathbb{E}_t(\Pi^N_{i,l+1}) < 0 \quad \forall l < t \end{cases} \quad \text{where:} \quad \begin{cases} \mathbb{E}_t(\Pi^A_{i,t+1}) &= f_A(X_{i,t}) \\ \mathbb{E}_t(\Pi^N_{i,t+1}) &= f_N(X_{i,t}) \end{cases}$$

In practice, competitors' characteristics do matter, as new products may impact a firms' productivity or its differentiation strategy. More importantly, as pointed out by Sarmiento and W. W. Wilson (2005), it would be unrealistic to assume firms take strategic decisions independently from one another in such localized and competitive markets. Observing competitors' choice to adopt can either deter adoption, resulting in a Hawk-Dove or "chicken" Nash equilibrium, or on the contrary provide incentives to adopt, which leads to a dominant-strategy equilibrium. This second case generates a spatial multiplier effect, meaning the higher the number of adopters at any given time, the higher the incentives for non-adopters to switch to the new technology. The individual choice to adopt or not can hence be considered conditionally on an adoption index $AI_{i,t}$, which takes into account rival firms' adoption decisions. Their influence is mitigated with each rival's distance to firm i. Formally, denoting $d_{i,t}$ the indicator variable equal to 1 if firm i is a new adopter at time t:

$$\begin{cases} d_{i,t} = 1 \quad \text{if} & \begin{cases} \mathbb{E}_t(\Pi^A_{i,t+1} - \Pi^N_{i,t+1} | AI_{i,t}) > 0 \\ \mathbb{E}_t(\Pi^A_{i,l+1} - \Pi^N_{i,l+1} | AI_{i,l}) < 0 \quad \forall l < t \end{cases} \\ d_{i,t} = 0 \quad \text{otherwise} \end{cases}$$

The computation of the adoption index for each firm and each period builds on R. Dubin (1995) and can be understood as a weighted sum of competitors' past adoption decisions, in which distance negatively impacts the influence rivals may have on a firm i. In other words, it has a high value for firms located at the heart of diffusion hubs and a low value for firms established in places where the technology has not been tried out locally. It is meant to capture the spatial aspect of diffusion, and more precisely the existence of clusters of early adopters. Formally, denoting D_{ik} the distance in kilometers between firm i and firm k:

$$AI_{i,t} = \sum_{k \neq i} \delta_{k,t-1} \times \gamma_1 \times \exp\left(\frac{-D_{ik}}{\gamma_2}\right) \quad \text{where} \quad \delta_{k,t-1} = \sum_{l=0}^{t-1} d_{k,l}$$

A firm k's former adopter status in period t is given by $\delta_{k,t-1}$, which is equal to one if they have adopted prior to t. The factor γ_1 captures the overall impact of neighboring firms' decision by a firm's own choice to adopt or not. The term γ_2 captures the rate at which this influence decreases with distance. Since $\lim_{\gamma_2 \to \infty} \exp\left(\frac{-D_{ik}}{\gamma_2}\right) = 1$, a high γ_2 would indicate that distance does not matter, meaning only the overall number of adopters affects a firm's decision. If both terms are found to be jointly insignificant, it would indicate that there is no spatial effect and that only the local and firm-specific characteristics matter in the adoption process.

In this setup, firms' individual decisions are assumed to be driven by the difference in their expected profits, denoted $\Pi^*_{i,t} = \mathbb{E}_t(\Pi^A_{i,t+1} - \Pi^N_{i,t+1} | AI_{i,t})$. These profits are unobservable in the data used for the estimations, as it only provides purchase information. It is thus further assumed that purchase decisions are the result of latent profit maximization and that the latent variable $\Pi^*_{i,t}$ depends on the controls $X_{i,t}$, on the adoption index $AI_{i,t}$ and on an individual and time-specific component $u_{i,t}$:

$$\Pi^*_{i,t} = X_{i,t}\alpha + AI_{i,t} + u_{i,t}$$

The error terms $u_{i,t}$ are assumed to be independent, meaning that the spatial interaction is fully captured by the adoption index. Assuming $u_{i,t}$ follows a logistic distribution, the probability of adoption is given by:

$$\begin{aligned}
\mathbb{P}(d_{i,t}=1) &= \mathbb{P}(\Pi^*_{i,t}>0)\times\textstyle\prod_{l=0}^{t-1}\mathbb{P}(\Pi^*_{i,l}<0)\\
&= \Big(1-\mathbb{P}(u_{i,t}<-(X_{i,t}\alpha+AI_{i,t}))\Big)\times\textstyle\prod_{l=0}^{t-1}\mathbb{P}(u_{i,l}<-(X_{i,l}\alpha+AI_{i,l}))\\
&= \frac{\exp\Big(X_{i,t}\alpha+AI_{i,t}\Big)}{1+\exp\Big(X_{i,t}\alpha+AI_{i,t}\Big)}\times\frac{1}{\prod_{l=0}^{t-1}\Big(1+\exp(X_{i,l}\alpha+AI_{i,l})\Big)}\\
&= \frac{\exp\Big(X_{i,t}\alpha+AI_{i,t}\Big)}{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha+AI_{i,l})\Big)}
\end{aligned}$$

The maximum likelihood estimator is then found by summing the following log-likelihood function over time [2]:

$$\begin{aligned}
\ln(L_t) &= \textstyle\sum_{i\in N}\Bigg(d_{i,t}\times\ln\Bigg(\frac{\exp\Big(X_{i,t}\alpha+AI_{i,t}\Big)}{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha+AI_{i,l})\Big)}\Bigg)\\
&\quad+(1-d_{i,t})\times\ln\Bigg(\frac{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha+AI_{i,l})\Big)-\exp\Big(X_{i,t}\alpha+AI_{i,t}\Big)}{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha+AI_{i,l})\Big)}\Bigg)\Bigg)\\
&= \textstyle\sum_{i\in N}\Bigg(d_{i,t}\times\ln\Bigg(\frac{\exp(X_{i,t}\alpha+AI_{i,t})}{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha+AI_{i,l})\Big)-\exp(X_{i,t}\alpha+AI_{i,t})}\Bigg)\\
&\quad+\ln\Bigg(\frac{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha+AI_{i,l})\Big)-\exp\Big(X_{i,t}\alpha+AI_{i,t}\Big)}{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha+AI_{i,l})\Big)}\Bigg)\Bigg)
\end{aligned}$$

2.3.2 Intra-firm diffusion

Inter-firm adoption is not sufficient to capture the overall adoption diffusion process. The panel structure of the data can be used to assess the intensity of use by adopters over time. Firms are assumed to make sequential choices, deciding first whether or not to adopt, and then the optimal quantity to purchase. It can be modeled following a double hurdle approach, originally developed by Cragg (1971) to estimate the demand for durable goods. This two-part model is more flexible than the Heckman framework as it allows null observations in the second stage. It is essential in the case of intra-firm diffusion since adopters may not repeat purchase, but that does not make them non-adopters. The first stage is estimated on the overall population based on the extended Dubin model described previously.

The second hurdle aims to determine the extent of adoption by specifying an outcome equation that will be estimated only among adopters. The observed quantity purchased

2. Estimation methods are described more extensively in Honoré and Kyriazidou (2000).

by a firm, denoted $q_{i,t}$, is assumed to be dependent on their current and past decisions to adopt, and the optimal quantity maximizing their profits, denoted $q^*_{i,t}$ - which is again an unobserved latent variable. Formally:

$$\begin{cases} q_{i,t} = q^*_{i,t} \quad \text{if} \quad q^*_{i,t} > 0 \quad \text{and} \quad \exists l \leq t \quad \text{such that} \quad \Pi^*_{i,l} > 0 \\ q_{i,t} = 0 \quad \text{otherwise} \end{cases}$$

Ultimately, the observed variable at each time t and for each firm i is $q_{i,t} = \delta_{i,t} \times q^*_{i,t}$. Following the extension of double hurdle models by W. H. Greene (1994), it is assumed that $q^*_{i,t}$ follows a Poisson distribution [3]. Assuming both hurdles are independent and denoting f the Poisson distribution function:

$$\begin{aligned}
\mathbb{P}(q_{i,t}=0) &= \mathbb{P}(\delta_{i,t}=0) + \mathbb{P}(\delta_{i,t}=1; q^*_{it}=0) \\
&= \textstyle\prod_{l=0}^{t} \mathbb{P}(\Pi^* < 0) + \Big(1 - \prod_{l=0}^{t} \mathbb{P}(\Pi^* < 0)\Big) \times f_t(0) \\
&= \frac{1}{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha + AI_{i,l})\Big)} + f_t(0) \times \frac{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha + AI_{i,l})\Big)-1}{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha + AI_{i,l})\Big)} \\
\mathbb{P}(q_{i,t}=k) &= \mathbb{P}(\delta_{i,t}=1; q^*_{it}=k) \quad \forall k \in \mathbb{N}^* \\
&= \Big(1 - \textstyle\prod_{l=0}^{t} \mathbb{P}(\Pi^*_{i,l} < 0)\Big) \times f_t(k) \quad \forall k \in \mathbb{N}^* \\
&= f_t(k) \times \frac{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha + AI_{i,l})\Big)-1}{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha + AI_{i,l})\Big)} \quad \forall k \in \mathbb{N}^*
\end{aligned}$$

It is then straightforward to show that the probability density function of the observed variable $q_{i,t}$ is given by:

$$\begin{aligned}
\mathbb{P}(q_{i,t}=k) &= f_t(q_{i,t}) \times \frac{\prod_{l=0}^{t-1}\Big(1+\exp(X_{i,l}\alpha + AI_{i,l})\Big)-1}{\prod_{l=0}^{t-1}\Big(1+\exp(X_{i,l}\alpha + AI_{i,l})\Big)} + \frac{1}{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha + AI_{i,l})\Big)} \times \mathbb{1}_{q_{i,t}=0} \\
&= \frac{\exp\Big(-\lambda_{i,t}\Big) \times \Big(\lambda_{i,t}\Big)^{q_{i,t}}}{\Big(q_{i,t}\Big)!} \times \frac{\prod_{l=0}^{t-1}\Big(1+\exp(X_{i,l}\alpha + AI_{i,l})\Big)-1}{\prod_{l=0}^{t-1}\Big(1+\exp(X_{i,l}\alpha + AI_{i,l})\Big)} \\
&\quad + \frac{1}{\prod_{l=0}^{t}\Big(1+\exp(X_{i,l}\alpha + AI_{i,l})\Big)} \times \mathbb{1}_{q_{i,t}=0}
\end{aligned}$$

$$\text{where:} \quad \begin{cases} k \in \mathbb{N} \\ \mathbb{1}_{q_{i,t}=0} = 1 \quad \text{if} \quad q_{i,t}=0; \quad 0 \quad \text{otherwise.} \\ \lambda_{i,t} = \exp\Big(X_{i,t}\beta\Big) \end{cases}$$

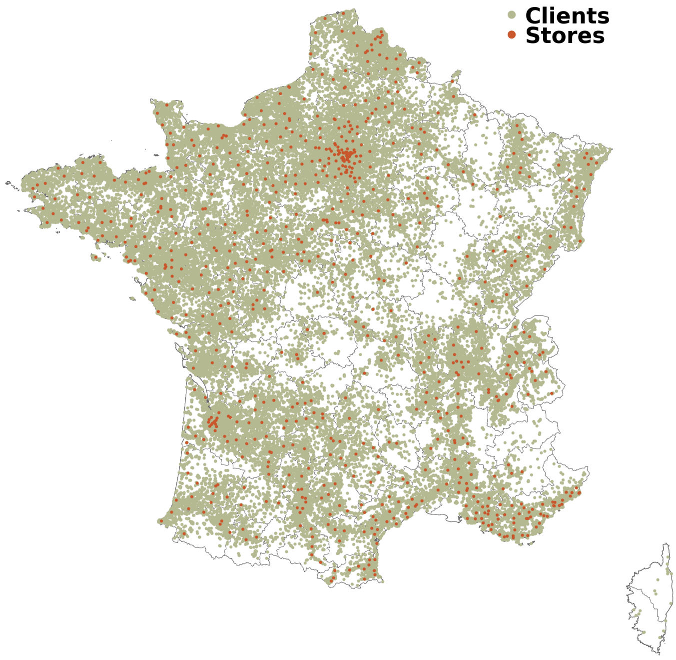
3. The original formulation by Cragg assumes the error terms of the two hurdles follow a normal distribution, while we follow a Logit-Poisson procedure.

The parameters can be estimated by maximizing the sum of the following log-likelihood function over time, where $N_t \subset N$ is the subset of adopters at time t [4]:

$$
\begin{aligned}
\ln(L_t) &= \sum_{i \in N_{t+1}} \ln\Big(\mathbb{P}(q_{i,t} = k)\Big) \\
&= \sum_{i \in N_{t+1}} \ln\left(\frac{\exp\Big(-\exp(X_{i,t}\beta)\Big)\times\Big(\exp(X_{i,t}\beta)\Big)^{q_{i,t}}\times\prod_{l=0}^{t-1}\Big(1+\exp(X_{i,l}\alpha+AI_{i,l})\Big)-1+\mathbb{1}_{q_{i,t}=0}\times\Big(q_{i,t}\Big)!}{\Big(q_{i,t}\Big)!\times\prod_{l=0}^{t-1}\Big(1+\exp(X_{i,l}\alpha+AI_{i,l})\Big)}\right)
\end{aligned}
$$

2.4 Data

2.4.1 Sales data and firms' characteristics



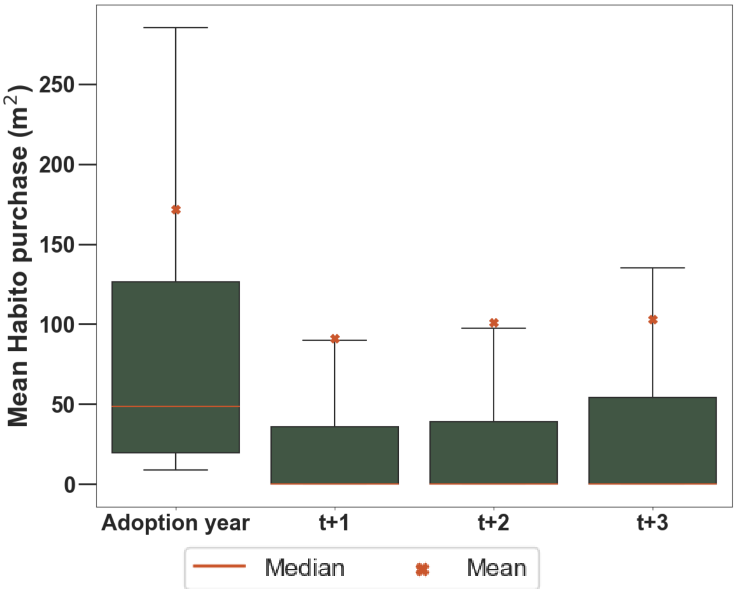
Source: Author computations.

Figure 2.4.1 – Locations of stores and clients

The model is applied to the diffusion of the Habito gypsum board, using sales data from one of the largest material retailer targeting professionals on the French market. They cover all subgroups of the construction activity, from masonry to plumbing or woodwork, and they

4. Computations of first and second derivatives can be found in W. H. Greene (1994).

have stores all over the metropolitan territory. Figure 2.4.1 displays the locations of the stores and their clients. They are not homogeneously distributed across the territory, as they are relatively more present in the South-West and less so in the North-East. Nevertheless, this dataset provides a dense coverage of construction firms in France. The Habito drywall was launched by the manufacturer Placo in January 2017 and has two major innovative characteristics. First, it is much stronger than standard gypsum boards [5], which can only hold up to 30 kg with anchors and 5 kg without, versus 60 kg and 20 kg for Habito. This also implies less breakage during transportation and a higher resistance to shocks, making for more durable buildings. Second, this board facilitates the installation of insulation underneath, for instance with vacuum insulation panels or using Isover's "Optimax mounting system". The latter is particularly interesting, as it both reinforces the energy efficiency of the wall by avoiding thermal bridges, and limits waste on the work site by suppressing 80% of the metal framing necessary to mount traditional drywall. From the contractor's perspective, it also means a faster and cleaner installation, as it reduces repetitive tasks like screw-driving and steel cutting. As drywall boards come in various dimensions, the quantity purchased was transformed into square meters - for instance a board of height 2.5m and width 1.2 is equivalent to 3m^2.



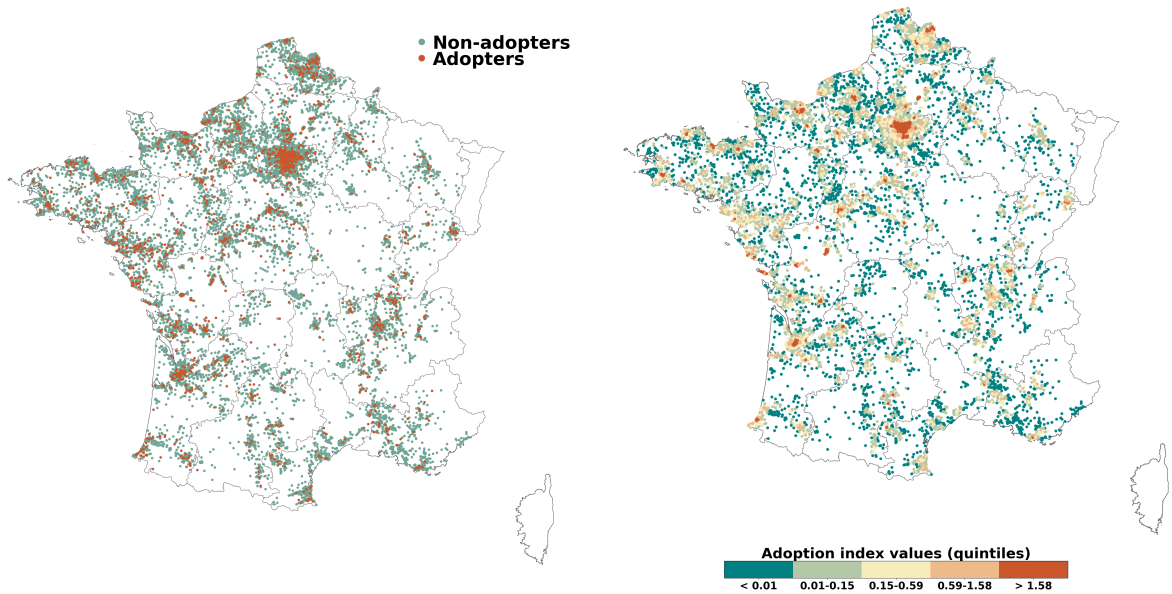
Source: Author computations.

Note: Adoption year corresponds to year t; group size varies for each t. The contractors who first adopted in 2017 appear in all four groups, while those who first-adopted in 2018 cannot appear in the "$t+3$" category, etc.

Figure 2.4.2 – Quantity purchased at and after adoption

5. Placo BA13 drywall is used as the baseline product.

Compared to previous work on diffusion, this dataset contains information on several years of material purchases by the same construction firms, hence the diffusion process is directly tractable. Since it is not an *ad hoc* survey, the usual non-respondent bias also isn't an issue. The initial data was restricted to stores from which an Habito board was purchased at least once, and to firms that purchased a standard BA-13 drywall board at least once over the four-year period and for which all information was available. The final sample contains roughly 20 000 firms for each year, which totals to 77 860 observations over the four years. At first glance, intra-firm diffusion appears quite low (Figure 2.4.2). There is a sharp decrease in the average quantity purchased and the median is at zero for all years after the first adoption. There is however a stronger uptake at $t+3$, suggesting some firms did repeat their purchase in the long run.

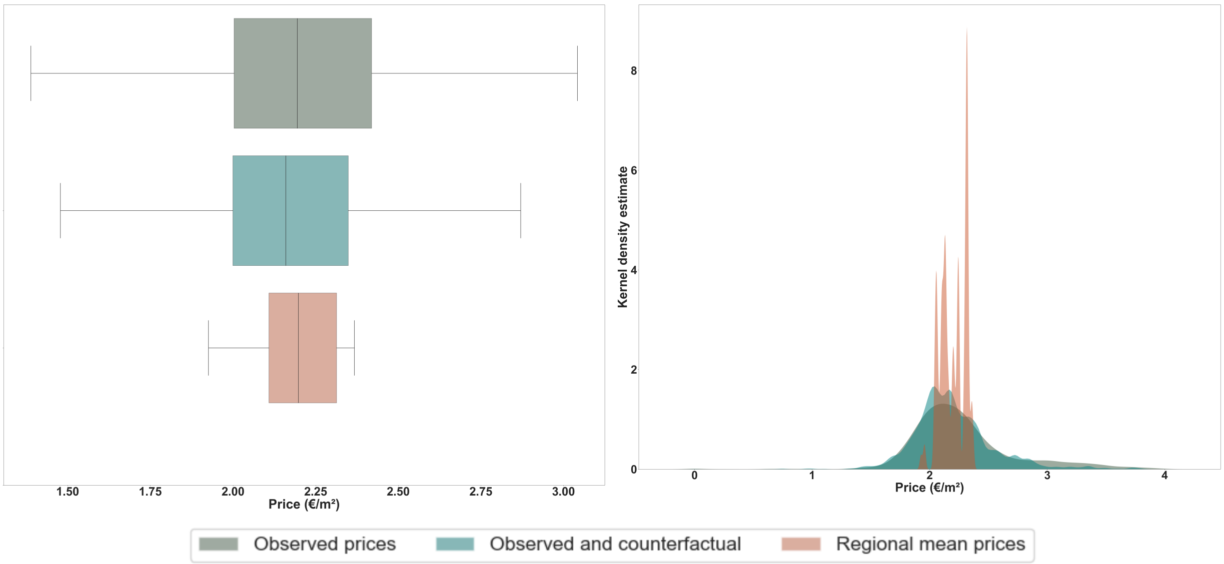


Source: Author computations.

Note: The adoption index is displayed for $\gamma_2 = 1.7$

Figure 2.4.3 – Adopters' locations (left) and individual adoption index values (right)

Firms' professional id (SIRET) was used to merge administrative information on each firm, such as their number of employees and the date of their creation, found in the SIRENE dataset produced by the French National Institute of Statistics and Economic Studies (Insee). Using their addresses, firms have been associated to GPS coordinates using the application programming interface of the "National Address Database" (BAN), also produced by the Insee. The adoption index for each firm was computed using these GPS coordinates. It seems to capture the spatial aspect of diffusion fairly well (Figure 2.4.3) - only 2020 values are displayed but the correlation holds throughout the period. Diffusion hubs appear quite clearly, mostly located in the North. Some of them are linked to urban concentration, like around the cities of Paris, Lyon or Lille, which is expected. Cities have more economic activity and information tends to spread faster. More surprisingly, adopters also ended up concentrating in sparser places, notably along the North-Western coast, hinting that urban density is not the only factor driving the emergence of adoption clusters.



Source: Author computations.

Note: The boxplots on the left display the median and the inter-quartile range, as well as the minimum and maximum values. Counterfactual prices for non-purchasers correspond to the store average. Leave-one-out mean prices were obtained for each firm j in sales-region s by averaging the price on the whole region excluding j. Formally, denoting J_s the number of firms in region s and P_k the price (observed or counterfactual) associated to each firm k in region s, the leave-one-mean for firm j is given by: $\sum_{k \neq j} \frac{P_k}{J_s - 1}$.

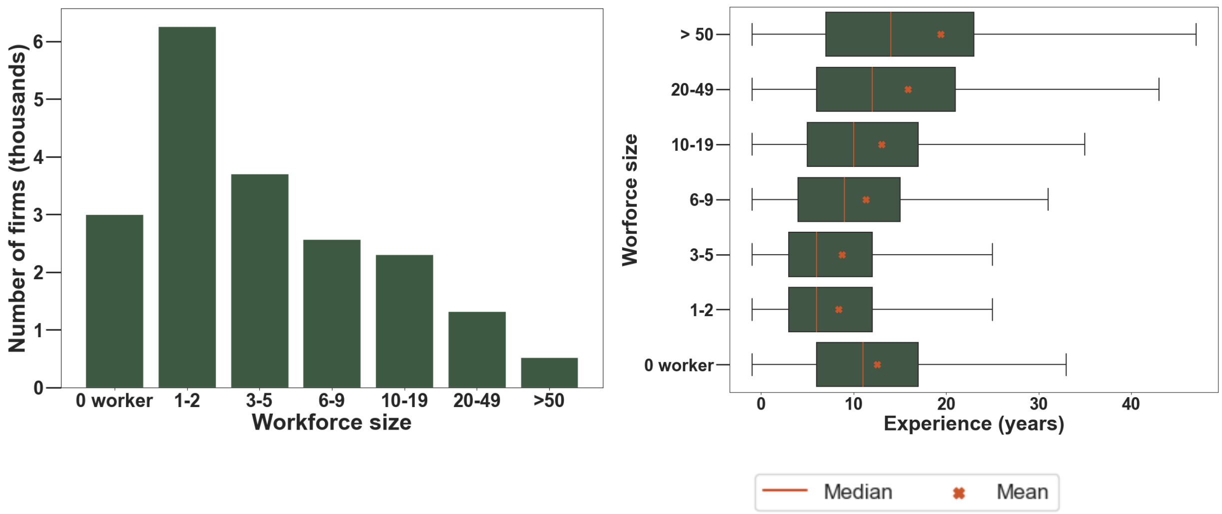
Figure 2.4.4 – Observed and counterfactual prices

Prices were left out of the analysis due to data inconsistency. Since adoption was low overall, the actual purchase price was available for roughly 14% of firms, for which there was at least one observation - in total, only 6% of the panel observations contained an observed price. Using the store average as a counterfactual price for non-purchasers has been considered, since it did not drastically decrease price variation and seemed to be a good fit for the observed price distribution (Figure 2.4.4). The real issue arised when dealing with price endogeneity. The retailers' stores being divided into 11 "sales regions" in terms of logistics and suppliers, aggregated leave-one-out mean prices could have been used to instrument retail prices. Since most observations consisted in counterfactual store-level prices, there was very little variation left in the leave one-out mean prices (Figure 2.4.4, left). Further, even though the median is similar, their overall distribution did not match the observed and counterfactual prices' (Figure 2.4.4, right). First-stage results were thus not compelling and prices were removed from the regressors, which prevented the estimation of price elasticities. In practice, prices are negotiated on a one-to-one basis with clients, which means that purchase prices are in fact dependent on each firm's characteristics. As such, the impact of firm determinants on adoption will provide some information on the effect of price - typically, larger firms and regular clients are offered lower resale prices.

Very small firms are slightly under-represented in our final sample compared to their importance among French construction firms as a whole (Figure 2.4.5, left). They still account for a large part of the sample, as 47% of firms have less than two employees. Figure 2.4.5 (right) displays the average, mean and quantiles of the number of years of experience per workforce size categories. It is interesting to note that workforce size does not linearly increase with experience, measured by the number of years during which a firm has been active on the market. In particular, a number of seasoned professionals have kept their productive structures small, having no employees, which matches figures on the overall market. Construction firms also differ with respect to their professional trades, meaning the nature of their activity (Figure 2.4.6). The seven categories used in this paper correspond to Insee intermediate categories for construction firms. The distribution of firms with respect to their size is comparable across categories, except Demolition and Civil Engineering, in which there is a majority of larger firms. The reference category used in the estimations is interior finishing, which contains trades which are expected to use the largest amounts of gypsum boards: drywallers, carpenters, plasterers, etc.

Additional information on the "*Reconnu Garant de l'Environnement*" (RGE)[6] certification was included. It is a costly label construction firms can obtain following a training program and an audit of the quality of their work. As energy retrofit tax rebates for homeowners are conditional on their contractor having the RGE label, skilled contractors have a high incentive to obtain the certification in order not to lose customers. Firms getting the label are then constrained to use products from a list of environmentally friendly materials defined at the State level, which contains Habito. The RGE label may also reveal a company's inclination towards more durable and sustainable practices. Information on labels was found in the "RGE historical dataset", published by the French Agency for the Environment and Energy Management (ADEME), which provides the precise time intervals during which a firm was

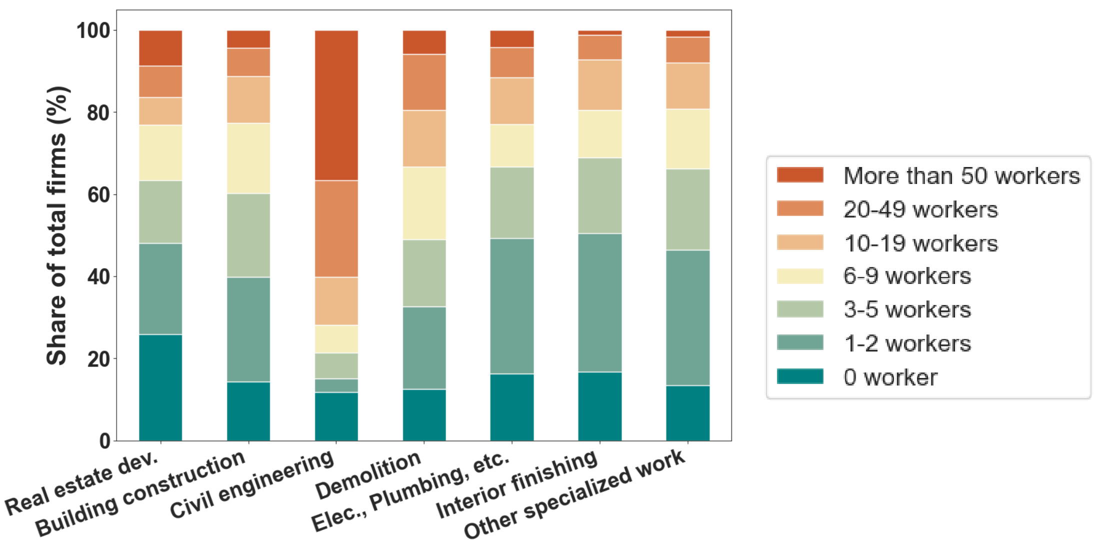
6. It can be translated to "*Recognised Environmental Guarantor*".



Source: Author computations from Insee data.

Note: Workforce size refers to the number of employees. Years of experience correspond to 2020 values.

Figure 2.4.5 – Workforce size and experience

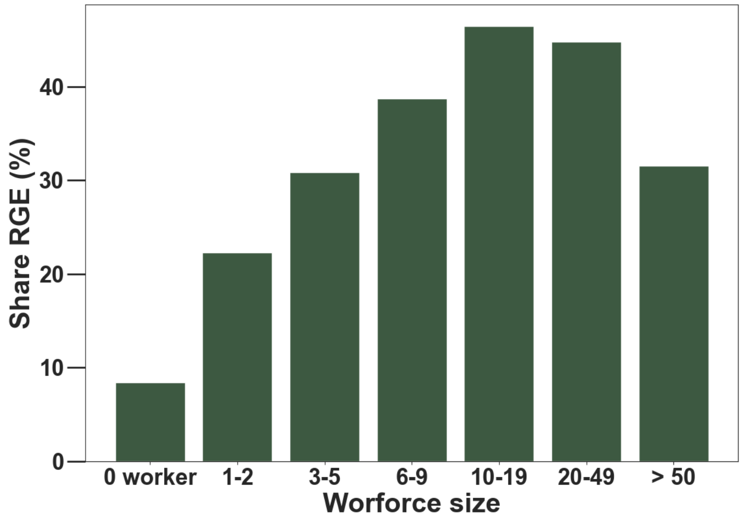


Sources: Author computation from Insee data.

Note: Shares correspond to 2020 values.

Figure 2.4.6 – Firms' professional trades

labeled. These intervals were used to determine how many months each firm has been labeled for since January 2017 - normalized to 0 for firms that were never labeled. On the final sample 63.4% of firms never got the label and more than 90% of firms which got the RGE label at least once have less than 20 employees, which is consistent with the figures found at the national scale (CGEDD 2017). There is a however higher proportion of labeled firms among larger firms, namely with more than 10 employees (Figure 2.4.7).



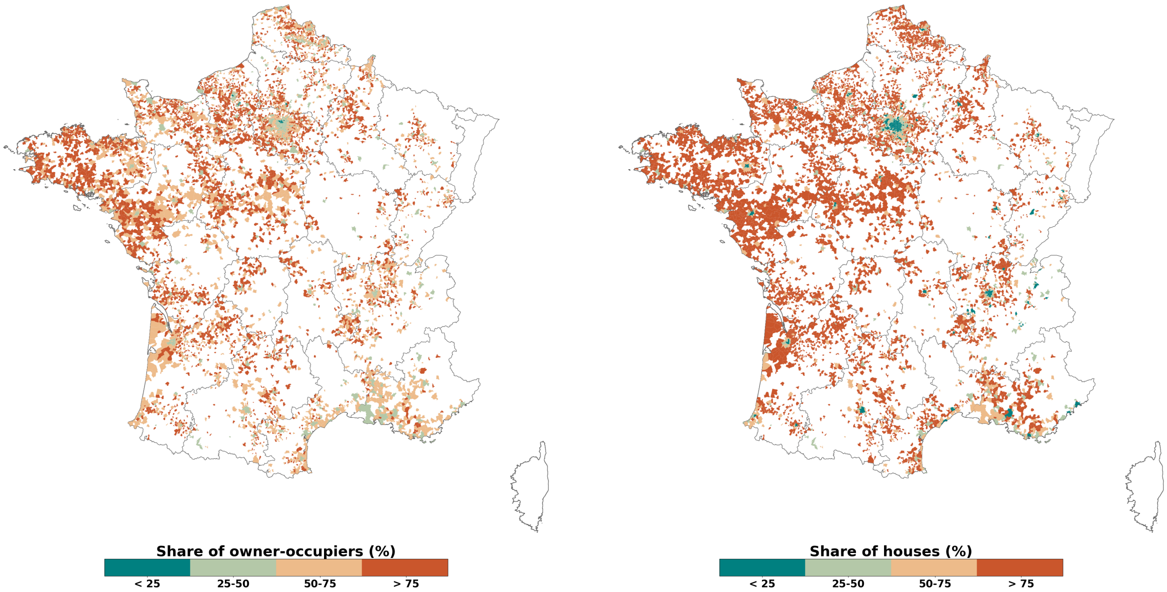
Source: Author computations from ADEME data.

Note: Workforce size refers to the number of employees. Shares of RGE firms correspond to 2020 values.

Figure 2.4.7 – RGE label

2.4.2 Local characteristics

Firms' locations were also used to cross the sales data with city-level information. Regarding households, who are contractors' end-clients, the French census provides information on the number of dwellings, the share of owners and on the share of houses among dwellings (Figure 2.4.8). These variables capture how local demand may drive or deter new technology adoption. In particular, owner-occupiers are known be more prone to renovating their dwellings than people who rent out their properties. The same goes for people living in houses, since collective living poses coordination challenges when considering home improvements. Both shares are largely above 50% on the metropolitan territory, meaning owner-occupied individual houses are the norm, but there are some disparities. They also appear quite correlated, except in city centers where there collective living is the norm, but the share of owner-occupiers remains high.



Source: Author's computations from Insee data.

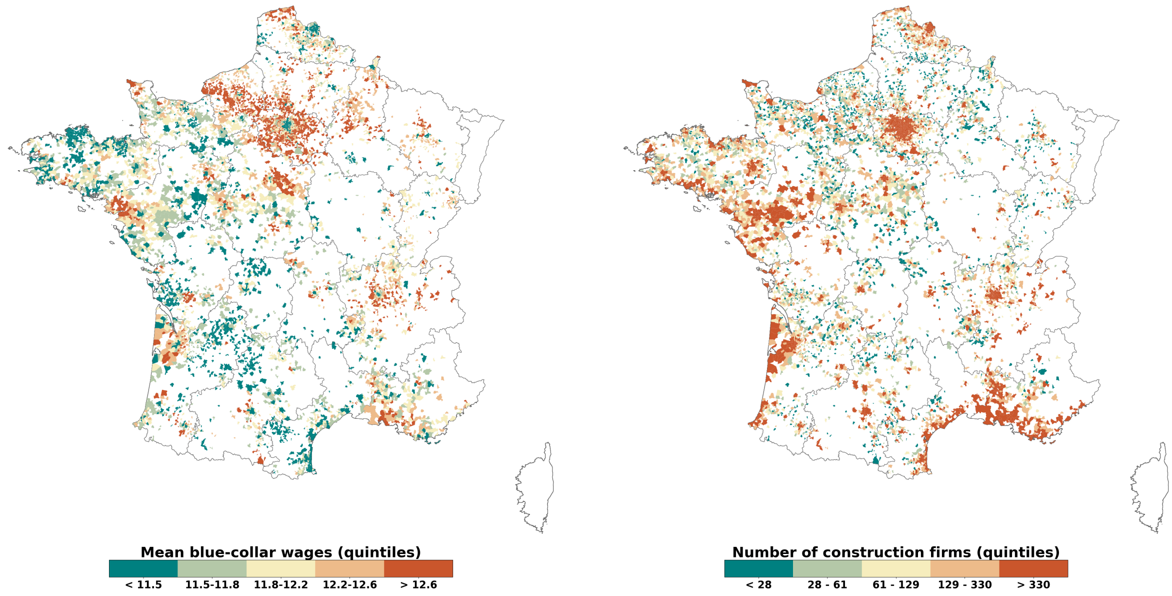
Note: The local share of homeowners is computed among all resident households in the area; the share of houses is computed among the total number of dwellings in the area.

Figure 2.4.8 – Local shares of owner-occupiers (left) and houses (right)

Information on households' incomes is not directly found in the census. The Insee releases the "Localized disposable income system" (Filosofi) database every year, which contains tax data aggregated at the city level. It contains inforamation on median standards of living, which were used as a proxy for households' purchasing power. Local characteristics also include heat sensitivity measures made available by the French electricity distributor ENEDIS, computed using the share of energy consumption due to temperature variations below or above reference temperatures for the area. The national average heat-sensitive consumption is 2400 MW (RTE 2019), but there is evidence of North-South heterogeneity due to local climate differences. Property prices per square meters were found in the "*Demandes de valeurs foncières*" (DVF)[7] database, produced yearly by the French Treasury using information on real-estate transactions. Finally, local average blue-collar wages were drawn from the Insee "*Base Tous Salariés*" (BTS)[8] dataset to account for firms' labor costs (Figure 2.4.9, left). There are some local variations in wages, but the difference between extreme values is not extremely drastic due to the inertia of the minimum wage in France. Firms' competitive environment is proxied using the number of construction firms in their

7. "*Property value requests*".
8. "*All Employees Database*".

town. (Figure 2.4.9, right). Competitive pressure appears particularly high along the West coast, as well as in the three biggest cities - Paris, Lyon and Marseille.



Source: Author's computations from Insee data.

Note: 2020 values; blue collar wages correspond to locally aggregated average net salaries, expressed in € per hour. Competition is proxied by the number of construction firms in the same city.

Figure 2.4.9 – Firms' economic environment

2.5 Empirical estimation

2.5.1 Main results

An overview of the main variables is provided in Table 2.5.1. Regression results are presented in Table 2.5.2, with specification (1) presenting a baseline regression without the adoption index. Coefficients in specification (2) were obtained by running the same model for different values of γ_2 in order to find $\gamma = (\gamma_1, \gamma_2)$ that best fits the data. This grid search process was conducted by increasing γ_2 by 0.1 from 0.1 to 10. The resulting γ_1, which measures the average impact adjacent firms have on one another, is significantly negative only in the second hurdle. It means that other firms do not impact new adoption decision, which hints at the fact that their own clients would be the ones asking for Habito drywall. It also hints at a positive word-of-mouth effect, meaning the proximity to previous adopters increases the intensity of use. The corresponding value for γ_2, that can be interpreted as the rate at which adjacent firms' impact diminishes, is however quite high. In other words, adoption by others would tend to undermine the quantity a firm may purchase, even though this influence decreases sharply as distance increases. Policy-wise, RGE contractors have a higher probability of adoption but tend to purchase less than their non-labeled counterparts. The higher first adoption probability is consistent with the restrictions on materials imposed by the label, which aim to favor new technologies, and hence boost first adoptions. This is also consistent with the idea that firms choosing the certification are more prone to innovate, and would thus be part of the early adopters. The negative effect on quantity could however hint that the Habito drywall did not meet their expectations and they went back to the baseline product after their first purchase.

Variable	Mean	Standard deviation	Max	Min
Adoption	0.08	0.27	1.00	0.00
Habito drywall (m^2)	6.15	109.24	13063.68	0.00
Standard drywall (m^2)	861.35	4675.38	256381.27	0.00
Purchase frequency (%)	7.06	14.69	210.00	0.00
Normalized Herfindahl index	0.48	0.48	1.00	0.00
Head office	0.88	0.33	1.00	0.00
Experience	10.83	11.31	120.00	0.00
RGE	0.32	0.47	1.00	0.00
Property prices	16681.80	97083.59	3904886.50	0.01
Competition	1802.59	4122.88	44614.00	1.00
Sh. heat-sensitive (%)	26.93	7.78	85.87	1.84
Dwellings	12034.52	23957.20	253061.88	15.00
Sh. owners (%)	62.31	17.63	98.16	14.96
Sh. houses (%)	66.03	29.92	100.00	0.32
Med. disp. income	21947.77	3870.85	46280.00	13025.77
$\mathbb{1}_{>30m^2}$	0.84	0.37	1.00	0.00
Blue collar wages (€)	11.53	0.77	19.04	8.44

Values are computed on the entire panel.

Table 2.5.1 – Summary statistics for non-categorical variables

Scanner data offers the possibility to control for contractors' purchasing behaviors beyond adoption. The quantity of baseline product purchased has a significantly positive effect on both adoption and quantity. Adopters seem to purchase large quantities of Placo drywall in general, meaning they are familiar with the standard BA13. An indicator equal to one if more than $30m^2$ of drywall - Habito or standard - was purchased and zero otherwise was also included in the regressors and has a significantly positive coefficient. The purpose of $\mathbb{1}_{>30m^2}$ is to indicate whether a contractor has purchased enough drywall over the year to complete at least one room. As there is no definition of a "standard" room in the industry,

	(1)		(2)	
	Adoption	Quantity	Adoption	Quantity
Standard drywall (m^2)	0.000006**	0.000001	0.000006**	0.0000001
	(0.000002)	(0.000012)	(0.000002)	(0.000000)
Purchase frequency (%)	0.047449***	0.054201***	0.047388***	0.055940***
	(0.002711)	(0.017781)	(0.002710)	(0.000393)
Normalized Herfindahl index	0.025991	0.621706**	0.026132	0.636920***
	(0.021647)	(0.313308)	(0.021720)	(0.009880)
Reference category: No employee				
1-2 workers	0.009202	-0.309367	0.007952	-0.446582***
	(0.082843)	(0.273580)	(0.082843)	(0.137640)
3-5 workers	0.039306	0.077695	0.037701	-0.060733
	(0.088898)	(0.327277)	(0.088818)	(0.149325)
6-9 workers	0.116966	0.482829	0.116025	0.293148*
	(0.093786)	(0.306610)	(0.093751)	(0.152346)
10-19 workers	-0.088349	0.370974	-0.089693	0.322290**
	(0.099724)	(0.260987)	(0.099745)	(0.156148)
20-49 workers	-0.076945	1.207289	-0.077785	1.535955***
	(0.118947)	(0.747164)	(0.118847)	(0.217272)
$>$ 50 workers	-0.035915	1.123403	-0.034692	1.617938***
	(0.176238)	(0.764231)	(0.176387)	(0.282006)
Reference category: Interior finishing				
Real estate dev.	0.388580	-0.386473	0.391152	-0.504311
	(0.239652)	(0.314850)	(0.239193)	(0.385341)
Civil engineering	-0.225610	0.844597	-0.223331	1.142316*
	(0.383055)	(0.878428)	(0.383021)	(0.587689)
Building construction	-0.114839	0.588642	-0.117193	0.554685***
	(0.077755)	(0.427084)	(0.077873)	(0.127169)
Demolition	-0.949931**	0.271231	-0.949097**	0.303376
	(0.378750)	(0.674879)	(0.378761)	(0.584897)
Elec., plumbing, etc.	-0.364626***	0.451476	-0.366216***	0.455013***
	(0.084934)	(0.307287)	(0.085004)	(0.135869)
Other specialized work	-0.254892***	0.224063	-0.255314***	0.372861***
	(0.061650)	(0.281206)	(0.061641)	(0.099415)
Head office	-0.112077	0.056594	-0.112595	0.106089
	(0.077211)	(0.206807)	(0.077204)	(0.127620)
Experience	-0.001837	-0.024566	-0.001922	-0.039643***
	(0.002413)	(0.028683)	(0.002421)	(0.002317)
RGE	0.228688***	-0.310818	0.229771***	-0.304792***
	(0.053064)	(0.279946)	(0.053076)	(0.009914)
Property prices	-0.000001	0.000001	-0.000001	0.000001***
	(0.000000)	(0.000001)	(0.000000)	(0.000000)
Competition	-0.000003	0.000321	-0.000004	0.000629***
	(0.000016)	(0.000316)	(0.000017)	(0.000019)
Sh. heat-sensitive (%)	-0.006601*	0.012346	-0.005696	0.014790***
	(0.003559)	(0.019203)	(0.003702)	(0.000627)
Dwellings	0.000001	-0.000042	0.000001	-0.000078***
	(0.000003)	(0.000038)	(0.000003)	(0.000003)
Sh. owners (%)	-0.007691**	0.085035	-0.007299*	0.087817***
	(0.003726)	(0.053613)	(0.003750)	(0.004864)
Sh. houses (%)	0.008741***	-0.044588	0.008830***	-0.042992***
	(0.002237)	(0.030377)	(0.002245)	(0.003322)
Med. disp. income	0.000016*	-0.000211	0.000015	-0.000237***
	(0.000010)	(0.000155)	(0.000010)	(0.000006)
Blue collar wages (€)	-0.069966*	-0.156580	-0.071990*	-0.149725***
	(0.039420)	(0.351155)	(0.039576)	(0.012619)
$\mathbb{1}_{>30\text{m}^2}$	2.334214***	3.340316***	2.332834***	3.346774***
	(0.100563)	(0.237066)	(0.100596)	(0.034476)
γ_1			0.038862	0.306033***
			(0.039482)	(0.008723)
Observations	80,240	3,854	80,240	3,854
Groups	21,590	1,642	21,590	1,642
γ_2			1.5	10
Robust s.e.	Yes	Yes	Yes	Yes

Robust standard errors in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.5.2 – Main results

the minimal wall surface of a livable room was derived from two norms. First, the minimum livable surface was set at 9m^2 by the 1996 Carrez law in France. Second, standard new construction usually come with 2.5 meter high ceilings. With these two constraints, the minimum amount of drywall necessary for a room, denoted $S_{\min}$, is obtained by solving the following program:

$$\begin{cases} \min_{(l,L)} \quad S = 2 \times 2.5 \times \Big(l + L\Big) \\ \text{s.t.} \quad l \times L = 9 \end{cases} \iff \min_{L} \quad 5\Big(L + \frac{9}{L}\Big) \iff \begin{cases} l_{\min} = L_{\min} = 3\text{m} \\ S_{\min} = 30\text{m}^2 \end{cases}$$

It corresponds to ten 2.5×1.2 drywall boards, which are the most commonly found. The frequency of purchase, measured in percentages of business days [9] also has a positive impact. The earliest adopters appear to be recurrent clients, who use large quantities of drywall in their day-to-day activity. Habito demand is also driven by firms with higher purchasing concentration. In other words, loyalty to a store appears to boost a firm's early demand for the new product. This is captured by a normalized Herfindahl Index (HI), which was computed for each firm i using $M_{i,t}$ the number of store they visited at time t and the share of their annual expense each store m represents, denoted $s_{i,t,m}$:

$$HI_{i,t} = \begin{cases} \frac{\sum_{m=1}^{M_{i,t}} s_{i,t,m}^2 - 1}{1 - \frac{1}{M_{i,t}}} & \text{if } M_{i,t} > 1 \\ 1 & \text{if } M_{i,t} = 1 \end{cases}$$

Specific trades were also included as a categorical control variable. The reference category in the regression is interior finishing, which includes professionals who are expected to use drywall: carpenters, drywallers, plasterers, etc. It is interesting to note that professionals in plumbing and electricity, as well as contractors specialized in new constructions, have a lower probability of adoption but tend to buy larger quantities when they do. For the former, it can be linked to the nature of their activity, as they work more often in kitchens and bathroom where heavy furniture is often suspended on the walls. It is possible that there are higher returns to adoption for these contractors. For the latter, it can be due to the scale of their projects - contrary to renovation projects, they are in charge of entire houses or apartment buildings. As both are however not specialized on plaster boards, they are not the earliest adopters. The size of the firm in terms of employees does not seem to impact adoption, but does positively affect the total quantity purchased, which can be related to the scale of the activity. It is consistent with the effect of the years of experience.

9. Business days exclude week-ends, bank holidays and confinement periods for each given year.

Overall, the nature of the activity seems to impact adoption - interior finishing specialists have a relatively higher chance to adopt -, but the scale of their business seem to drive the quantity used.

Ultimately, drywall is only an intermediate input, purchased by a contractor to meet their client's needs. It is hence important to account for local market characteristics. Property prices in the city where the firm is located have an ambiguous effect, having no effect on the probability of adoption but positively impacting the quantity. Higher prices can indicate the presence of households with a higher willingness to pay for housing, hence the positive coefficient on the quantity purchased after adoption. The share of houses also has a positive impact on the probability to adopt but not on quantity. Regarding firms' potential market, the number of dwellings has a negative impact on quantity and the share of owner-occupiers seems to deter first adoptions. Everything else equal, they are both indicators of a larger potential market available for each firm, which could lower firms' need for differentiation. These coefficients are consistent with the positive impact of competition, measured by the number of firms in the same city. In other words, firms seem to suggest more state-of-the-art materials to their customers when they are located in more competitive environments. Finally, mean blue-collar wages were included to reflect local labor costs for contractors. As expected, higher labor costs are associated with a decrease in diffusion, both inter and intra firm.

2.5.2 Extensions

Local word-of-mouth is not the only determinant behind the geographical aggregation of adopters. Local market characteristics also have a significant effect, as adoption is also driven by household demand. Further, inter-firm diffusion appears to be driven by those end-clients and not the spread of information among firms. Proximity to previous adopters does however have a positive effect on intra-firm diffusion. To further investigate the channel through which information may circulate between contractors, specification (1) in Table 2.5.3 displays results obtained with clustered standard errors at the store level. As most firms visit different stores during a given year, the "main" store was defined as the store where they spent the most. Only firms that had the same main store over the year were kept in the estimation sample. Estimation results on this sub-sample are consistent with those presented in Table 2.5.2 (2), except that γ_1 is non-significant, nor the normalized Herfindahl index. It supports the idea that contractors get information on products from their local store, either through exchanges with the staff or with other contractors.

	(1)		(2)	
	Adoption	Quantity	Adoption	Quantity
Standard drywall (m^2)	0.000005	0.000005	0.000029***	0.000002
	(0.000004)	(0.000037)	(0.000006)	(0.000011)
Purchase frequency (%)	0.056447***	0.105551	0.042705***	0.059695***
	(0.005881)	(0.465064)	(0.002910)	(0.016344)
Normalized Herfindahl index	0.493849	0.380810	0.053295***	0.726059**
	(0.479148)	(1.523897)	(0.013772)	(0.305728)
Reference category: No employee				
1-2 workers	-0.037771	-0.157528	-0.000764	0.265791
	(0.098966)	(151.089223)	(0.097471)	(0.639725)
3-5 workers	0.013735	0.430212	0.064496	0.780108
	(0.101405)	(163.122395)	(0.104708)	(0.737823)
6-9 workers	0.011836	0.245311	0.092778	0.778786
	(0.122015)	(231.910637)	(0.111748)	(0.518880)
10-19 workers	-0.043138	0.646870	-0.027117	0.728883
	(0.134542)	(196.055039)	(0.115481)	(0.446421)
20-49 workers	-0.125543	2.530119	-0.019092	0.899149
	(0.174497)	(762.749853)	(0.135608)	(0.561291)
> 50 workers	-0.115002	1.478826	0.008052	1.018751
	(0.317179)	(1,026.611020)	(0.198886)	(0.662949)
Reference category: Interior finishing				
Real estate dev.	0.262044	-0.753077	0.295850	-0.527640
	(0.296578)	(154.217226)	(0.289388)	(0.412805)
Civil engineering	-0.016366	2.122693	-0.371106	1.241395
	(0.461526)	(363.892346)	(0.457120)	(0.977483)
Building construction	-0.020609	0.840401	-0.101529	0.654522*
	(0.111451)	(172.750115)	(0.090069)	(0.337827)
Demolition	-0.986077**	1.193233	-1.091584**	0.922918
	(0.448965)	(347.500805)	(0.452459)	(0.688000)
Elec., Plumbing, etc.	-0.341561***	1.048588	-0.379426***	0.654745
	(0.110958)	(256.698684)	(0.097851)	(0.528507)
Other specialized work	-0.265781***	0.732240	-0.221998***	0.186080
	(0.091580)	(101.170995)	(0.070027)	(0.269189)
Head office	-0.114028	-0.019871	-0.114950	-0.149365
	(0.089509)	(248.556976)	(0.089567)	(0.242698)
Experience	-0.002992	-0.027240	-0.002156	0.046896
	(0.003322)	(4.274294)	(0.002937)	(0.096005)
RGE	0.188472***	-0.297392	0.231110***	-0.215371
	(0.071502)	(2.186814)	(0.061253)	(0.338389)
Property prices	-0.000001**	0.000003	-0.000000	0.000001
	(0.000001)	(0.000061)	(0.000000)	(0.000001)
Competition	-0.000000	0.000608	-0.000008	0.001082**
	(0.000019)	(0.203373)	(0.000021)	(0.000545)
Sh. heat-sensitive (%)	-0.005562	0.022898	-0.002157	0.012474
	(0.005045)	(0.301820)	(0.004009)	(0.020321)
Dwellings	0.000002	-0.000073	0.000001	-0.000122**
	(0.000003)	(0.024331)	(0.000004)	(0.000050)
Sh. owners (%)	-0.007080	0.116116	-0.007002	0.082181
	(0.005646)	(6.081543)	(0.004310)	(0.058495)
Sh. houses (%)	0.009300***	-0.057067	0.008242***	-0.033394
	(0.003540)	(4.213211)	(0.002586)	(0.028714)
Med. disp. income	0.000017	-0.000292	0.000018	-0.000253
	(0.000015)	(0.006653)	(0.000011)	(0.000174)
Blue collar wages (€)	-0.112195*	-0.357388	-0.127457***	0.031679
	(0.057828)	(11.881018)	(0.046347)	(0.481141)

$\mathbb{1}_{>30m^2}$	1.980879***	3.426789	2.289837***	3.497761***
	(0.383200)	(4.771981)	(0.109988)	(0.237078)
γ_1	0.039153	0.354638	0.180704	0.390103*
	(0.051091)	(35.501012)	(0.450840)	(0.223201)
Standard drywall t-1			-0.000026***	-0.000008
			(0.000007)	(0.000009)
Habito t-1				-0.000232**
				(0.000104)
Observations	61,862	2,333	58,227	3,506
Groups	16,839	993	20,619	1,614
γ_2	1.7	1.1	0.1	1.3
Standard error	Main store cluster	Main store cluster	Robust	Robust

Robust standard errors in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.5.3 – Extensions

The adoption index also becomes non-significant when introducing consumption lags in the regressors (Table 2.5.3, (2)). It is most probably due to the *de facto* exclusion of 2017 observations, which act as a baseline to estimate the effect of the adoption index. The coefficients associated with standard drywall purchase however remain consistent with previous results. The quantity of BA-13 drywall purchased in $t - 1$ interestingly has a significantly negative effect on the probability of first adoption, while the quantity of Habito purchased in $t - 1$ has a negative impact on the quantity of Habito purchased in t. It is consistent with the fact that a large share of first-adopters did not repeat their purchase. Building construction professionals are still more likely to buy larger quantities of Habito drywall, which can be linked to the scale of their activity and the fact that new buildings are much more strictly regulated than retrofits in France in terms of materials. It should also be noted that the impact of RGE on adoption is still significantly positive across all specifications, but it is non-significant on the quantity purchased.

2.6 Conclusion

This paper contributes to the literature on new technology diffusion by firms in several ways. There are very few papers exploiting trackable firm-level panel data, and none of them investigates the diffusion of an intermediate input. The econometric specification also allows for both spatial and time effects, which are usually studied separately. Estimation results show that (1) the characteristics of both the local market and the individual firm drive adoption, (2) only intra-firm diffusion is impacted by proximity to previous adopters, with information seemingly circulating through the stores visited and (3) store-level loyalty appears to be key determinant of the adoption process. These results also highlight the importance of accounting for intra-firm diffusion, as an increasing number of first adopters does imply that more households are getting the new drywall over time. The spatial clusterization of new adoptions appears to be due to local demand specificities as well as information circulating between firms through the stores they visit. It hints at the fact that end-client demand contributes to the inter-firm diffusion locally.

As in all empirical applications, there are some limitations to this work. The dataset used is restricted to metropolitan France, which may be problematic in border areas. As France is part of the European market, firms are free to operate on both sides of the borders with neighboring countries. It means that that can not only interact with foreign firms that are not referenced in the SIRENE dataset, but they can also buy materials in other countries. It is mainly an issue regarding Southern borders, as prices are usually lower in Italy and Spain. More generally, the sales data does cover a wide range of firms, but it does not provide a complete picture of the French market. It is a common issue with scanner data, which is simultaneously very broad but still incomplete. Whether their clients are a representative subset of all French firms cannot be assessed, and there could be a selection bias. Finally, two issues are linked to the diffusion process more specifically. The data only covers the four years after the launch of the board, which is not a long period of time. Firms that chose to try it out are hence very early adopters, which may have unobservable hidden characteristics. The results may also be specific to the Habito board and not to the construction sector, and it would be interesting to see how the diffusion processes of other innovations compare.

However limited, these results shine an interesting light on public policy issues. The French residential sector accounts for roughly 28% of final energy consumption (SDES 2020), making it a major environmental policy target. Facilitating the diffusion of green building materials among construction firms could be a way to achieve this goal, and it has not yet been directly addressed. The RGE label is the only energy-efficiency policy currently implemented that targets firms directly. It does favor new adoptions, but not the intensification of usage over time. As hiring a RGE contractor is a necessary requirement for households to access the national financial aid for energy retrofits in France, the positive impact of the label could solely indicate that reducing their financial burden allows them to ask for better products than the baseline. Its impact on intra-firm diffusion being zero or negative however indicates that this new technology was used for one-off projects, rather than a part of long-term strategies. Estimations results further suggest that material stores act as information hubs for contractors. In practice, they visit them several times a week, and it is a place to meet both other contractors and specialized vendors. A diffusion policy could thus rely on these local information hubs to spread knowledge about high-performance products. Finally, identifying which firms are more likely to offer state-of-the-art products to their clients and supporting their efforts could be effective, but not sufficient if end-consumers are left out of the equation. Household policies are currently limited to financial help for retrofits, and more focus could be put into providing them with information. Local policies could also be established to target areas where innovation uptake would be slow otherwise. It would be interesting to see if these results is specific to the Habito board, or if it holds up for other innovative products.

* * *

«Eh bien! en revenant au roman, nous voyons également que le romancier est fait d'un observateur et d'un expérimentateur. L'observateur chez lui donne les faits tels qu'il les a observés, pose le point de départ, établit le terrain solide sur lequel vont marcher les personnages et se développer les phénomènes. Puis, l'expérimentateur paraît et institue l'expérience, je veux dire fait mouvoir les personnages dans une histoire particulière, pour y montrer que la succession des faits y sera telle que l'exige de déterminisme des phénomènes mis à l'étude.»

Emile Zola – *Le Roman expérimental.*

* * *

Chapter 3

Building Castles in the Sky? A Discrete Choice Experiment Approach to Barriers to Innovation Adoption in the Construction Sector

* * *

The European construction sector accounts for a significant share of the EU's waste production and carbon emissions. Regulations and policies have thus been implemented to set quality standards on materials while promoting new technologies. Innovation uptake has yet remained low, which could be attributed to construction professionals' preferences towards materials, and how much they are willing to pay for innovative characteristics. This paper presents a Discrete Choice Experiment (DCE) to examine their choices when presented with hypothetical materials characterized with respect to their tried-and-true baseline. Estimations run on a sample of French construction professionals suggest that innovations on technical and environmental aspects of materials are valued, but also show that uncertainty with respect to the actual product performance comes with a high cost. Willingness to pay, preference clusters and policy scenarios were further investigated to provide insights on how innovations could diffuse faster on the market. These results provide interesting insights on the current challenges faced by policymakers.

* * *

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3.1 Introduction

The construction sector accounts for 38% of waste production in the European Union, and the building stock represents roughly and 36% of CO_2 emissions (ECSO 2018a). Consequently, policymakers have established regulations to improve the energy efficiency of buildings, with an emphasis on setting standards regarding the quality of the material used. Taking the example of France, "Thermal Regulations", first implemented in 1974 and revised throughout the years to become more constraining (1982, 1988, 2000, 2005, 2012, 2020) aim to improve the quality of materials with a focus on insulation performance. In parallel, innovation policies have been implemented to support industrial firms' R&D efforts, making France one of the leading construction patent issuer within the European Union (ECSO 2022). Innovation uptake appears however hindered by structural barriers, in particular the competitive pressure put on construction firms. As firms usually obtain contracts in a bid-like manner, they tend to keep cost as low as possible, which makes more expensive innovative technologies less attractive. Insurance-wise, contractors are also responsible for the long-term functioning of the appliances and materials they install, and tend to favor materials with a proven track record. Further, new technologies sometimes require skills from different traditional trades, hence the need for updated professional training to boost their diffusion. Tackling these structural barriers to innovation diffusion was thus an explicit goal in the 2018 French *Plan de Rénovation Energétique des Bâtiments*[1] (PREB), with an estimated budget of 40 billion euros to boost innovation development and uptake.

As construction firms are intermediaries from a material being manufactured to its installation in a dwelling, it is important to better understand how they perceive innovative products, and how much they would be willing to pay to improve materials' performance. The fact that new product adoption can take time to be widespread is a well documented issue in economics since Mansfield (1963) and Bass (1969), mainly because they come with a certain level of uncertainty regarding their actual performance. As more and more people adopt the product, information becomes more readily available for the more risk-averse customers, who may ultimately become adopters. The impact of the source of information on agents' probability to adopt has been less extensively studied. In the case of construction professionals, information on product performance can be provided by other contractors, in-store staff, the manufacturer or even their own clients, which may not all be seen as equally reliable. The innovativeness of a product can also affect different dimensions of its performance. For simplicity, improvement made to an existing product were grouped into

1. It can be translated to "Plan for the Energy Retrofit of Buildings".

two categories. "*Technical*" improvements aim to facilitate a product' installation, making it faster or more comfortable. "*Green*" improvements aim to improve a product's sustainability, by decarbonizing its production process or reducing the waste it generates. Two recent examples are the Isover-Placo Optimax mounting system, marketed as an improvement on the technical aspects of fiberglass installation (Figure 3.1.1, left), and Lafarge's Planet cement, advertised as a more sustainable version of their previous products without hindering their performance (Figure 3.1.1, right). These aspects are not necessarily valued equally, and individual preferences may vary depending on education, experience, etc.

Figure 3.1.1 – Adverts for two recent material innovations

This paper aims to better understand barriers to innovation uptake in the construction sector, focusing on the central role of information and looking into which kind of technological improvement is more likely to trigger adoption. A Discrete Choice Experiment (DCE) was designed and administered to French construction professionals. The DCE methodology assumes that individuals make choices between alternatives based on the attributes of these alternatives, which may yield different utility or profit levels. It is a quantitative technique used to derive individual preferences with respect to the choices' attributes, which in turn are used to compute their willingness to pay for each attribute. Contrary to a scaled preference approach, DCEs are not subject to traditional self-reporting biases - for instance, respondents may feel socially pressured to state a high interest for the environment. In practice, survey respondents were presented with hypothetical innovative products varying in attributes and levels. They were asked to rank two innovations and whether they would choose to use thir preferred theoretical alternative instead of their baseline product in a real-world scenario. DCEs rely on hypothetical choices, which is particularly interesting for the construction market, as professionals of different trades do not use the same baseline products - it would be difficult to find a material used by both a plumber and a mason. The experimental design accounted for differences in respondents' day-to-day jobs, and the questionnaire gathered additional individual characteristics to allow for inter-individual comparisons. This paper differs from previous contributions by focusing on innovation uptake by professionals rather than households, and by looking into preferences for intermediate goods - while the few DCEs carried out on innnovation uptake have explored durable goods.

Estimation results suggest that (1) green characteristics are less valued than technical characteristics and (2) the reliability of information on a new product depends on its source. The Technology Readiness Index (TRI) developed by Parasuraman (2000), which is a self-reported scaled preference approach to measure individuals' attitude towards new technologies, was used to further assess the strength and cross-validity of the estimation results. Information on respondents' characteristics was used to explore different diffusion policies: policymakers can either create incentives to boost adoption, targeting groups with a lower appetence for innovation, or force adoption by setting higher standards through regulation. Additional estimations run on specific sub-samples hint at heterogeneity in individual preferences, depending on education and firms' certifications or labels. Voluntary-based labels are often used in France to guarantee a firms' technical skills or indicate the sustainability of its activity, hence it is interesting to see if professionals working in firms that hold green or technical certifications value product attributes differently. Education requirements could alternatively be used to further boost innovation adoption.

Section 3.2 presents a selective literature reviews on barriers to innovation adoption, with a focus on DCE papers and emprical work on firm behaviors. The experimental design is detailed in section 3.3 and the estimation sample is presented in section 3.4. Estimation results and policy implications are discussed in section 3.5, and section 3.6 concludes.

3.2 Literature review

The diffusion of new technologies has been a long standing topic in economics since Griliches (1957) first established the now well documented S-shaped path of diffusion over time, which was then refined by Bass (1969). These models laid the groundwork to study the mechanisms behind individuals' choice to adopt new products or not. They both used a holistic approach, based on contagion models: each individual was assigned a certain probability of adoption, which increases as the number of adopters grew and more information became available to non-adopters. In other words, their motives did not endogenously impact the model, nor could they change over time. Jensen (1982) made an important contribution to establish the microeconomics foundations of the diffusion curve. His model relied on the role of information and uncertainty, formalizing the trade-off between adopting now or waiting for more information on a new technology. The diffusion of information was however formalized as an exogenous process, meaning agents' strategic interactions were not taken into account. Ten years later, separate contributions by Banerjee (1992) and Bikhchandani, Hirshleifer, and Welch (1992) both included information cascades in the diffusion process. Decision makers were assumed to observe outcomes from previous adoptions before making a choice in each period. These theoretical insights on the key role played by information in the diffusion process have led to a growing body of empirical work on the topic.

In practice, firms and consumers do not jump on the opportunity to try out new services or technologies for a variety of reasons. Erdem and Keane (1996) used data on detergent sales in the United States to explain consumer loyalty to a brand, with the idea that it reduced the risk associated with purchasing a new product. They found that consumers supported their decisions with positive past experiences of product performance, instead of trying new brands. Similar work by Erdem, Keane, et al. (2005) showed that past experience with a product and the observation of its price variation acted as indicators of quality, and were therefore vectors of diffusion. Using Italian panel data on prescriptions for anti-ulcer drugs, Coscelli and Shum (2004) also found that the increase in market share of a new drug was mainly explained by the accumulation of direct experiences of doctors with their patients. Their results suggested that the provision of free samples would boost the early accumulation of information and therefore speed up the diffusion of the product. Using the same dataset, Crawford and Shum (2005) further strengthened these results, showing that the equilibrium was close to a scenario with perfect information. Exploiting incremental innovations on the same product over time, Van Rijnsoever and Oppewal (2012) also found that early adoption of augmented products was mainly triggered by experience with its previous generations. Further, when a new generation was introduced on the market, the earliest consumers were those who purchased past versions. In all cases, consumers seem to seek reliable information before trying a new technology. Positive experiences with a brand, a previous generation product or the product itself can thus provide information and increase early diffusion. Focusing on green technologies more specifically, Arvanitis and Ley (2013) found that firms' main barrier to adoption was the risk of non-compatibility with their existing means of production. The lack of information was particularly cited as an issue by adopting firms, which accounted for 53.5% of the sample. Few papers have focused on the construction sector in particular. Du et al. (2014) carried out an in-depth analysis on a small sample of Chinese construction firms, focusing on 15 potential barriers to adoption grouped *ex post* by factor analysis. Small firms appeared especially constrained by regulations, hence having a relatively lower probability of adoption. Looking into new sustainable practices in the construction sector, Akadiri and Fadiya (2013) exploited a medium-sized sample of UK firms and found similar results. In particular, new regulations came out as the main driver of adoption. In all cases, the diffusion of new technologies among firms was found to be rather slow, even when private gains were superior to costs.

These papers provided evidence-based insights into the role played by information in the diffusion process, but could not evaluate agents' actual biases and preferences. A more recent strand of literature in experimental economics looked into subjective barriers to new technology adoption and diffusion. Discrete choice experiments have not yet been widely used to explore innovation uptake. In the existing literature, respondents were given choice tests and asked to choose between two or more alternatives, characterized by specific attribute levels. They were tasked with random and repeated tests in which attributes vary, allowing the estimation of their preferred level. The idea is to have enough attributes to estimate realistic preferences without causing fatigue for respondents, who might have inconsistent answers out of "laziness". DCEs have proven to be a robust technique to derive agents' preferences with regards to various situations. Previous DCEs on preferences towards innovative products showed that providing customers with relevant information on a new product is essential to trigger adoption. Using a non-hypothetical choice experiment, Q. Chen, Anders, and An (2013) for instance found that when a food product was manufactured using a new technology, early adopters needed information on this new technique and were very sensitive to price increases. Focusing on customer's choice of energy source, Van Rijnsoever, Van Mossel, and Broecks (2015) tested participants with different levels of information on eco-labels. They found that nuclear and biomass were more likely to be chosen when no label was presented, while renewable energies and natural gas were favored when participants were presented with additional information. In the case of green innovations, it has been shown that improved environmental performances should not compromise the pre-existing product's essential characteristics as perceived by customers. For instance, Ewing and Sarigöllü (2000), found that consumers only valued their cars' environmental impact if it did not compromised their acceleration capacity or increased their charging or refueling time. Using data on the adoption of electric vehicles, Jones et al. (2013) also concluded that technical improvements were necessary from the customer's point of view, in order to maintain a level of performance equivalent to that of a similarly priced gas-powered vehicle. Both papers looked into the potential impact of environmental regulations, with Ewing and Sarigöllü (2000) finding no effect of fuel taxes or changes in norms on people's preferences while Jones et al. (2013) found that a change in the vehicle tax had a greater effect than a change in price of the same amount. These DCEs all explored consumers' behaviors and to our knowledge, there is no paper that have studied firm's choices except Jourdain et al.(2020). They conducted an experiment with Laotian farmers on their choice of production mode and found signs of heterogeneity in their preferences towards the transition to a more sustainable farming system, meaning they did not all make the same investment choices when given the same information. The DCE conducted for this paper differs from their contribution by focusing on intermediate goods, and focusing more extensively on product attributes where they put more emphasis on the impact of farmers' economic context.

The DCE method has proven to be an effective tool to derive agents' preferences, but it has been criticized for being too dependent on context. An alternative way to derive preferences is to rely on people's self-scaling of their own beliefs, which can be affected by reporting bias but has the advantage of producing comparable estimators. Among these tools, the Technological Readiness Index (TRI) is a multiple-item scale developed by Parasuraman (2000) to assess "*people's propensity to embrace and use new technologies for accomplishing goals in home life and at work*" [2]. Technology readiness is assumed to be driven by a combination of positive feelings ("*drivers*") and negative feelings ("*inhibitors*") towards new technologies. He initially identified 36 items through surveys on US customers. Each item is a statement, to which the respondent had to assign a level of agreement from zero to five. These items were then assigned to four scales categories, composed of two drivers (optimism and innovativeness) and two inhibitors (discomfort and insecurity). The TRI scale has since been used in various contexts such as healthcare (Caison et al. 2008), hotels (Victorino, Karniouchina, and Verma 2009), or e-services (C.-H. Lin, Shih, and Sher 2007). Most papers focusing on the construction sector relied on Malaysian data - the Malaysian government mandated surveys in 2006 as part of their global development

2. Parasuraman (2000), p308.

plan and their effort to promote ICT in the contruction sector. In particular, Jaafar et al. (2007) found that contractors' TRI was rather high, advising the national construction industry development board to provide further ICT training to managers. The survey conducted for this paper included the "TRI 2.0" (Parasuraman and Colby 2015), which is an updated version reduced to 16 items and proven to be as valid and reliable as the initial 36-item TRI. Meng, Elliott, and Hall (2009) and Rojas-Mendez, Parasuraman, and Papadopoulos (2017) have further shown the TRI's applicability in other countries, finding that education was the most consistent predictor among demographic variable to explain people's willingness to adopt new technologies. To our knowledge, our paper is the first to focus on France specifically. Previous cross countries studies have included France to draw out global patterns. For instance, C. G. García, C. B. García, and R. S. Gómez (2019) found that among EU member states, higher TRI levels implied a better environmental efficiency, but not the other way around.

The experimental design for this paper aims to assess construction professionals' preferences towards material attributes. Contrary to previous papers on innovation diffusion, it focuses on intermediate inputs rather than investments in durable goods. It also focuses on strict improvements to existing products, meaning that respondents were never put in a situation were they would have to sacrifice performance on an attribute in order to increase another. The TRI scale is used to control the estimated preferences by checking their consistency with respondent's stated preferences. Further, the survey data is used to provide insight on several diffusion policy scenarios, namely professional training and quality labels.

3.3 Experimental framework

3.3.1 Identification of attributes and level

Following D. McFadden (1973), individual preferences are modeled within the random-utility framework, meaning the expected utility of each choice depends on the setting: what is the other choice and who is the respondent? Formally, the utility an individual i derives from choosing alternative j takes the following form: $U_{i,j} = \beta_i X_{i,j} + \epsilon_i$. Coefficients were estimated using a mixed logit model, also known as a random parameters logit model. Its main interest is to allow for some parameters to vary between individuals, reflecting preference heterogeneity. Contrary to the standard logit model, the individual subsctript i on the coefficients β_i reflects the variability among individuals. As individual i knows their own preference, they choose alternative j if and only if $U_{i,j} > U_{i,k} \quad \forall k \neq j$. As preferences are by definition not observed, the probability that individual i chooses the alternative j is expressed conditionally on the value of β_i:

$$\mathbb{P}_{i,j}|\beta_i = \frac{\exp\left(X_{i,j}\beta_i\right)}{\sum_{k=1}^{J}\exp\left(X_{i,k}\beta_i\right)}$$

The full model was derived by D. McFadden and K. Train (2000), who expressed the mixed logit probability as the integral of $\mathbb{P}_{i,j}|\beta_i$ over all β_i:

$$\mathbb{P}_{i,j} = \int \frac{\exp\left(X_{i,j}\beta\right)}{\sum_{k=1}^{J}\exp\left(X_{i,k}\beta\right)} f(\beta)\partial\beta$$

Where f is the density function of the coefficient distribution in the population.

The integral does not have a closed-form solution and is estimated using maximum simulated likelihood, following K. E. Train (2009). In practice, respondents were presented with hypothetical materials, varying in attributes and levels: green characteristics, technical characteristics, source of information and price. Their responses were then used to assess which type of innovation is relatively more important from their perspective, how much they would be willing to pay for such an improvement, and how costly it is for them to rely on information that is not their own experience. The attributes and their level were defined using prior in-depth semi-structured interviews and field work with contractors in France. They were asked broad questions on their day-to-day jobs, the materials they used and their clients, which led them to detail what constitutes a good material, what constitutes an innovation, and who they would trust when looking for information on a product they had never used. As a results, these three attributes were identified as potentially impacting adoption beyond the price increase. Hypothetical products were thus defined from three attributes with three levels (green characteristics, technical characteristics and information source) and the price increase, which has five levels (Table 3.3.1). Price increase was included in the questionnaire rather than an actual price in euros since respondents can work in different professional trades, hence the price of their baseline reference material can vary. Respondents were also asked the average price they paid for their reference product, in order to compute imputed prices and use them in the estimations to derive their willingness to pay.

GREEN CHARACTERISTICS	TECHNICAL CHARACTERISTICS
1. Same as reference product. 2. Lower carbon footprint. 3. Less on-site waste.	1. Same as reference product. 2. Faster installation. 3. More comfortable installation.
INFORMATION SOURCE	PRICE INCREASE
1. Your client. 2. Another contractor. 3. Staff at your usual building-supply store.	5, 10, 20, 30 or 40% more expensive than your reference material.

Table 3.3.1 – List of attributes and levels

You are putting together a quote for a client. The "reference material" refers to your answer to question 5: [**REFERENCE**]. Keeping this material in mind, you will be presented with other alternatives in the same product category. You will be presented each time with two product sheets describing a new product you have never used before, and which may replace your reference product. After reading both product sheets, you will be asked two questions:

1. If you had to choose between product A and B, which one would be your favorite?
2. Between your favorite alternative and your reference material, which one would you choose?

	Product A	Product B
Environmental characteristics	Lower carbon footprint.	Same as reference product.
Technical characteristics	Same as reference product.	More comfortable installation.
Price increase with respect to the reference product	20% more expensive than your reference product.	20% more expensive than your reference product.
Person who recommended the product	Your client.	Staff at your usual building-supply store.
Favorite alternative:	☐ A	☐ B
With respect to your reference material:	☐ Reference material	☐ Try out the new product

Note: The questionnaire was administered in French and translated here for clarity.

Figure 3.3.1 – Example of a choice

Table 3.3.1 provides an example of a choice respondents had to make. Respondents were both asked about their preference between two hypothetical products and given an opt-out option in order to reduce bias in the final parameter estimates. In the absence of the opt-out option, adoption would be forced onto respondents, which could result in an overestimation of their willingness to pay.

3.3.2 Empirical design

Overall, there are $5 \times 3^3 = 135$ possible hypothetical products, resulting in $135 \times \frac{134}{2} = 9\,045$ unique choice sets characterizing the full factorial design. The DCE was reduced to an empirical design of 15 iterations using orthogonal design methods without interaction terms. Denoting Ω the variance-covariance matrix of the conditional logit model, the D-efficient design produces the set of choice sets minimizing the determinant of Ω given a prior for β. In other words, a D-efficient design is meant to minimize the variation of estimated parameters. It is found by minimizing the The D-error, which is given by $|\Omega|^{\frac{1}{K}}$, where K is the number of estimated parameters. It was assumed that green and technical characteristics 1 and 2 would have a positive effect on adoption, everything else equal, while the price would have a negative effect. No assumptions were made regarding the prior distribution of the coefficient attached to the information level. The D-efficiency of the design was ultimately 1.41. It was generated using Stata's *dcreate* command, which relies on a modified Fedorov algorithm (Hole 2015). The final choice sets have relatively good level balance, with the 5% price increase being slightly over-represented. It is probably due to the negative assumption made on the prior distribution of the price coefficient. Table 3.3.3 displays the correlations between attributes for the end design. There are only a few non-zero coefficients and their levels are low enough avoid being be problematic with respect to the orthogonality condition (WHO 2012).

The survey was administered to construction professionals who are used to either working with materials or choosing them for projects, with no discrimination *vis-à-vis* their professional trades. A pilot questionnaire was conducted on 42 respondents and minor changes were made. Respondents who chose only alternative A or only alternative B were systematically excluded from the survey. Additional questions were asked to characterize the estimation sample with respect to heir education, income, gender, etc., which will be further detailed in the next section. These variables were used to conduct policy analysis. In particular, the TRI scale will be used to assess the internal validity of the estimation results.

	Number of appearances	Share (%)
Technical: Same as reference product	7	23.3
Technical: Faster installation	12	40
Technical: More comfortable installation	11	36.7
Green: Same as reference product	8	26.7
Green: Lower carbon footprint	11	36.7
Green: Less on-site waste	11	36.7
Information: Own client	9	30
Information: Another contractor	11	36.7
Information: In-store staff	10	33.3
Price: + 5%	12	40
Price: + 10%	4	13.33
Price: + 20%	6	20
Price: + 30%	4	13.33
Price: + 40%	4	13.33

Table 3.3.2 – Level balance

	Price	Green1	Green2	Green3	Tech.1	Tech.2	Tech.3	Info.1	Info.2
Price	1								
Green1	0.0834	1							
Green2	-0.1619	-0.4504**	1						
Green3	0.0915	-0.4198**	-0.6213***	1					
Tech.1	-0.0797	-0.3327*	0.2770	0.0104	1				
Tech.2	0.0366	0.2344	-0.1977	-0.0048	-0.4588**	1			
Tech.3	0.0366	0.0709	-0.0565	-0.0048	-0.4588**	-0.5789***	1		
Info.1	0.0577	-0.0172	-0.0891	0.1057	0.0987	-0.0453	-0.0453	1	
Info.2	-0.0183	-0.0927	0.2259	-0.1483	0.0104	-0.1483	0.1388	-0.4981***	1
Info.3	-0.0374	0.1115	-0.1443	0.0489	- 0.1066	0.1956	-0.0978	-0.4629***	-0.5380***

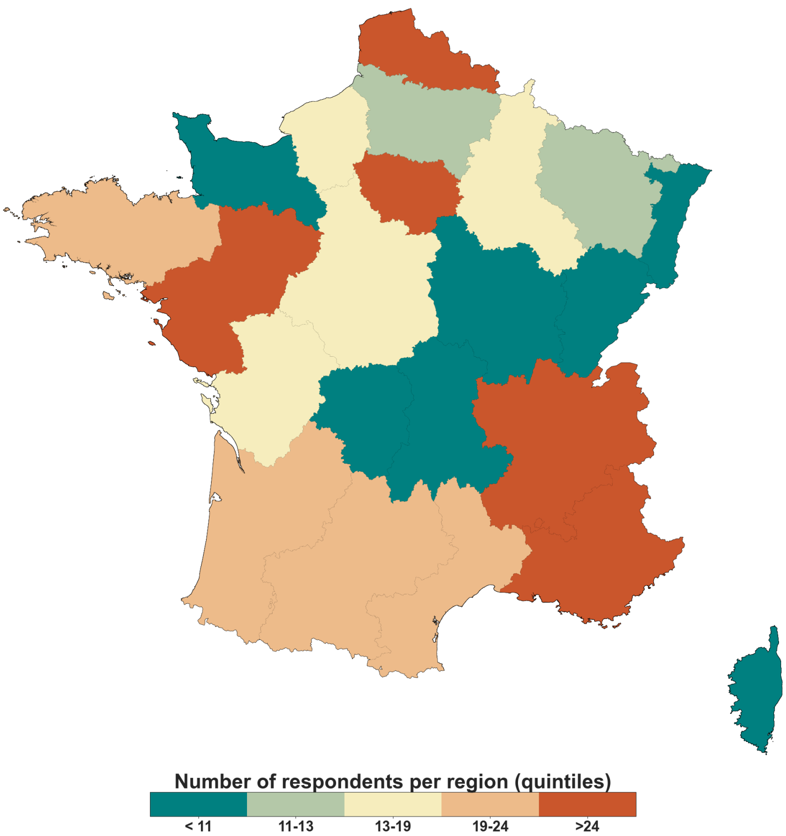
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3.3.3 – Correlation matrix

3.4 Data

3.4.1 Sample characteristics

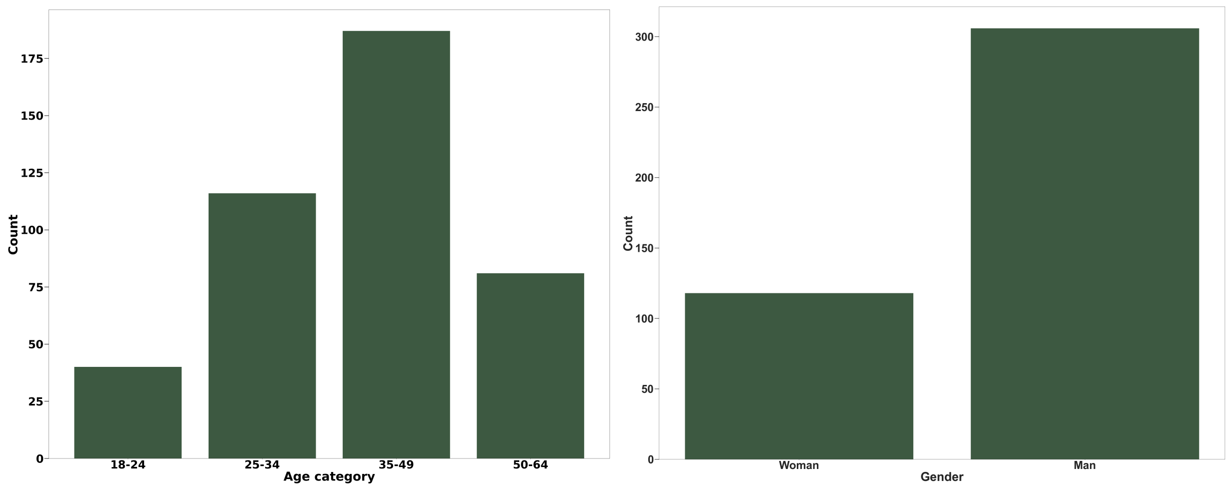
The survey was administered in March 2023. Respondents were presented with the questionnaire in French and used a computer to complete it in their own time. The final dataset contains 424 individuals currently working in construction, who faced a total of 15 choices and responded to the two questions for each choice. There is a good geographical coverage of the metropolitan territory (Figure 3.4.1), with some heterogeneity reflecting the population differences between French regions. There is a prevalence of male respondents and the 25-49 age group (Figure 3.4.2). Most of the respondents hold at least one degree, and 55% of them have some vocational training - BEP, CAP or Vocational Baccalaureate (Figure 3.4.3, left). The reported net monthly income was in most cases comprised between 1 000 and 3 000 € (Figure 3.4.3, bottom), which is in line with the sector. On average, monthly income is around 1 950 € for independent contractors (Insee 2020a) and 2 275 € for salaried employees (Insee 2020b). Full time employees compose the majority of the sample, working in all the main professional trades (Figure 3.4.4).



Source: Authors' computations.

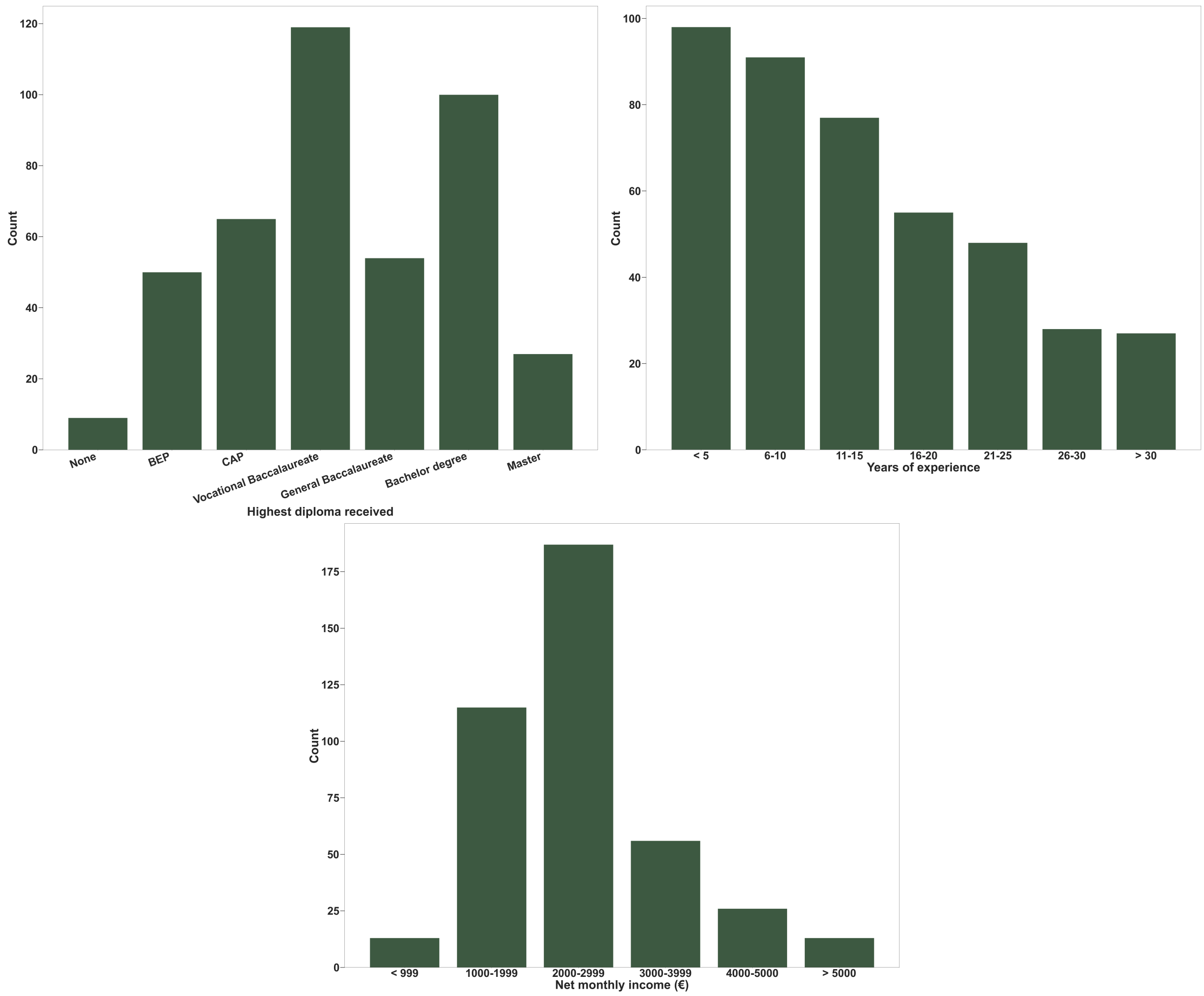
Note: Data is presented by quintiles.

Figure 3.4.1 – Respondents' localization



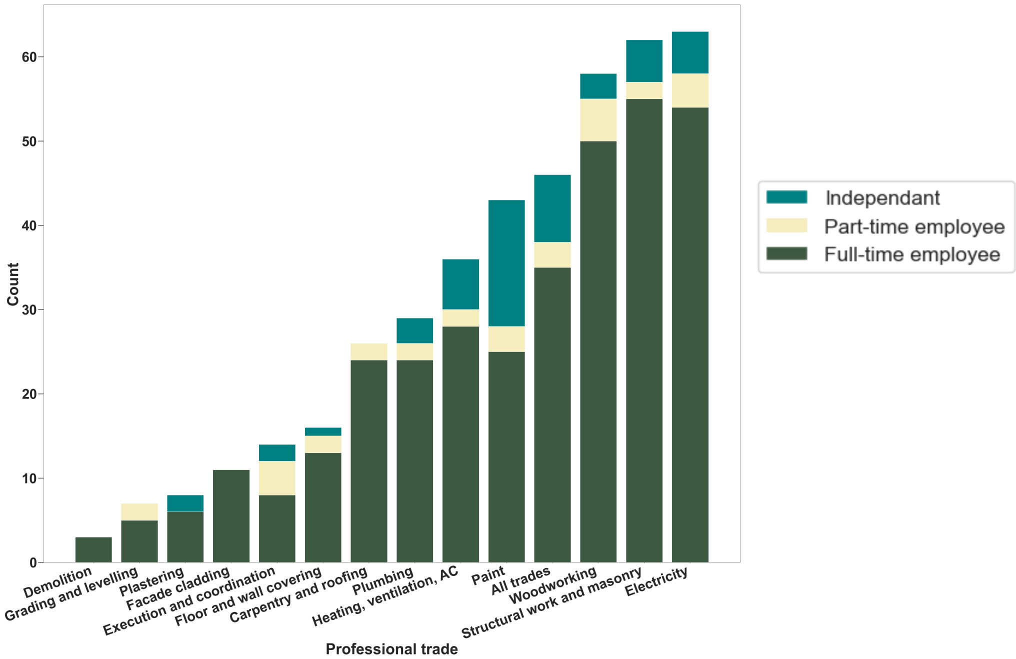
Source: Authors' computations.

Figure 3.4.2 – Individual characteristics



Source: Authors' computations.

Figure 3.4.3 – Individual skills



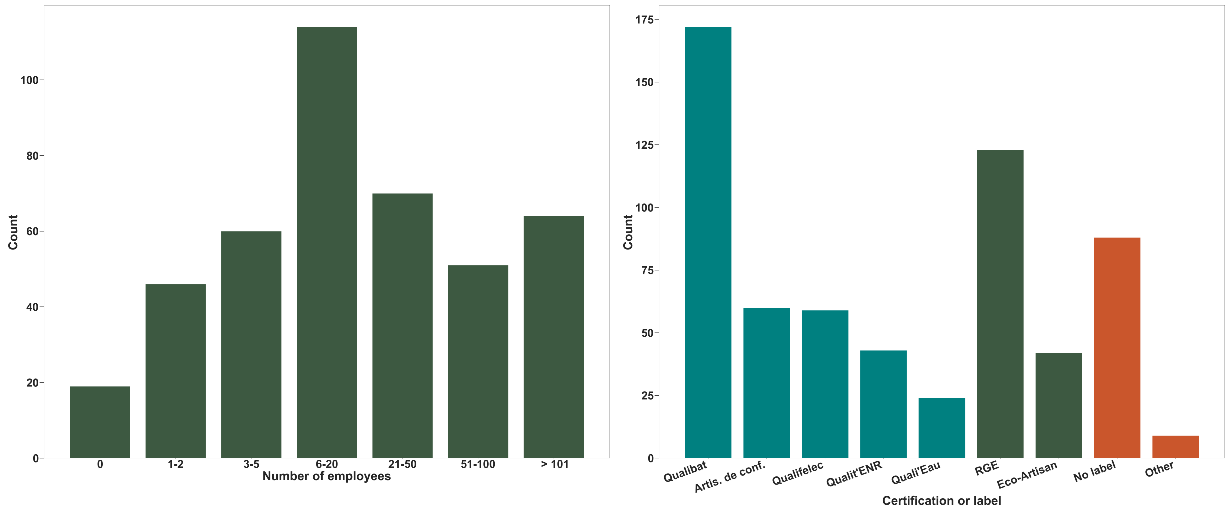
Source: Authors' computations.

Figure 3.4.4 – Occupation

Small firms, meaning firms with less than 20 employees, represent 56% of the sample (Figure 3.4.5, left). Larger firms are more represented than in the restricted construction sector due to the inclusion of "*maîtres d'oeuvre*", who are typically involved with the deisgn but not the execution (eg. architects). This is also reflected in the relatively high share of university graduates. There are various certifications and labels available for construction firms, which were self reported in the questionnaire (Figure 3.4.5, right). The *Qualibat* and *Artisan de confiance*[3] certifications are meant to guarantee a contractor's technical skills in their trade. Contractors have to file an application and go through a selection process, and certified firms may have their worksites audited once a year. The *Qualifelec*, *Quali'Eau* and *Quali'ENR* labels are also meant to guarantee technical skills, in electricity, plumbing and the installation of renewable energy equipment respectively. The *Reconnu Garant de l'Environment*[4] (RGE) and *Eco-Artisan* labels can be obtained through a similar process,

3. "*Trustworthy contractor*".
4. "*Recognised Environmental Guarantor*".

to which two days of training are added. They are meant to signal firms' ability to perform efficient energy retrofits and/or to install renewable energy equipment. These two green labels are less often reported than technical labels: 36% of firms are either RGE or *Eco-Artisan* certified, while 67% of them have at least one technical certification.

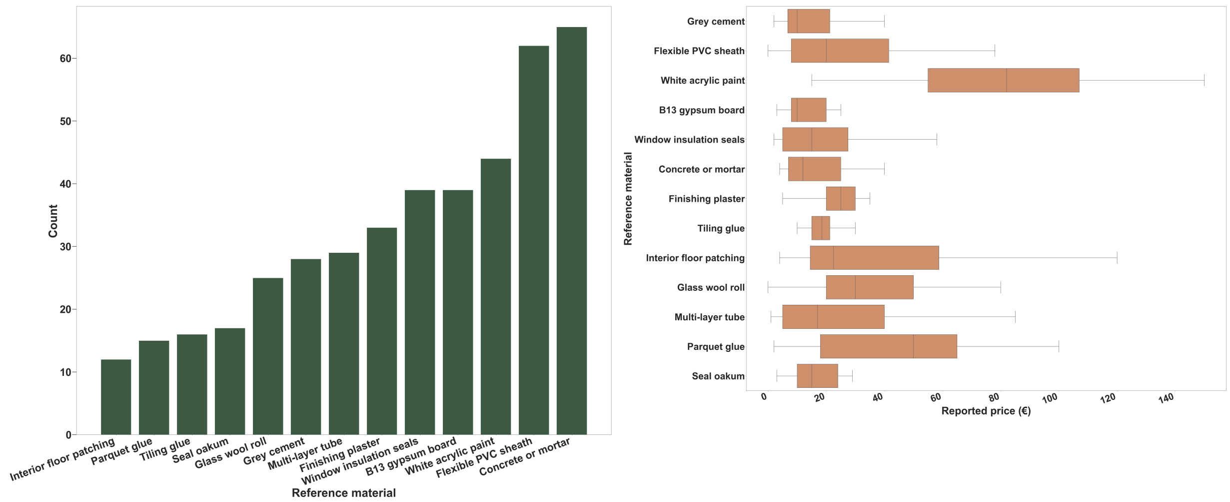


Source: Authors' computations.

Note:. Firms may have several labels, hence the total count may be larger than the sample size.

Figure 3.4.5 – Firm characteristics

As the materials used by respondents' in their day-to-day jobs are highly dependent on their professional trade, there is no material that could be used as the baseline for all of them. In order to have comparable attributes, respondents chose which material they knew best within a list (Figure 3.4.6. left). This list was put together using qualitative interview with contractors and product catalogs from both large professional-oriented building-supply store (Point P, Plateforme du Bâtiment, CBA Matériaux) and manufacturers (eg. Placo, Isover, Weber, etc.). The goal was to identify materials that were commonly used by a majority of firms in each trade, and for which there were ways to innovate - excluding raw materials like two-by-fours for instance. After selecting a material, respondents were also asked to report its average unit price in euros (Figure 3.4.6). It was used to compute imputed prices in the DCE: for instance if a theoretical product presented in the DCE has the attribute "*5% more expensive than the reference material*", its imputed price would be $P_{\text{reported}} \times 1.05$, where the "*reference material*" is the product they selected.

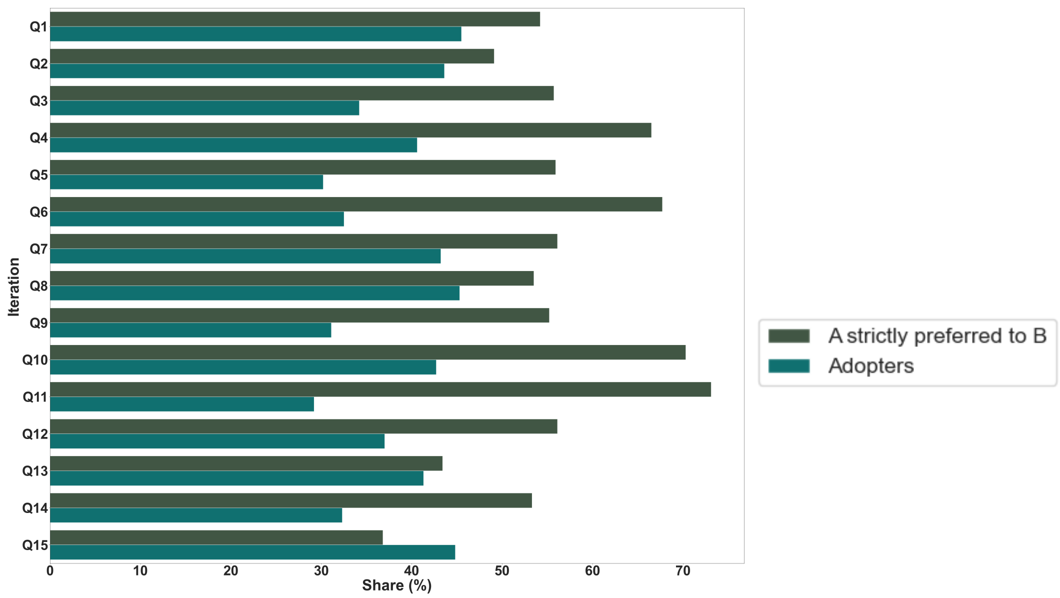


Source: Authors' computations.

Note: Each material was listed with a specific quantity (eg. white acrylic paint - 15L). The boxplots display the distributions of reported prices, with the median, quartiles and minimum and maximum values. Outliers are not displayed.

Figure 3.4.6 – Materials

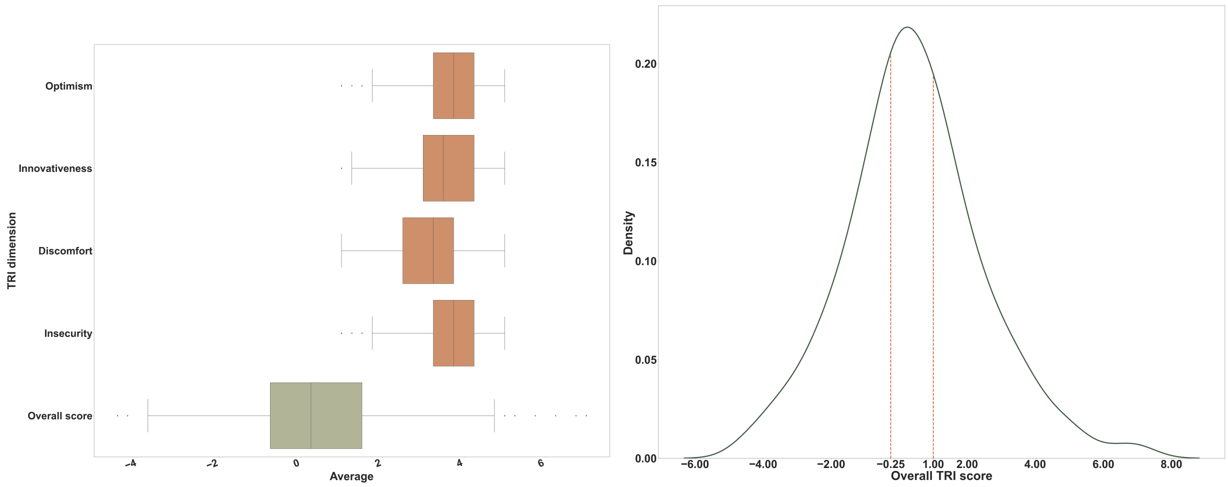
3.4.2 DCE and TRI



Source: Authors' computations.

Figure 3.4.7 – DCE responses

Figure 3.4.7 provides an overview of the responses given by respondents to each iteration of the DCE. Each respondent was presented with 15 choices and the order was randomized. Overall, they chose to try out a new product in question 2 in 38% of cases, which is consistent with low innovation uptake observed in the sector. The distribution of TRI scores are displayed in Figure 3.4.8. The kernel density estimate plot seems to indicate that the overall score [5] follows a normal distribution, with a third of respondents below -0.25 and a third of respondents above 1. Respondents' self-scaled preferences are thus not reflecting a strong bias pro or against new technologies. Rather, most individuals seem rather neutral, and a minority expressed strong negative or positive feelings towards innovative products.



Source: Authors' computations.

Note: Dashed lines on the distribution of the overall score correspond to 33 and 66 percentile thresholds.

Figure 3.4.8 – TRI average scores and kernel density estimate

3.5 Estimation results

3.5.1 Individual preferences

The estimation sample contains 424 respondents, who completed 15 choices each, meaning there are 19 080 observations when including the opt-out option. The reference product was specified by setting the price increase, technical and green characteristics as 0 - meaning "*Same as the reference product*" for the categorical variables. The information source was coded as the respondent's own experience with the reference product, which is defined as

5. The overall TRI score corresponds to the averaged sum of the drivers (first 8 items) minus the inhibitors (items 9 to 16).

the reference category in the regressions presented thereafter. Each choice set was thus characterized with three options: the reference product and the two hypothetical materials A and B. Using respondents' answers to both questions, their choice was the reference product if they said no to trying out a new product. If they did not opt out, their choice was their preferred alternative between A and B.

	Whole sample estimation			
	(1)		(2)	
	Coefficient	Std. deviation	Coefficient	Std. deviation
Reference green attribute: No change				
Lower carbon footprint	0.164*	1.112***	0.206**	1.098***
	(0.099)	(0.088)	(0.098)	(0.086)
Less on-site waste	0.177**	0.864***	0.189**	0.843***
	(0.090)	(0.105)	(0.088)	(0.102)
Reference technical attribute: No change				
Faster installation	0.339***	1.020***	0.314***	1.003***
	(0.095)	(0.091)	(0.094)	(0.091)
More comfortable installation	0.360***	0.925***	0.328***	0.918***
	(0.089)	(0.099)	(0.089)	(0.099)
Reference info. attribute: Own experience				
Own client	-1.867***	1.085***	-2.243***	1.096***
	(0.130)	(0.109)	(0.123)	(0.107)
Other contractor	-1.543***	1.069***	-1.890***	1.063***
	(0.121)	(0.111)	(0.116)	(0.111)
In-store staff	-1.495***	1.060***	-1.827***	1.021***
	(0.124)	(0.113)	(0.117)	(0.113)
Price increase (%)	-0.026***			
	(0.003)			
Imputed price (€)			-0.012***	
			(0.004)	
Log-likelihood	-5152.67	-5152.6	-5198.85	-5198.85
Observations	19080	19080	19080	19080
Individuals	424	424	424	424

Standard errors in parentheses.
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3.5.1 – Mixed logit estimation results on the whole sample

The price variable was included as a fixed variable while the other attributes were modeled with a random component. Estimations results on the whole sample are presented in Table 3.5.1, with the price being specified as the percentage increase with respect to the reference material (1) and as the imputed price using respondents' reported price (2). As expected, price has a significantly negative effect on adoption in both cases. Green attributes appear to be less valued than technical attributes in specification (1), while coefficients have similar magnitudes in specification (2). In all cases, coefficients are positive, meaning each innovative attribute is on average perceived as an improvement and can potentially trigger adoption. All coefficients attached to information attributes are negative, meaning that, as expected, respondents value their own experience more than any other source of information. Further, sources are not perceived as equally reliable: information coming from a contractor's client appears to be less valued than information from other professionals or in-store staff.

The coefficients estimated using specification (1) were used to derive uptake rates for green and technical attributes (Table 3.5.2), that is, how the adoption probability evolves if one dimension of the reference material is changed. Formally, the uptake rate of offering any attribute js on a new product is given by the difference in logit probabilities:

$$\mathbb{P}_{\Delta P,j} - \mathbb{P}_{\Delta P} = \frac{\exp\left(\beta_{\Delta P} \times \Delta P + \beta_j\right)}{\exp\left(\beta_{\Delta P} \times \Delta P\right) + \exp\left(\beta_{\Delta P} \times \Delta P + \beta_j\right)} - \frac{\exp\left(\beta_{\Delta P} \times \Delta P\right)}{\exp\left(\beta_{\Delta P} \times \Delta P\right) + \exp\left(\beta_{\Delta P} \times \Delta P + \beta_j\right)}$$

Where ΔP refers to the price increase with respect to the reference product. At first glance, uptake rates are rather low for all attributes, which is consistent with the reality of the sector. Differences in uptake rates reflect the difference in magnitude between the coefficients: everything else equal, the uptake rate of a new material with a lower carbon footprint would be 8%, against 18% for a material with a more comfortable installation.

Simulated scenario	Uptake probability	Std. error	90% confidence interval
Lower carbon footprint	0.0819*	0.0491	[0.00110.0011]
Less on-site waste	0.0882**	0.0445	[0.0150.015]
Faster installation	0.1679***	0.0462	[0.09190.0919]
More comfortable installation	0.1779***	0.0433	[0.10660.1066]

$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

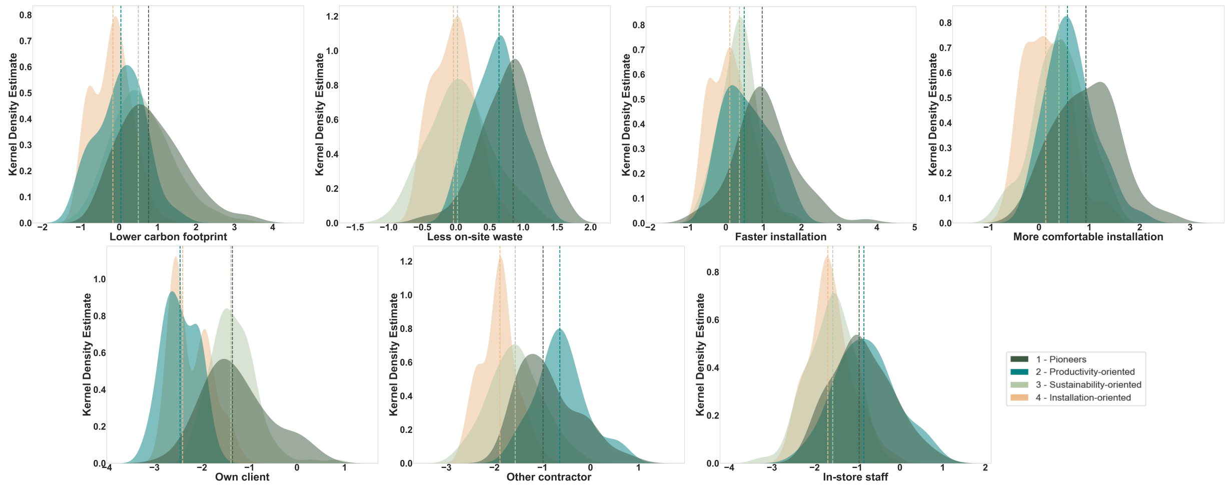
Table 3.5.2 – Simulated preferences for innovation uptake under different potential scenarios

The individual-level coefficients associated to the random attributes were further used to run a hierarchical cluster analysis. Each cluster reflects individuals with homogeneous preference patterns. Five clusters were identified based on the values of the coefficients. Table 3.5.3 provides descriptive statistics for each cluster, and pair-wise Dunn test statistics can be found in Appendix 3.A. Krustal-Wallis (KW) tests assessing the significance of the differences between clusters are reported, with respect to median coefficient values and respondent mean characteristics - for clarity, only the characteristics for which the p-values were less than 10% are reported. These characteristics were tested using dummies, and overall were not predictors of behaviors. The distribution of the attributes' coefficients across clusters is further displayed in Figure 3.5.1.

	Cluster 1: Pioneers	Cluster 2: Productivity-oriented	Cluster 3: Sustainability-oriented	Cluster 4: Installation-oriented	Cluster 5: Laggards	Kruskal Wallis test
Median coefficient values						
Lower carbon footprint	0.7629	0.0432	0.4967	-0.1643	-0.6331	0.000
	(0.8477)	(0.6022)	(0.7809)	(0.484)	(0.0658)	
Less on-site waste	0.8485	0.6389	0.022	-0.0381	-0.3324	0.000
	(0.4137)	(0.3345)	(0.4629)	(0.3031)	(0.0498)	
Faster installation	0.963	0.4861	0.3605	0.1057	-0.3344	0.000
	(0.79)	(0.6124)	(0.483)	(0.5127)	(0.0675)	
More comfortable installation	0.933	0.5664	0.3987	0.1347	-0.2208	0.000
	(0.6259)	(0.472)	(0.5098)	(0.4426)	(0.0588)	
Own client	-1.36	-2.4601	-1.3914	-2.4064	-2.4285	0.000
	(0.718)	(0.3576)	(0.4861)	(0.4113)	(0.068)	
Other contractor	-0.9885	-0.6377	-1.5673	-1.884	-2.302	0.000
	(0.6246)	(0.5296)	(0.5475)	(0.3634)	(0.0602)	
In-store staff	-0.9579	-0.8442	-1.5762	-1.6895	-2.2328	0.000
	(0.7017)	(0.701)	(0.5389)	(0.5125)	(0.0586)	
Individual characteristics (Share of cluster in %)						
21-50 workers	21.05	11.9	13.21	22.5	10.0	0.085
	(41.04)	(32.78)	(34.02)	(41.93)	(30.19)	
51-100 workers	3.95	14.29	15.09	15.83	8.75	0.082
	(19.6)	(35.42)	(35.97)	(36.66)	(28.43)	
Technical label	65.79	66.67	70.75	72.5	55.0	0.109
	(47.76)	(47.71)	(45.71)	(44.84)	(50.06)	
No label	21.05	28.57	16.98	15.0	30.0	0.06
	(41.04)	(45.72)	(37.73)	(35.86)	(46.11)	
Vocational training	43.42	64.29	58.49	52.5	61.25	0.105
	(49.89)	(48.5)	(49.51)	(50.15)	(49.03)	
Income < 1999EUR	32.89	50.0	24.53	30.83	41.25	0.022
	(47.3)	(50.61)	(43.23)	(46.37)	(49.54)	
Income > 3000 EUR	27.63	11.9	26.42	24.17	15.0	0.109
	(45.01)	(32.78)	(44.3)	(42.99)	(35.93)	
Individuals	76	42	106	120	80	

Median coefficients are derived from specification (1) in Table 3.5.1, standard deviations in parentheses.

Table 3.5.3 – Median value and standard deviation of individual coefficients by preference cluster



Note: Cluster 5 (Laggards) are not represented for visualization purposes. Individual coefficients are derived from estimation (1) in Table 3.5.1. Dashed lines correspond to median coefficient values for each cluster, reported in Table 3.5.3.

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Figure 3.5.1 – Distribution of individual coefficients by clusters

Cluster 1 ("*Pioneers*") is composed of individuals with high valuations of all innovative characteristics, which would be likely to be first adopters. There is an over-representation of high-incomes and and under-representation of respondents with vocational training with respect to sample shares, which is consistent with previous results in the literature regarding early adopters. By contrast, respondents in cluster 5 ("*Laggards*") appear innovation-averse, with negative median coefficients for all attributes. Medium and large companies are under-represented, as well as firms with technical labels, while low-income individuals and firms without any labels are over-represented. Positioned between clusters 1 and 5 in terms of attribute valuations, the characteristics of cluster 2, 3 and 4 do however stray from the well-known typology established by Rogers (1962). These respondents do not differ in how much they value innovative attributes *per se*, but rather on which attributes they do value. Respondents in cluster 2 ("*Productivity-oriented*") have higher valuations than those in clusters 3 and 4 with respect to efficiency improvements: faster installation and reducing on-site waste. They seem to have an installer profile, with an over-representation of low-incomes and of individuals with vocational training. They are close to individuals in cluster 4 ("*Installation oriented*") in that regard, except that respondents in cluster 4 are much more risk-averse. They seem to value technical characteristics, and, contrary to individuals in cluster 2, expressed distaste for green characteristics. Finally, respondents in cluster 3 ("*Sustainability oriented*") have positive median valuations of all innovative attributes, but value productivity improvements less than respondents in cluster 2, while they have higher valuations for reducing the carbon footprint and improving the ease of installation. Large firms are strongly over-represented, as well as high incomes. It can be noted that the KW tests performed on material unit prices, experience and gender were not conclusive, meaning there was no significant difference between clusters. Overall, pioneers and laggards account for 18% and 19% of the sample respectively, meaning 63% of the respondents belong to one of the late adopter clusters. Higher education and income seem to drive green innovations, while vocational training and technical labels tend to be linked to a bias towards technical attributes. This cluster analysis reinforces the idea that technical improvements should find their audience much faster than green ones on the construction market, especially those improving productivity.

	TRI score					
	Bottom third		Middle third		Top third	
	Coeff.	Std. dev.	Coeff.	Std. dev.	Coeff.	Std. dev.
Ref. green attribute: No change						
Lower carbon footprint	-0.061	1.212***	0.124	1.061***	0.220	1.317***
	(0.183)	(0.156)	(0.166)	(0.140)	(0.178)	(0.154)
Less on-site waste	0.207	0.947***	-0.023	0.933***	0.179	0.984***
	(0.163)	(0.204)	(0.165)	(0.164)	(0.160)	(0.184)
Ref. technical attribute: No change						
Faster installation	-0.112	1.617***	0.246	0.791***	0.639***	0.895***
	(0.207)	(0.185)	(0.162)	(0.157)	(0.151)	(0.148)
More comfortable installation	0.052	1.427***	0.350**	0.932***	0.525***	0.519***
	(0.181)	(0.156)	(0.164)	(0.163)	(0.138)	(0.180)
Ref. info. attribute: Own experience						
Own client	-1.760***	1.464***	-1.958***	0.594***	-1.740***	-0.907***
	(0.238)	(0.193)	(0.209)	(0.182)	(0.206)	(0.167)
Other contractor	-1.230***	-0.544**	-1.758***	0.984***	-1.500***	1.114***
	(0.200)	(0.259)	(0.211)	(0.166)	(0.212)	(0.172)
In-store staff	-1.345***	-0.335	-1.611***	0.748***	-1.276***	1.421***
	(0.189)	(0.237)	(0.200)	(0.191)	(0.218)	(0.198)
Price increase (%)	-0.027***		-0.021***		-0.028***	
	(0.005)		(0.004)		(0.004)	
Log-likelihood	-1658.52	-1658.52	-1660.55	-1660.55	-1802.39	-1802.39
Observations	6345	6345	6345	6345	6390	6390
Individuals	141	141	141	141	142	142

Standard errors in parentheses.
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3.5.4 – Mixed logit estimation results by TRI score

Finally, the TRI measures were used to assess the validity of these estimates: a high TRI score signals a strong appetence for new technologies, which should translate into a higher valuation of green and technical attributes. Table 3.5.4 displays results obtained using specification (1) from Table 3.5.1 run on three sub-samples based on respondents' TRI levels. Focusing on technological attributes, it appears that respondents in the top third of the TRI derive more utility from innovations more than their counterparts in the bottom and middle thirds. The ranking of information attributes is consistent across the three sub-samples, meaning they exhibit the same perception of the risk linked to imperfect information. Theses results seem to confirm that respondents' self-reported preferences on the 1-5 scale are in line with the DCE estimates, corroborating the suitability of the experimental design.

3.5.2 Willingness to pay

	Mean WTP	Std. error	90% confidence interval
Lower carbon footprint	17.13*	9.96	[0.75;33.51]
Less on-site waste	15.76*	8.96	[1.02;30.5]
Faster installation	26.14**	11.32	[7.51;44.77]
More comfortable installation	27.31**	11.39	[8.58;46.05]
Own client	-186.88***	62.64	[-289.92;-83.85]
Other contractor	-157.47***	53.34	[-245.21;-69.73]
In-store staff	-152.26***	51.55	[-237.06;-67.47]

$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3.5.5 – Willingness to pay

Beyond the relative value of the parameters, the estimation results presented in Table 3.5.1 (2) were used to derive respondents' willingness to pay (WTP) for each attribute. Table 3.5.5 displays mean WTP values for each attribute level j, estimated using the imputed unit price:

$$WTP_j = -\frac{\frac{\partial U}{\partial (j)}}{\frac{\partial U}{\partial (\mathbf{price})}} = -\frac{\beta_j}{\beta_{\mathbf{price}}}$$

For each attribute level j, β_j refers to the mean of the $\beta_{i,j}$ over all individuals. Again, the ranking of each attribute is clearly established: while respondents are on average willing to pay 26 and 27 € for each of the technical attributes, their WTP falls to 17 € for a lower carbon footprint and 16 € for a reduction of on-site waste. There is also more variation in the estimate of their WTP for green attributes, which hints at more heterogeneity in preferences.More interestingly, the mean cost attributed to trusting information from another party is extremely high, ranging from 152 € (in-store staff) to 187 € (own client). If a product were innovative in all four dimensions, their mean WTP for it would sum up to 86€, which does not compensate for the cost of uncertainty, even from the most reliable source. Low uptake rates on the construction sector may thus not be the result of professionals' distaste for new technologies, but rather the magnitude of the cost of information uncertainty. It could be linked to contractors' insurance commitments, as they have a mandatory ten-year

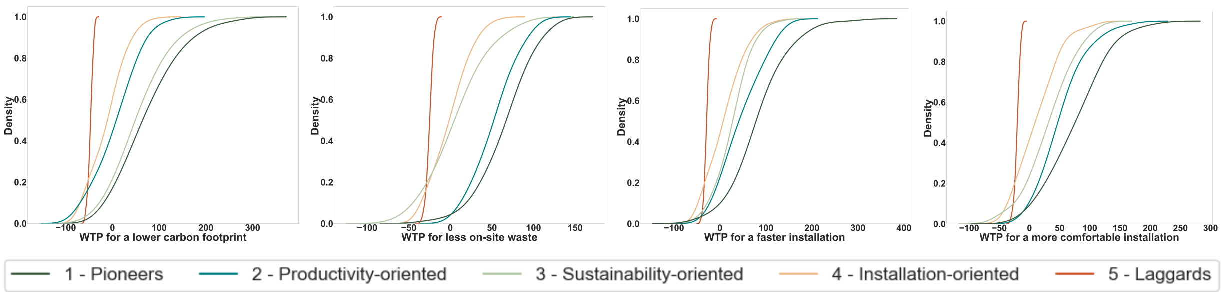
<u>Source:</u> Authors' computations.

<u>Note:</u> Materials correspond to the eight most reported items. Individuals' willingness to pay are derived from estimation (2) in Table 3.5.1.

Figure 3.5.2 – Mean willingness to pay per material

guarantee under which they are liable for any malfunction in the equipment or materials they installed. In practice, it means that if their client feels the materials installed are under-performing - say, a leak in the roof after it was redone -, the contractor has to come back and look it up, eventually fix the issue, for free and up to ten years after the completion of the work. It may contribute to explain why construction professionals are particularly reluctant to deviate from their tried-and-true baseline materials.

It could be argued that the sample mean WTP does not reflect respondents' preferences well, since they use different materials bought at different price points. Figure 3.5.2 displays the distribution of the price respondents are willing to pay for each improvement, for the eight materials that are the most frequent in the sample. They do differ in value, but the pattern is consistent throughout: technical attributes are more valued than green ones, and information uncertainty comes at a much higher cost, especially if the information source is their own client.



Note: Individuals' willingness to pay are derived from estimation (2) in Table 3.5.1; clusters can be found in Table 3.5.3.

Figure 3.5.3 – Distribution of individual coefficients by clusters

Respondents' willingness to pay does however vary across clusters. Figure 3.5.3 displays the estimated cumulative distributions of individual WTP for each cluster. They all follow a S-shaped curve, meaning there is some heterogeneity within clusters, but there is a clear ranking. Cluster 1 respondents have higher WTP than their counterparts in clusters 2 to 4, and individuals in cluster 5 display much lower values, and with less variation. Assuming innovations' prices decrease over time, new technologies would be first adopted by the pioneers, followed in order by productivity-oriented, sustainability-oriented and installation oriented individuals, and ending with laggards. The only exception would be innovations with a lower carbon footprint, for which cluster 3 would be second in line. Green characteristics, and especially a reduction of the carbon footprint, are assigned lower WTP in general. This could hinder the development of green products by material producers, as they would expect lower penetration rates. The decarbonation of production chains typically comes with a significant cost, which they would have a hard time carrying over to their clients through a price increase.

3.5.3 Policy analysis

	Highest degree			
	Vocational training		Higher education	
	Coeff.	Std. dev.	Coeff.	Std. dev.
Reference green attribute: No change				
Lower carbon footprint	0.151	1.109***	0.067	1.465***
	(0.130)	(0.118)	(0.166)	(0.155)
Less on-site waste	0.154	0.683***	0.200	1.156***
	(0.112)	(0.121)	(0.154)	(0.160)
Reference technical attribute: No change				
Faster installation	0.238**	0.687***	0.551***	1.230***
	(0.115)	(0.128)	(0.158)	(0.143)
More comfortable installation	0.386***	0.626***	0.424***	1.176***
	(0.109)	(0.131)	(0.156)	(0.150)
Reference info. attribute: Own experience				
Own client	-2.031***	1.145***	-1.663***	0.870***
	(0.173)	(0.171)	(0.191)	(0.155)
Other contractor	-1.715***	1.109***	-1.283***	0.966***
	(0.163)	(0.117)	(0.183)	(0.177)
In-store staff	-1.719***	1.262***	-1.290***	0.974***
	(0.167)	(0.139)	(0.186)	(0.166)
Price increase (%)	-0.014***		-0.043***	
	(0.003)		(0.004)	
Log-likelihood	-2852.94	-2852.94	-2142.29	-2142.29
Observations	10530	10530	8145	8145
Individuals	234	234	181	181

Standard errors in parentheses.
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3.5.6 – Mixed logit estimation results by type of degree

Respondents' and firms' characteristics were used to look into policy options to boost innovation uptake, by running the mixed logit model on sub-samples. Would higher adoption rates be achieved by providing additional training or professional labels? Respondents' degrees were aggregated into two categories to have a sufficient number of observations: vocational training (CAP, BEP or vocational Baccalaureate) and higher education (general Baccalaureate, Bachelor or master degree) - the nine respondents holding no degree were left out due to sample size. Estimations results are presented in Table 3.5.6. Non-zero coefficients appear larger for people with a higher education background, except for a lower carbon footprint. It is also interesting to note that comfort is valued over speed of installation by respondents with vocational training, while the order is reversed for higher-educated respondents. These coefficients are likely to be a reflection of people's hierarchical positions, as the former tend to be directly involved with the installation while the latter would tend to hold supervision positions, hence the focus on productivity.

	Type of label or certification					
	None		Technical label		Green label	
	Coeff.	Std. dev.	Coeff.	Std. dev.	Coeff.	Std. dev.
Ref. green attribute: No change						
Lower carbon footprint	0.672	0.266	0.174	1.112***	0.626**	-0.866***
	(0.502)	(0.955)	(0.130)	(0.116)	(0.261)	(0.279)
Less on-site waste	0.428	0.676	0.161	0.674***	0.265	-1.068***
	(0.648)	(0.596)	(0.111)	(0.120)	(0.271)	(0.265)
Ref. technical attribute: No change						
Faster installation	0.699	-0.031	0.221*	0.678***	0.377	1.708***
	(0.426)	(0.375)	(0.114)	(0.128)	(0.345)	(0.334)
More comfortable installation	0.695	0.819	0.365***	0.621***	0.520*	1.412***
	(0.549)	(0.609)	(0.108)	(0.130)	(0.281)	(0.320)
Ref. info. attribute: Own experience						
Own client	-1.655**	-0.706	-2.280***	1.145***	-2.886***	1.549***
	(0.748)	(0.787)	(0.165)	(0.170)	(0.429)	(0.287)
Other contractor	-2.289***	1.252	-1.954***	1.105***	-2.147***	1.196***
	(0.839)	(1.230)	(0.157)	(0.116)	(0.365)	(0.319)
In-store staff	-1.666**	1.449*	-1.949***	1.253***	-1.911***	1.081**
	(0.772)	(0.776)	(0.161)	(0.139)	(0.329)	(0.465)
Price increase (%)	0.026		0.000		0.010	
	(0.078)		(0.004)		(0.013)	
Log-likelihood	-1001.29	-1001.29	-3523.42	-3523.42	-1901.58	-1901.58
Observations	3960	12780	6840			
Individuals	88	88	284	284	152	152

Standard errors in parentheses.
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3.5.7 – Mixed logit estimation results by type of certification of label

Turning to certifications and labels, the sample was divided into firms with no certifications, those with technical certifications (eg. *Qualibat*) and those with green certifications (RGE or *Eco-Artisan*). These are not mutually exclusive sub-samples, since 24% of the respondents work in firms that have both a green and a technical certification. From the results displayed in Table 3.5.7, adoption seems to be driven mainly by certified firms, as both green and technical attribute coefficients are not significant for the no label sub-sample. It also appears that green attributes, in this case the reduction of the carbon footprint, are only valued by professionals working in firms with a green label. Green labels are indeed supposed to constrain the materials a firm can use, in particular with regard to their environmental impact. This condition is in line with respondents' preferences, which could either mean that the label provides enough incentives for them to turn to green products more systematically, or that professionals getting the label are already wired that way. In any case, the label seems to be efficient to signal a firm's greener practices to households. It is also interesting to note that firms with some kind of technical label attach more importance to faster installation, while green companies value comfort more. For all subs-samples, information uncertainty comes out as an extra cost. Regarding the source, in-store staff is preferred to another contractor, which is still perceived as more reliable than their own client. Overall, these results confirm the effectiveness of labelling institutions in their selection of companies. Ultimately, labels and certifications are thus efficient signals of firms' skills for households, at least regarding their choice of products.

3.6 Conclusion

The DCE presented in this paper aimed to shine a light on construction professionals' barriers to innovation adoption. Despite differences in professional trades and baseline materials, the survey was designed to obtain comparable inter-individual responses. The DCE's internal validity was consolidated using a self-declared TRI scale, as low-scoring respondents valued innovative improvements less and high-scoring respondents seemed slightly less impacted by imperfect information. Estimations results indicate that even though innovative attributes are valued, the perceived cost of imperfect information on product performance, with respect to their own experience, is larger. Innovation uptake was found to be rather low overall, which is consistent with the reality of the sector. Moreover, technical attributes were almost systematically preferred to green attributes, meaning that environmental-friendly materials may have hard time finding their market. The resulting willingness to pay reflected these differences, and seemed robust to differences in terms of baseline materials. Five clusters of homogeneous preferences were further identified. Two of them can be related to the well known pioneers and laggards groups established by Rogers (1962). More interestingly, three clusters of late adopters were identified, reflecting differences in which attributes were valued by respondents. There was no strong individual characteristic determining to which cluster respondents were likely to belong to, which can make diffusion policy harder to fine-tune. In particular, traditional indicators like experience the price of the baseline were not good predictors of individual behavior.

As any survey-based approach, there are limitations to consider when interpreting these results. First, the DCE methodology relies on what respondents declare they would do rather than observing their actual behaviors when making a choice between products. Given the complexity of the topic studied here however, organizing a randomized experiment in real-world conditions would prove to be difficult, if not impossible. The DCE method is particularly interesting here to overview material attributes that do not necessarily exist, which could provide insights for R&D efforts. Second, the sample size limited the number of policy and use-cases reviewed. It could be relevant to see how household preferences would impact firms' behaviors, since materials are ultimately intermediate goods. As innovative products tend to be more expensive, the end-client's payment capacity must play a part in determining professionals' decisions.

Nonetheless, our results open interesting perspectives in term of diffusion policies. The construction industry is one of most polluting sector in Europe, and reducing its carbon emissions could start with the production and diffusion of greener products. The most consistent result is the cost of information uncertainty, which was always found to be high. A free-sample distribution when a product is launched could thus trigger early adoption, by allowing professionals to have their own experience with a product before making their buy-or-not decision. Higher education does not seem to bias preferences towards green attribute, but rather towards the efficiency of installation. Information campaign or professional training could be offered to decrease the cost of uncertainty and increase the value attached to green attributes. Our analysis also showed that labeled companies seem to be driving innovation uptake, and that the type of labels (technical or green) they hold is reflected in their preferences. These results cannot be used to establish causality between labels and preferences, but they at least confirm the quality of the signal labels send to end-consumers looking for renovation or construction services. This paper did not explore the impact green labels for materials could have on adoption, which would be a relevant topic for future research.

Appendices of Chapter 3

3.A Dunn tests

	Cluster pairs									
	1 - 2	1 - 3	1 - 4	1 - 5	2 - 3	2 - 4	2 - 5	3 - 4	3 - 5	4 - 5
Lower carbon footprint	4.4308	1.4504	8.3495	11.9948	-3.4767	2.0756	5.6123	7.5473	11.5011	4.8311
	(0.0000)	(0.0735)	(0.0000)	(0.0000)	(0.0003)	(0.019)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Less on-site waste	**1.0775**	8.1643	9.6932	13.3768	5.5942	6.7705	10.1576	1.4544	6.1819	5.0
	(0.1406)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0729)	(0.0000)	(0.0000)
Faster installation	2.3979	4.9455	8.0425	12.4462	1.5483	4.0047	8.0429	3.2686	8.4422	5.6438
	(0.0082)	(0.0000)	(0.0000)	(0.0000)	(0.0608)	(0.0000)	(0.0000)	(0.0005)	(0.0000)	(0.0000)
More comfortable installation	1.6331	4.401	7.9438	12.2628	1.9059	4.7442	8.6606	3.774	8.7965	5.5406
	(0.0512)	(0.0000)	(0.0000)	(0.0000)	(0.0283)	(0.0000)	(0.0000)	(0.0001)	(0.0000)	(0.0000)
Own client	9.0262	**-0.2912**	9.4268	10.0518	-9.7584	-1.9717	**-0.6578**	10.6961	11.1672	1.5807
	(0.0000)	**(0.3854)**	(0.0000)	(0.0000)	(0.0000)	(0.0243)	**(0.2553)**	(0.0000)	(0.0000)	(0.057)
Other contractor	-1.4024	5.5091	9.4854	13.1258	6.0204	9.2601	12.4489	4.2199	8.6053	4.9326
	(0.0804)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
In-store staff	**-0.4761**	5.9835	6.4084	12.407	5.4347	5.7506	10.9099	**0.3009**	7.3464	7.2601
	(0.317)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	**(0.3818)**	(0.0000)	(0.0000)
21-50 workers	1.28	1.4042	**-0.2656**	1.8563	**-0.1922**	-1.5899	**0.2689**	-1.8755	**0.5827**	2.3299
	(0.1003)	(0.0801)	**(0.3953)**	(0.0317)	**(0.4238)**	(0.0559)	**(0.394)**	(0.0304)	**(0.2801)**	(0.0099)
51-100 workers	-1.651	-2.2772	-2.4895	**-0.9206**	**-0.1362**	**-0.2651**	**0.892**	**-0.1702**	1.3154	1.5069
	(0.0494)	(0.0114)	(0.0064)	**(0.1786)**	**(0.4458)**	**(0.3955)**	**(0.1862)**	**(0.4324)**	(0.0942)	(0.0659)
No label	**-0.9631**	**0.6671**	**1.0168**	-1.3757	1.5656	1.8643	**-0.1846**	**0.3661**	-2.165	-2.5595
	(0.1677)	**(0.2523)**	**(0.1546)**	(0.0845)	(0.0587)	(0.0311)	**(0.4268)**	**(0.3572)**	(0.0152)	(0.0052)
Technical label	**-0.0969**	**-0.7016**	**-0.9722**	1.4306	-0.4762	**-0.691**	1.3004	**-0.2781**	2.2593	2.5751
	(0.4614)	**(0.2415)**	**(0.1655)**	(0.0763)	**(0.317)**	**(0.2448)**	(0.0967)	**(0.3905)**	(0.0119)	(0.005)
Vocational training	-2.1796	-2.0137	**-1.2439**	-2.2355	**0.6384**	1.3203	**0.32**	**0.9027**	**-0.3742**	**-1.2176**
	(0.0146)	(0.022)	**(0.1068)**	(0.0127)	**(0.2616)**	(0.0934)	**(0.3745)**	**(0.1834)**	**(0.3541)**	**(0.1117)**
Income < 1999EUR	-1.8828	**1.178**	**0.2976**	**-1.1039**	2.9566	2.2625	**0.9718**	**-1.0011**	-2.3895	-1.5273
	(0.0299)	**(0.1194)**	**(0.383)**	**(0.1348)**	(0.0016)	(0.0118)	**(0.1656)**	**(0.1584)**	(0.0084)	(0.0633)
Income > 3000 EUR	1.9594	**0.1939**	**0.5662**	1.889	-1.9064	-1.6384	**-0.3891**	**0.4041**	1.8464	1.5213
	(0.025)	**(0.4231)**	**(0.2856)**	(0.0294)	(0.0283)	(0.0507)	**(0.3486)**	**(0.3431)**	(0.0324)	(0.0641)

Dunn test statistics, P-values in parentheses.

Table 3.A.1 – Pair-wise comparisons of cluster characteristics

* * *

«Je n'étais pas loin de penser que tout aurait été différent si notre maison avait été plus petite, dotée d'un seul étage, sans chambres secrètes où il était interdit de pénétrer, pour ne pas parler des celliers, de la citerne souterraine et du cachot.»

Ismaïl Kadaré – *La Poupée.*

* * *

Chapter 4

Improving the Energy Efficiency of the French Residential Sector: The Role of the Middlemen

* * *

Increasing prices and the growing scarcity of resources call for an urgent reduction of energy use. The residential sector has become a major policy target in that regard, as it accounts for a non-negligible part of final consumption. Part of this consumption has been attributed to the "*energy efficiency gap*", meaning the difference between the energy consumption that could be achieved if every building were made with state-of-the-art materials and the actual energy consumption. Ambitious reduction targets have been set in developed countries, relying on a mix of awareness, regulatory and financial instruments. This paper exploits the originality of the French context to explore the efficiency of these policies, for which there are very few *ex post* evaluations. More specifically, the caveats this paper aims to address are (1) the role of construction contractors as middlemen between policymakers and households while (2) controlling for factors affecting energy consumption, especially spatial ones. A comprehensive dataset was built at the neighborhood level by compiling information from various sources. Results are estimated through spatial panel regressions and suggest areas of improvement for French financial aid schemes.

* * *

4.1 Introduction

Increasing prices, growing scarcity of resources and, more generally, climate issues call for an urgent reduction of energy use. The residential sector has become a major policy target in that regard, as it accounts for a non-negligible part of final energy consumption - reaching 26% among European Union countries (Eurostat 2020). At the individual level, energy expenses are also an important part of households' yearly budgets, accounting on average for 25.7 % of their expenses in the EU. Part of this consumption has been attributed to the "*energy efficiency gap*", which was first defined by Hirst and Brown (1990). In the residential sector, it refers to the difference between the energy consumption that could be achieved if every building were made with state-of-the-art materials, and the actual energy consumption of buildings. In other words, a significant decrease could be achieved by bridging this gap through the retrofit of existing dwellings. Ambitious reduction targets that have yet to be reached have been set at the European level by the "*Energy Performance of Buildings Directive*" adopted by the European Commission in 2010, which promoted three policy tools. First, awareness campaigns aim to spread good practices and information about the need to lower the energy consumption and the potential individual gains, relying on individual willingness. Second, financial instruments are meant to further incentivize agents to retrofit existing buildings, through grants or loans, in order to diminish the cost borne by companies and households. Third, regulatory instruments are to be put in place to constrain new builds and professional practices - materials used, access and implantation. Optimally, a combination of these policies should boost household investments in the energy efficiency of their dwellings, as the current levels remain too low. Such investments typically involve high upfront costs and become profitable only over a long period of time. Despite the large impact they would have overall on energy usage, a number of households are thus reluctant to commit.

The actual impact of these policy mixes on the energy consumption of the residential sector remains somewhat unclear. Most of the evaluations conducted to this day were based on simulations with *ex-ante* data. They exploited information on dwellings' technical characteristics, which are the main focus of these policies. Better insulation, double glazing and more recent heating systems do in theory favor energy savings, but these simulations usually lack a number of controls. Individual characteristics, such as income and family structure, also shape households' energy needs and capacity to pay. An increasing number of *ex-post* surveys have for instance shown that low-income households are often unable to afford their desired level of comfort, especially with respect to heating. In these cases, improving the energy-efficiency of the dwelling will not necessarily lead to a decrease of consumption, as households may prioritize increasing their comfort. Using real-world data rather than consumption projections will in most cases produce lower estimates of the potential for energy savings. These evaluations are however usually based on one-off regional policies, not long-term national programs. Broader evaluations would require controls for location, local climate and housing density, which all impact individual energy demand but are usually not included. Typically, less energy is required to maintain an indoor temperature of 21°C in denser areas (P. P. Combes and Gobillon 2015). Finally, the quality of installation is almost never accounted for, despite being central to the actual performance of the materials and appliances installed during a retrofit (Hamilton and Huessy 2010). Dwelling refurbishment are in most cases undertaken by small construction companies, which are very heterogeneous in their skill levels, experience and training. Further, the majority of households have little to no knowledge of what they need and how it should be installed. Hiring contractors hence poses typical procurement issues, as refurbishment activity is not as regulated as new construction. The only widespread policies targeting professionals are labels assessing the quality of their work, which are not mandatory. As there are virtually no quality controls by parties other than the contractors, poor workmanship and/or dishonesty on the professional's part can seriously hinder the energy savings effectively achieved.

The caveats this paper aims to address are (1) the role of construction contractors as middlemen between policymakers and households while (2) controlling for factors affecting energy consumption, especially spatial ones. Do financial aid schemes for households stimulate the implantation of higher-quality firms? Does access to these companies lead to energy savings over time? These questions are tackled by taking advantage of the specificities of the French policy mix. A broad range of fiscal incentives for households has been established, including lowering the V.A.T. to 5.5% for retrofit projects since 2013, low-interest loans since 2009, tax credits for all households since 2005, and additional rebates for low-income ones since 2010 (Robinet, Hainaut, and Postic 2018). Regarding companies, the "*Reconnu Garant de l'Environnement*" (RGE) [1] certification was implemented in 2011. It is a costly label for firms, based on a few days of training and an audit of several work sites. Labeled firms are committed to use better materials and are certified to have the skills required to perform efficient energy retrofits. The explicit goal of the RGE label is to reduce fraud in the construction sector and ensure a minimal quality of the retrofits. Most importantly, if a household wants to benefit from three out of the current five current financial aid schemes, they have to hire a RGE contractor. Overall, these policies benefited roughly 2.1 million dwellings from 2016 to 2019, which represents 7% of French metropolitan

1. It can be translated to "*Recognized Environmental Guarantor*".

dwellings [2] (ONRE 2020). A comprehensive panel dataset was built using information on RGE firms' precise location in metropolitan France, household aid spendings by the State and household consumption of gas and electricity over the 2011-2018 period. It contains information on technical, socioeconomic and location-specific characteristics. The objective is to use spatial and temporal disparities in both the distribution of RGE firms and fiscal aid to estimate the impact of these policies, while controlling for household determinants. If tax credits for households favor the undertaking of energy retrofits, then higher levels of spending should lead to a higher number of RGE-certified companies locally. Additionally, if having access to a certified firm favors the undertaking of energy retrofit, there should be a decrease of energy consumption per capita in areas where there are relatively more of them, everything else equal.

This paper is organized as follows. First, a literature review will examine the main contributions in the fields of energy and urban economics, which are both relevant to this work. Second, the various data sources will be presented, with specific attention given to the construction of some key variables. Regression results and robustness tests will then be presented, followed by a discussion of their implications in terms of policy design.

4.2 Literature review

A large number of papers have explored the optimal policy mix to incentivize households to make their homes more energy-efficient. Following Sebi et al. (2019), two types of policy tools can be distinguished: regulatory instruments, which establish the minimum standards imposed on new construction, and financial instruments, which are meant to boost homeowners' will to undertake projects. The former imposes restrictions on people's behaviors while the latter focuses on their incentives to reduce barriers. Voluntary-based instruments, such as incentive-based schemes for households and eco-labeling of buildings can be more efficient than regulatory instruments as they offer more flexibility, even if their outcomes may be more unpredictable (Tambach, Hasselaar, and Itard 2010; W. L. Lee and Yik 2004). High upfront costs, perceived or real, have indeed been identified as the primary obstacle deterring the undertaking of energy retrofits by households, as shown in the UK (Caird, Roy, and Herring 2008), in Ireland (Aravena, Riquelme, and Denny 2016), in Germany (Achtnicht and Madlener 2014), and in Switzerland (Alberini, Banfi, and Ramseier 2013). The level of grant also significantly increased the probability of undertaking a renovation projects, while households' uncertainty about future energy prices had a negative effect.

2. Metropolitan France refers to the European territory of France, which excludes overseas regions.

Financial aid schemes should in that regard be efficient to boost the number of retrofits. Additionally, Fischbacher, Schudy, and Teyssier (2021) found that less risk-averse decision-makers were more likely to retrofit, and that less present-biased individuals were likely to live in more efficient houses. Comfort and concerns for the environment were also often cited as motivations to undertake a renovation project, but appeared less important - even though they could impact the nature of the investment. Households whose primary issue was comfort were found to invest in insulation, while drought proofing and solar panels were more likely to be installed by cost-driven households (Collins and J. A. Curtis 2017). Detailed surveys in Ireland have highlighted more precise factors when it comes to household decision-making, such as the proximity to the gas-network when choosing a heating system (J. Curtis, McCoy, and Aravena 2018). Rural households tend to undertake more energy retrofits than their urban counterparts, but they are less comprehensive on average (Collins and J. Curtis 2016). These findings overall highlight the need to design policies that account for household's characteristics and location.

Early evaluations of financial aid schemes for households focused on cost-efficiency: is it viable for states or local institutions to finance large-scale retrofit programs? A major source of inefficiency is the potential for a rebound effect. After a retrofit, households may change their behaviors and consume more energy, as its efficiency becomes relatively higher. It has been a long-standing topic in the economic and engineering literature [3], and was more recently studied in the context of energy retrofit programs. The impact of any type of financial aid has been found to be impaired by the rebound effect, which was even larger for low-income households (eg. Jin 2020). Further, from a total surplus perspective, grant programs can have a negative social impact and differentiated policy instruments should target households in situation of fuel-poverty (Dresner and Ekins 2006). Financial aid programs can also be subject to free riding. In this context, it refers to households using state subsidies to finance a retrofit project they would have taken on either way using their private founds. D'Alpaos (2021) found that the Italian tax credit scheme led to an over-investment that was not socially optimal, given current energy prices. Based on a survey on beneficiaries of State grants in Switzerland, Studer and Rieder (2019) found that 49.5% of households were free riders, meaning the subsidy did not increase the quality nor the scope of the retrofit. In France, Nauleau (2014) found that grants always had a significant and positive effect on households' propensity to retrofit, but that the share of free riders rose to 40% for low-income households after 2006, and up to 85% for high-

3. See Greening, D. L. Greene, and Difiglio (2000) for a literature review on different methods to characterize the rebound effect.

income ones. Overall, European and North-American surveys found large shares of free riders among state program beneficiaries. Grants were found to induce more retrofits than loans but at a much higher cost for the state in that regard (Kerr and Winskel 2020b). Even though financial schemes are efficient tools in theory, they have to lead to substantial improvements and not deter private investments to be cost-efficient in practice. The type of policy implemented - zero interest, tax credits, grants, etc. - also seems to impact the effectiveness of public investments.

These estimations of policies' cost-effectiveness however assumed savings would be achieved through the policy. A more recent strand of literature explored whether fiscal aid programs actually induced energy savings in practice. European countries were found to differ significantly in their overall energy consumption, and in how it evolved after these policies were established (Filippini, Hunt, and Zorić 2014). The type of policy was identified as one of the main source of variation. Studying the transformation of a grant scheme to a low-interest loan program in the US, Gillich (2013) also found that the former reached more households, while the latter seemed to encourage larger-scale projects. The grant came out as more effective, both in terms of cost-effectiveness and regarding the overall energy savings achieved. The type of buildings targeted can impact the outcome as well. Exploiting another local subsidy program in the US, Liang et al. (2018) measured a 12% energy consumption reduction for commercial buildings and only a 8% one for the residential sector. Their results further indicated that the latter were subject to a rebound effect, with no significant savings for low-income households. Regarding the optimal scale of regulations, Bonifaci and Copiello (2017) further found that programs facilitating partial renovations were sub-optimal, as they were more expensive and did not have a large-enough impact on consumption.

More generally, specific areas of work could have more of an impact than others. In Ireland, Clinch and Healy (2000) found a significant effect of retrofits on consumption, particularly when drought-proofing and roof insulation were undertaken. Insulation proved to be effective to reduce consumption of electricity and gas in New Zealand, while results were mixed for heat pump installation (Grimes et al. 2011). Webber, Gouldson, and Kerr (2015) analyzed the Kirklees Warm Zones program in New-Zealand and found higher effective savings than predicted, despite a significant rebound effect for households. Galvin and Sunikka-Blank (2013) however concluded to the contrary for German households. A more recent randomized-encouragement design conducted by Fowlie, Greenstone, and Wolfram (2018) in the context of the Michigan Weatherization Assistance Program also led to relatively low estimates of energy savings. A 10% to 20% energy consumption reduction was achieved on average, which made up for roughly half the mean cost of retrofits. Similar conclusions were drawn by Blaise and Glachant (2019) regarding French households over the 2010-2013 period. Again, the outcome of these aid schemes seems very dependent on the policy design and local contexts. The lack of consensus on the impact of these policies reinforces the importance of comprehensive *ex-post* evaluations to improve their governance.

Further, a common blind spot of these papers is the lack of control regarding the quality of the retrofits. The structure of the supply side could have a non-negligible impact. It is mainly composed of micro-firms, which tend to be risk-averse and to not have the resources to face the higher bureaucracy cost induced by eco-certifications (Owen, Mitchell, and Andrew Gouldson 2014) - and it is especially the case in France. As these firms are key to both the diffusion of retrofit policies and the actual undertaking of these retrofits, their skill level has to be accounted for. The multiplicity of stakeholders on a renovation project, from the household to the various contractors and potential state institutions involved, does make policy implementation relatively harder in the construction sector (Zhang et al. 2021). In particular, bad advice from contractors, due to a lack of skills or incentives, can deter energy retrofit investments (Risholt and Berker 2013). Fuller (2010) went as far as describing contractors as a "*primary sales force for home energy improvements*"[4], insisting that quality control should be at the heart of any program. Contractors' costs and incentives are yet almost always overlooked, both in economic evaluations and by policymakers. They directly impact the cost-effectiveness of financial schemes: "*Supply side policy can generate additional retrofit activity via an installer recommending a policy measure [...] or in terms of improved training for installers*"[5]. Poor installation and wrong material choices on contractors' part can drastically hinder the performance of a retrofit, as was already pointed out by Goldman (1985) after finding "*systematic variations in the choice of retrofit options – for example, caulking and weatherstripping were installed in almost all low-income homes; energy savings from these measures are likely to be small and are directly related to the quality of workmanship*"[6]. Smaller-scale ethnographic surveys have also highlighted the key role of installers. They were found to be instrumental in convincing households to switch to a heat pump (Wade, Shipworth, and Hitchings 2016), and it has been shown that repeated interactions are needed for individuals to trust their contractors (De Wilde 2019). Firms have also been shown to act as intermediaries facilitating or hindering the adoption of energy-efficient technologies when households plan on simpler refurbishment projects (Decuypere et al. 2022; Zaunbrecher et al. 2021). This aspect has to be addressed in the economic field, and there has not been a proper evaluation of the link between quality labels for firms and energy efficiency policy diffusion thus far.

4. Fuller (2010), p59.
5. Kerr and Winskel (2020),p.7.
6. Goldman (1985), p144.

4.3 Data

4.3.1 Overview

This paper focuses specifically on the role played by high-quality professionals in the outcome of energy-efficiency programs targeting households. In France, households have to hire a RGE contractor to apply for several tax credits and grants, hence financial programs may encourage certifications. Controls include aggregated census information on household, dwelling and climate-related characteristics, which have been found to drive residential energy demand in France (Risch and Salmon 2017). Another contribution of this paper is to examine the impact on energy consumption of both the improvement of existing dwellings and the change in local density due to new builds. The panel dataset contains information the evolution of the number of dwellings and their occupancy status. Theses are important factors to account for, as a number of contributions in urban economics have established that higher-density areas tend to have lower consumption per capita due to agglomeration externalities (P. P. Combes and Gobillon 2015). This can be attributed to the "*urban heat island*" phenomenon: local temperatures are significantly higher in cities than in rural areas, mostly due to a more intense human activity. Urban households may thus have lower needs in terms of heating (Santamouris et al. 2001) but higher air conditioning needs (Wong et al. 2011). Dense city centers are also typically composed of shared living spaces. These dwellings have been proven to be more energy-efficient since they have less exposed walls and as a result require less energy to heat up each square-meter (Madlener and Sunak 2011). Overall, this negative relationship between residential energy demand and population density has been corroborated by surveys in France (Lampin 2013), Québec (Larivière and Lafrance 1999), China (Y. Liu, Song, and Arp 2012; H. Chen, Jia, and Lau 2008), Norway (Holden and Norland 2005) and the USA (Erwing and Rong 2008b).

Administrative data from the French census was combined with income declarations, energy consumption information published by two distributors (ENEDIS and GRDF), and local climate information. Metrics in the final sample are computed based on "*tax households*" units, meaning the groups of tax-paying individuals listed in the same dwelling - this *de facto* excludes collective housing such as hospitals, retirement homes, etc., and homeless individuals. Accessibility to RGE firms was computed using the list of RGE firms provided by the French Agency for the Environment and Energy Management (ADEME). Their addresses were turned into GPS coordinates through the application programming interface of the "*National Address Database*" (BAN) produced by the French National Institute of Statistics and Economic Studies (Insee). The data is restricted to metropolitan France and covers the 2011-2018 period. For clarity, only the year 2018 was used for the cross-section figures displayed in this section. Observations are provided at the "*aggregated unit for statistical information*" (IRIS) [7] level. It is a spatial unit defined by the Insee in order to publish infra-municipal data while protecting anonymity. They can be one of four types :

— Activity IRIS, or A-type IRIS, which gather roughly 1 000 employees and has at least twice more workers than residents.
— Habitat IRIS, or H-type IRIS, the population of which lies between 1 800 and 5 000 inhabitants. The habitat is homogeneous and the borders are based on the main dividers of the urban space (eg. main roads, train tracks, rivers, ...).
— Non-subdivided IRIS, or Z-type IRIS, which are cities that are too small to be subdivided into infra-communal area. Their population has to be under 5 000 inhabitants.
— Miscellaneous IRIS, or D-type IRIS, which are specific zones with few inhabitants, covering large surface areas (eg. leisure parks, harbors, forests, ...).

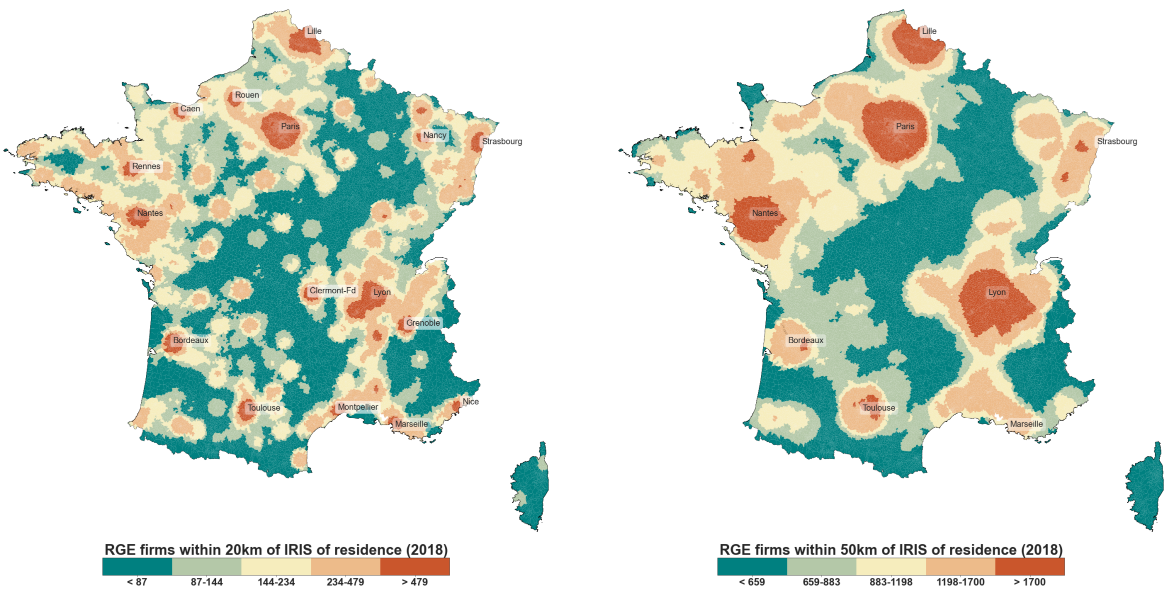
The final dataset regroups 48 619 IRIS-level observations for each year, established following the 2020 update of the mapping, which comprises 820 A-types, 14 428 H-types, 33 049 Z-types and 322 D-types.

4.3.2 RGE Firms

The RGE label was created following previous quality certifications established by professional organizations (CGEDD 2017). The Construction Sector Artisan Federation CAPEB created the "*Eco-artisan*" brand in 2008, while the French Building Federation (FFB) launched the "*Pros de la performance énergétique*" [8] in 2009. Both labels aim to guarantee the quality of the energy efficiency diagnosis to final clients, and relied on auditing of at least one worksite. In 2010, both organizations signed a professional training convention with the French state and other institutional actors to improve construction firms' skills regarding energy-efficiency-specific tasks. The RGE label followed, formally introduced in 2011. The objective was both to strengthen and consolidate preexisting labels, and to set the ground for the cross-compliance of financial aid schemes. The RGE label became regulatory in 2014, following amendments making financial aid conditional on hiring a certified company for three policy initiatives - namely the tax credit, zero-interest eco-loans and white certificates, which will be detailed in the next subsection.

7. "*Ilots Regroupés pour l'Information Statistique*".
8. "*Professionals of energy performance*".

The ADEME historical dataset provides the exhaustive list of RGE firms, with the time period during which they were certified and their precise addresses. GPS coordinates were then interacted with buffer zones around IRIS zones' centroids. Figure 4.3.1 displays the number of RGE firms within a 20km (left) and 50km (right) euclidean distance of each zone's centroid, per quintile. Their spatial distribution is far from homogeneous. The 50-km buffers hint at the existence of four main hubs around the cities of Nantes, Lille, Lyon and Paris. Two smaller hubs appear around Bordeaux and Toulouse in the South-West. At first glance, the presence of RGE firms does not seem to be directly related to city size, as Marseille is the third French city in terms of population and is merely in the fourth quintile in these graphs. The last quintile threshold is 5.5 times higher than the first one's for the 20km buffer, and 2.6 times higher for the 50km buffer. Such disparities in the access to RGE firms is concerning, since several aid schemes for households are conditional on hiring these contractors. The same method was applied to the entire stock of active French firms using the SIRENE database provided by the Insee in order to obtain the total number of firms in each buffer. The share of RGE companies is relatively low everywhere, reaching a maximum of 32.3% in 20km buffers and 26.4% in 50km buffers.



Source: Author's computations from ADEME data.

Note: Data is presented by quintiles from the whole sample. For instance, only 20% of IRIS zones had more than 479 RGE firms within 20km of their centroids in 2018.

Figure 4.3.1 – Access to RGE firms per IRIS

4.3.3 Financial aid schemes

This paper focuses on the five national-scale policies for the retrofit of private housing in France. The smallest spatial aggregation available was used in the regressions. Policies targeting State-owned buildings and social housing were left out. Additional policies may also exist at the department or region level. They usually take the form of a grant or a property tax reduction attributed to owner-occupiers undertaking a renovation. They are excluded from the analysis due to lack of data and was captured by fixed effects. This section aims to clarify the purpose and application of each policy, as well as indicate how the data was retrieved [9].

— White certificates are the most widespread policy in Europe and have been implemented in France since 2006. The general principle is to set energy-saving targets for key economic actors, mainly energy suppliers. They can either achieve the reductions themselves, in particular by financing retrofits, buy certificates from other actors or pay a penalty to the State. National-level spendings were computing using the Emmy database, which is the institution in charge of overlooking the policy.

— The *Agence Nationale de l'Habitat* [10] (ANAH) has delivered financial aid on behalf of the Environment and Economy ministries since 2010. Its specific goal is the elimination of energy poverty, hence the grants are delivered to low-income households only. National and regional-level amounts were compiled from the agency's yearly activity reports (eg. ANAH (2018) for the year 2018). As region borders officially changed in 2015, amounts were projected to keep the previous borders for the 2016-2018 period.

— Zero-interest eco-loans (EPTZ) have been established in 2009. They are monitored by the public financial institution *Caisse des Dépôts et des Obligation* [11], but they are are granted by private banks. Households can borrow up to 30 000€ , depending on the targeted area of work (roof insulation, double glazing, etc.), and the state compensates the banks for the loss of interest profits. National and department-level information were found in the statistical reports produced every quarter by the *Société de Gestion des Financements et de la Garantie de l'Accession Sociale à la propriété* [12] (SGDAS).

9. I would like to thank L. Gouiffes and M. Ledez from the Institute for Climate Economics (I4CE) for their helpful pointers when I was compiling information on public spending.
10. "*National Housing Agency*".
11. "*Deposits and Consignments Fund*".
12. "*Financing Management Company and Social Homeownership Guarantee*".

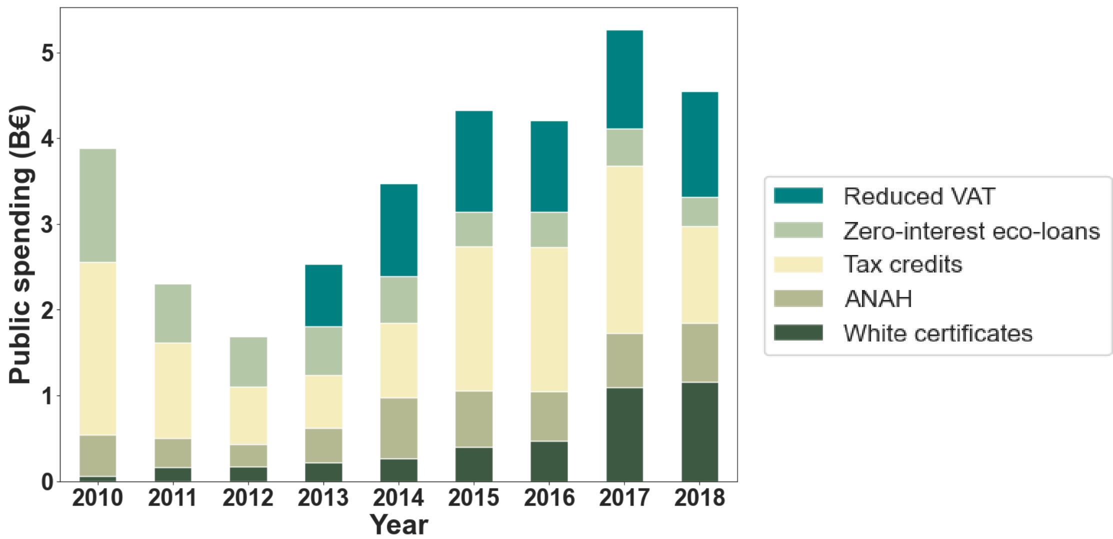
— Tax credits were first introduced in 2005 with the *Crédit d'Impôt Développement Durable*[13] (CIDD). It also relied on a list of areas of work, for which households could get tax deductions as a percentage of their cost. This percentage has varied over the years and depending on the area of work. It became the *Crédit d'Impôt pour la Transition Energétique*[14] (CITE) in 2015, with two major changes. First, the rebate rates were all set at a unique rate of 30%. Second, they dropped the bunch of work requirement. National level amounts were compiled from financial expenses appendices to yearly Finance Acts. For instance, the precise amount received by households in 2018 can be found in the appendix to the 2021 Act (PLF 2021) as the 2019 public spending, since there used to be a one-year fiscal delay in France. Regional-level amounts were deduced using the shares received by each region, found in the official report by the *Inspection Générale des finances* (IGF 2017) for the 2010-2015 period, which were used to get projected shares for the remaining years.

— VAT reduction measures have been implemented since 1999 in order to boost economic activity and employment in the construction sector. The normal VAT rate is set at 20%, and the reduced rate has varied between 5.5% and 10% over the years. A 2013 modification created two different VAT regimes, distinguishing energy retrofit work from the rest of construction activities. Current rates are set at 5.5% and 10% respectively. Given the general nature of the measure prior to 2013, only the spending related to energy retrofit were kept in the main analysis[15]. National level amounts were also compiled from financial expenses annexes to yearly Finance Acts.

Figure 4.3.2 displays the evolution of these policies over time. For simplicity, "*public spending*" refers to the amounts *perceived* by households and firms for each year, not *spent* by the state - or the firms in the case of white certificates, or the banks for the eco-loans. There was a steep overall decrease from 2010 to 2012, mostly driven by the reduction of the amounts spent on tax credits. Overall amounts increased rather steadily afterwards. ANAH grants have not increased significantly, despite efforts to boost demand by loosening the application conditions in 2013, extending to non owner-occupiers and increasing the maximum revenue condition. Investments induced by white certificates were also increasing, which is in line with the higher energy reduction targets set by the state over time. Zero-interest eco-loans represent a decreasing share of the overall amounts, which can in

13. "*Tax Credit to support Sustainable Development*".
14. "*Tax Credit to support the Energy Transition*".
15. See Appendix 4.A for the evolution of public spending related to VAT reduction measures. Given the differences in amounts between the energy-efficiency improving work and general renovation activity, including the policy prior to 2013 appeared mistake-inducing

part be explained by the overall low interest rates offered by commercial banks during that period, which made them less attractive (IGF 2017). Another important factor was the change of regulation regarding the cumulation of aids. Households were not allowed to apply for a tax credit and a loan for the same project after 2011. Cumulation was allowed again in 2012 for low-income households, and in 2016 for all households, but it did not seem to affect the trend. Spending related to reduced VAT has been stable since 2014, and has contributed significantly to the general increase.

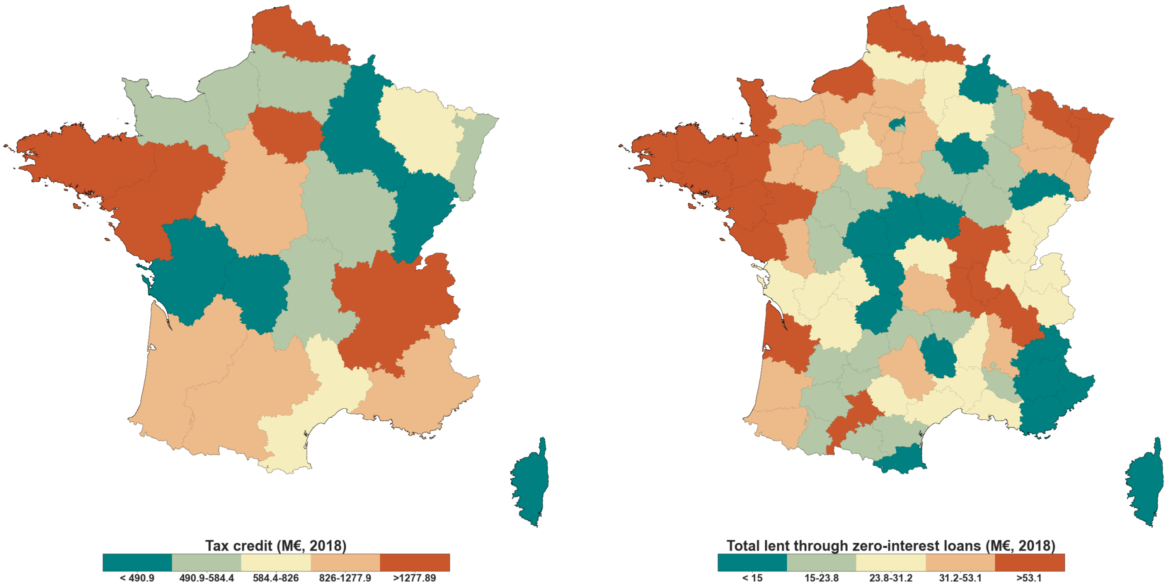


Sources: Author's computations using official documents from various public institutions.

Note: Public spending refers to what households actually received during each given year.

Figure 4.3.2 – Evolution of French public policies since 2010

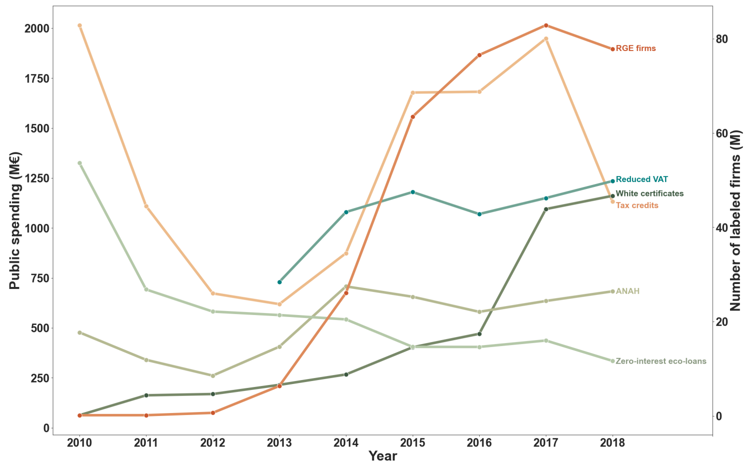
Hiring a RGE contractor has become a condition for households to be able to apply for white certificates, tax credits and zero-interest eco-loans since 2014. The financial aid received locally through the eco-conditional schemes should hence be directly linked to the access to RGE firms. There seems to be a positive correlation between the four main clusters visible on Figure 4.3.1 and tax credit spending at the regional level (Figure 4.3.3, left). The areas around Bordeaux, Toulouse and Strasbourg also seemed to have received more zero-interest loans in in 2018 (Figure 4.3.3, right), which is consistent with the spatial distribution of RGE firms. The number of labeled firms followed a similar overall trend to the total amount of aid distributed through white certificates and tax credits (Figure 4.3.4). ANAH grants and reduced VAT spending seem to follow an independent trend, and the link with zero-interest loans is not clear before 2016.



Sources: Author's computations using official documents from various public institutions.

Note: Public spending refers to what households actually received. Data is presented by quintiles. For instance, in 20% of the departments, households received less than 490.9 M€ overall in 2018.

Figure 4.3.3 – Public spending at the local level



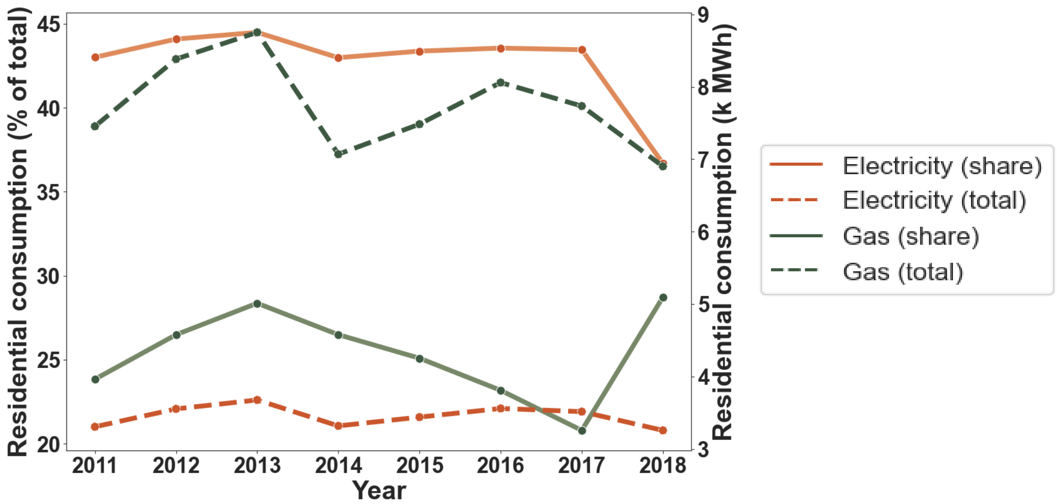
Sources: Author's computations from ADEME data and official documents from various public institutions.

Note: Public spending refers to what households actually received during each given year.

Figure 4.3.4 – Public spending and RGE firms over time

4.3.4 Energy consumption data

Electricity consumption data has been made available at the IRIS level by the firm ENEDIS, which is in charge of the management and the maintenance of 95% of the electricity network in metropolitan France (1 324 045 km of power lines). Following the French data protection laws, areas where there are less than 11 distribution points are systematically anonymized. The main advantage of working with producer data is that, contrary to previous studies, the analysis can be conducted using actual consumption in physical units rather than household expenses, which are less reliable. A few drawbacks should be noted. The annual information is provided using the IRIS mapping that year, which changes every year. As a result, 1 300 IRIS could not be matched because of border modifications over the years and were excluded from the final dataset. Finally, the region of Corsica is missing in the data, and was thus removed from the final sample. The share of the residential sector among total consumption has remained around 40% since 2011, peaking around 45% in 2013 and dropping to 37% in 2018 (Figure 4.3.5).

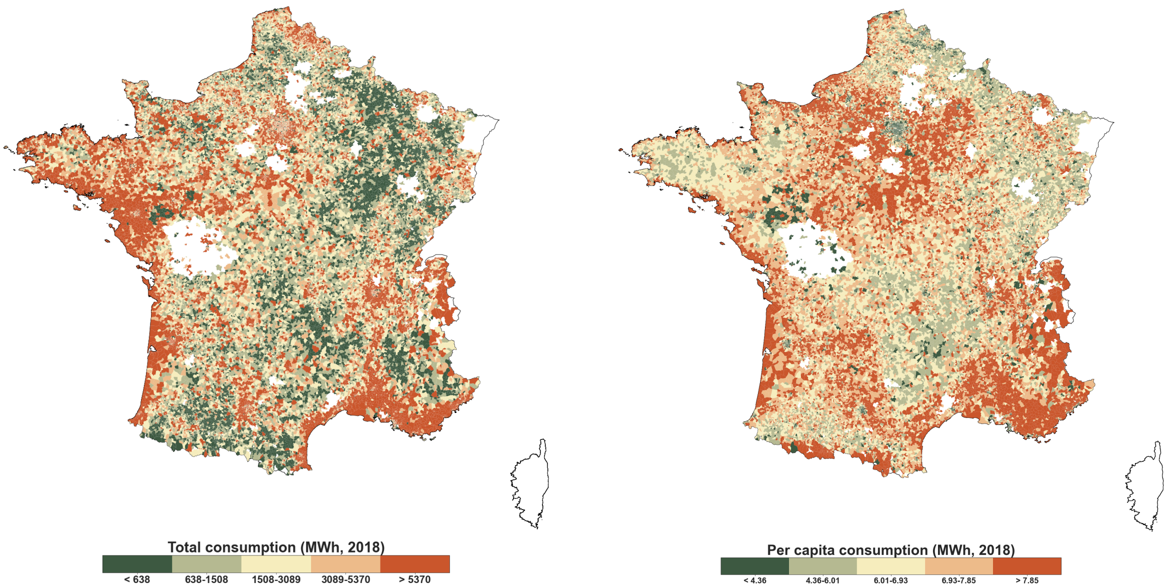


Sources: Author's computations from ENEDIS and GRDF data.

Note: Average shares are derived from IRIS-level consumption data for each year.

Figure 4.3.5 – IRIS-level mean energy consumption

Information on gas consumption has been published by the French company *Gaz Réseau Distribution France* (GRDF). It is the main provider of natural gas in France and in Europe, serving roughly 11 million French households as of 2018. Their distribution network has a length of 200 000 km, serving 9 515 cities and 77% of the population of these cities [16]. There are 30 other distributors in France, serving the remaining households. Gas meters are read every 6 months for "6M" clients, who represent 99% of the total; they are read every month for roughly 100 000 "MM" clients and every day for nearly 3 000 "JJ" clients. The annual consumption is thus computed by summing daily measures for JJ types, and by summing mean daily consumption for MM and 6M types. The sample is restricted to their residential-sector clients, meaning those who consume less than 300 MWh per year and are subject to the T1 and T2 natural gas transmission tariffs set up by the French state. Following legal restrictions on open data, IRIS-level information can be made available only if there are strictly more than 10 distribution points within the IRIS and if the measured consumption is above the "*residential threshold*" of 200 MWh - in practice, 4% of the 23 634 IRIS were removed. Overall, 95.28% of the annual measures made by GRDF are available. The residential sector holds a fairly constant share in total physical gas consumption over time before, peaking at 28% in 2013 and in 2018 (Figure 4.3.5).



Source: Author's computations from ENEDIS data.

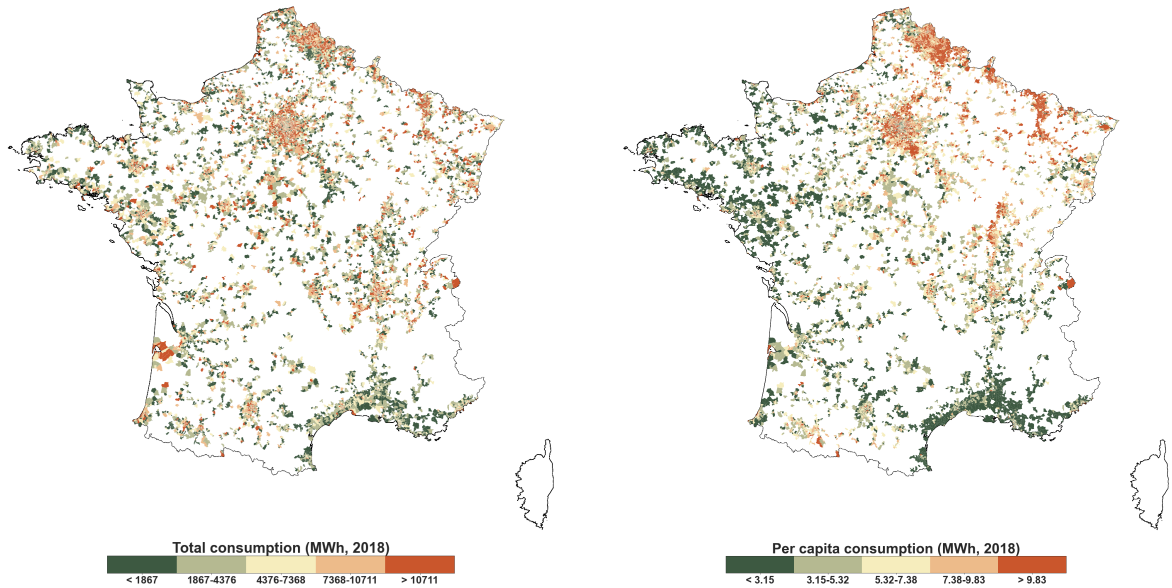
Note: Data is presented by quintiles. For instance, 20% of IRIS zones had a total electricity consumption of less than 638 MWh in 2018.

Figure 4.3.6 – Electricity consumption in physical units in the residential sector

There are clear disparities in electricity consumption in metropolitan France (Figure 4.3.6). At first glance, more energy appears consumed in cities, but the picture changes when

16. See Appendix 4.B for a map of their 2018 network.

looking at per-capita quantities. Focusing for instance on the Paris urban area on these maps, it is in the 5th quintile with respect to overall consumption and falls in the first in terms of per-capita consumption. This can be linked back to aggregation externalities, as urban centers are more densely populated. There is a similar spatial pattern for gas consumption total and mean consumption, but it is less pronounced (Figure 4.3.7). Given these spatial differences in consumption for a given year, controls for local weather and housing densities have to be included.



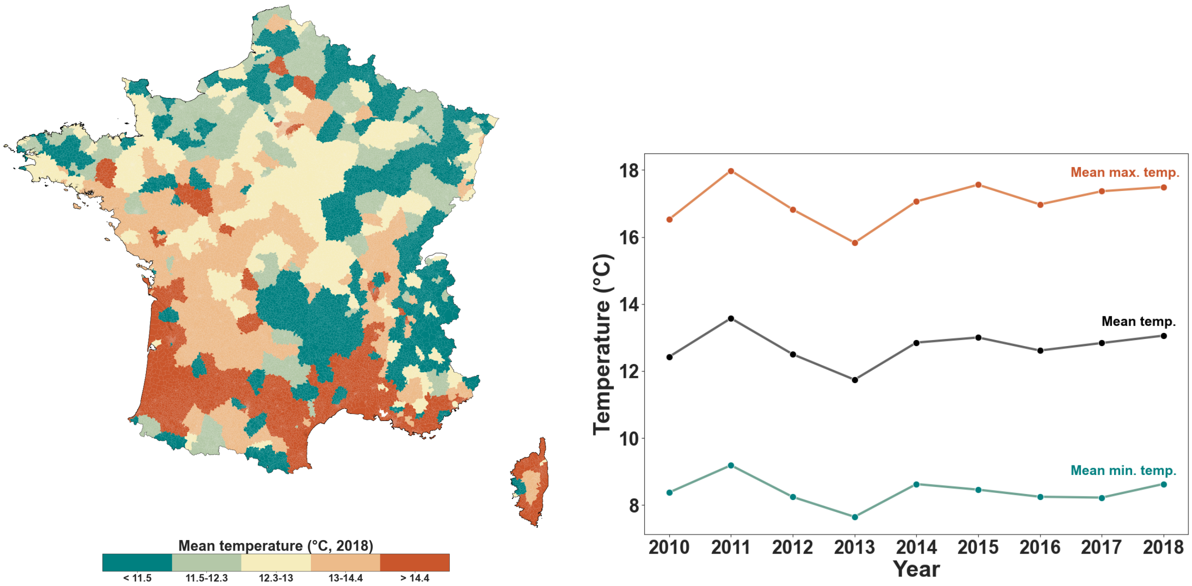
Source: Author's computation from GRDF data.

Note: Data is presented by quintiles. For instance, 20% of IRIS zones had a total gas consumption of less than 1867 MWh in 2018.

Figure 4.3.7 – Gas consumption in physical units in the residential sector

4.3.5 Local weather

Local weather is proxied by average temperatures. For each IRIS, they are equal to the temperatures measured by the nearest weather station. The information was scrapped from the French NGO *Infoclimat*'s website, which hosts monthly records from every station in France. Appendix 4.C provides an overview of stations across the metropolitan territory. Temperatures are higher in the South and along the West coast (Figure 4.3.8, left). Large urban areas, such as Paris or Lille, appear relatively warmer than their surroundings, which is likely due to density effects. Averages are not constant throughout time, with 2013 being an especially cold year (Figure 4.3.8, right). Mean maximal and minimal temperatures refer to daily minimal and maximal recorded temperatures, averaged over the year. They appear to follow similar trends, which is well captured by the overall mean.



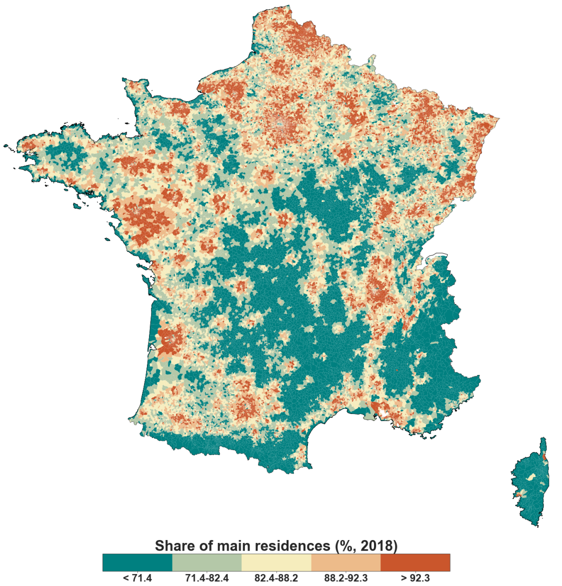
Source: Author"s computations from Infoclimat data.

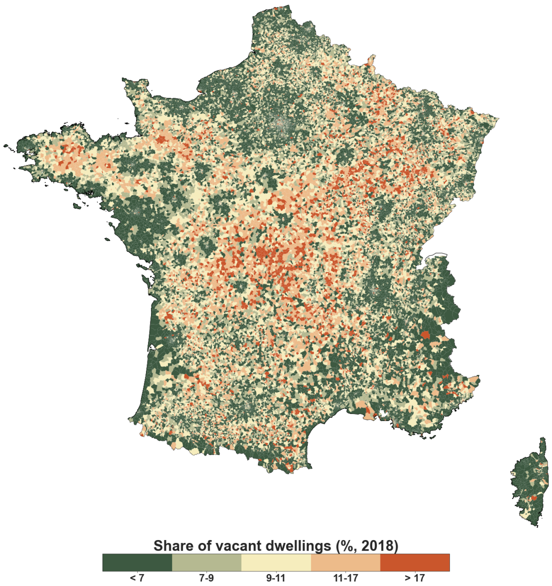
Note: Data is presented by quintiles on the map. For instance, 20% of IRIS zones had a yearly average temperature below 11.5°C in 2018. Yearly averages are derived from weather station-level data on the right-hand side graph.

Figure 4.3.8 – Local temperatures

4.3.6 Insee data on French households

French census data is collected over five-year cycles, which limits year-to-year comparisons. For instance, part of the information contained in the 2012 dataset is exactly the same as the information provided for the year 2011, as some cities would not have been subjected to new data collection. Cities with less than 10 000 residents conduct a full census collection every five year, meaning only a fifth of these cities gather new information during a given year. Cities with more than 10 000 residents conduct a yearly survey among a representative sample of roughly 8% of their inhabitants and housing. The estimations are run on a time span larger than 5 years, which allows for at least one complete collection cycle.





Source: Author's computations from French census data.

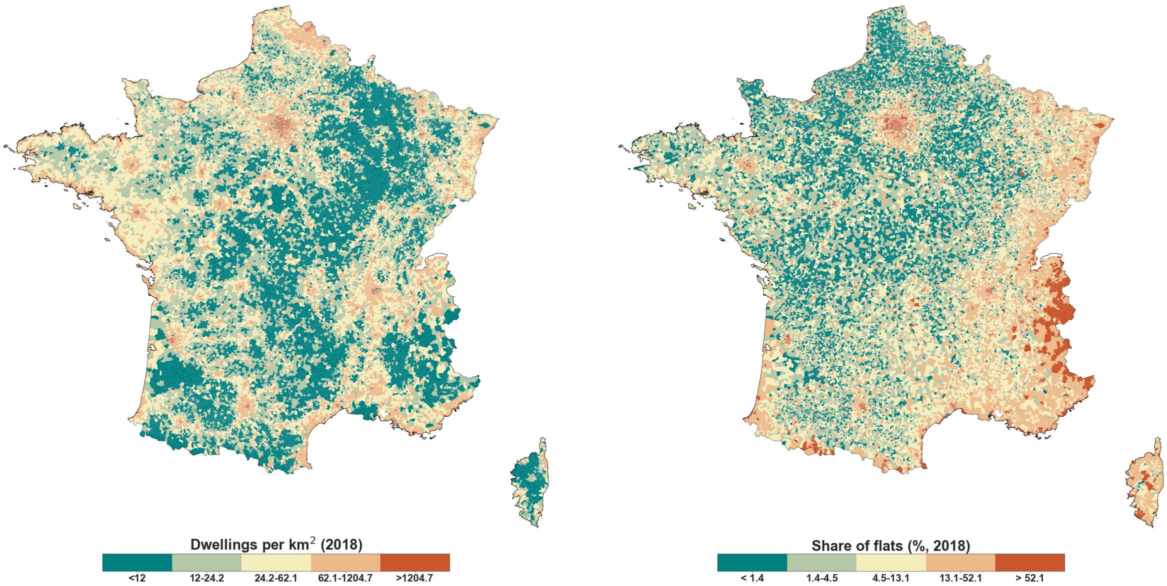
Note: The share of main residences is represented by quintiles on the map: for instance, the share of main residences was below 71.4% in 20% of IRIS zones in 2018. For clarity, because the share of vacant dwellings is rather low everywhere in France, the categories used here are not quintiles but follow the typology used in reports from public institutions (eg. Trésor 2020).

Figure 4.3.9 – Dwelling usage

As the data is aggregated, it is crucial to control for the share of dwellings that are actually inhabited. As displayed in Figure 4.3.9 (left), most areas contain mostly main residences. There are relatively more secondary residences along coastal areas and in the South, while cities are clearly defined by the highest shares of main residences. Vacant dwellings [17] are also quite rare (Figure 4.3.9, right), except in the center regions, which are more rural and less populated. It appears correlated to large differences in dwelling densities (Figure 4.3.10, right). Gaps are especially large between the two top quantiles and the rest, with city centers having up to 100 times the number of dwellings per square kilometer found in rural areas. Dwelling types are also accounted for. The French societal standard is the individual house, which is known to not be the most energy-efficient dwelling. More than 50% of dwellings are individual houses in the vast majority of France, except in the Paris urban area and in eastern regions. Shared housing is only the norm in dense city centers (Figure 4.3.10, left), keeping in mind that less than 20% of IRIS zones have a majority of flats. This is

17. Vacant dwellings refer to unfurnished dwellings that were never used during the reference fiscal year, while secondary residences are occupied for at least a few days annually.

consistent with the fact that dwellings are on average smaller for a given household size in denser areas.

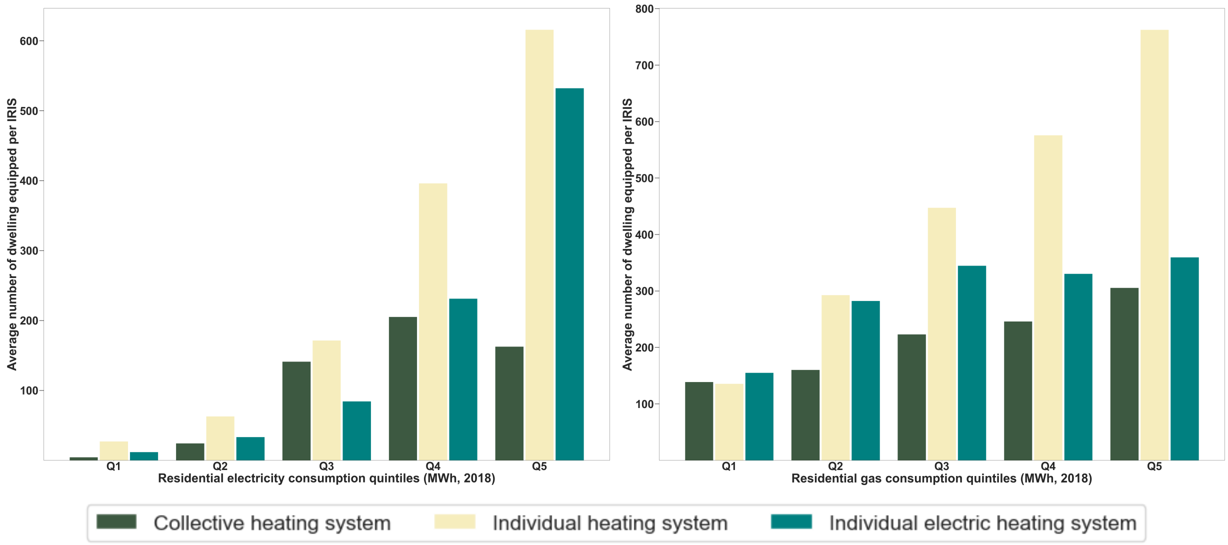


Source: Author's computations from French census data.

Note: Data is presented by quintiles. For instance, the density of dwellings was above 1204.7 units per km^2 in 20% of IRIS zones in 2018.

Figure 4.3.10 – Dwelling distribution

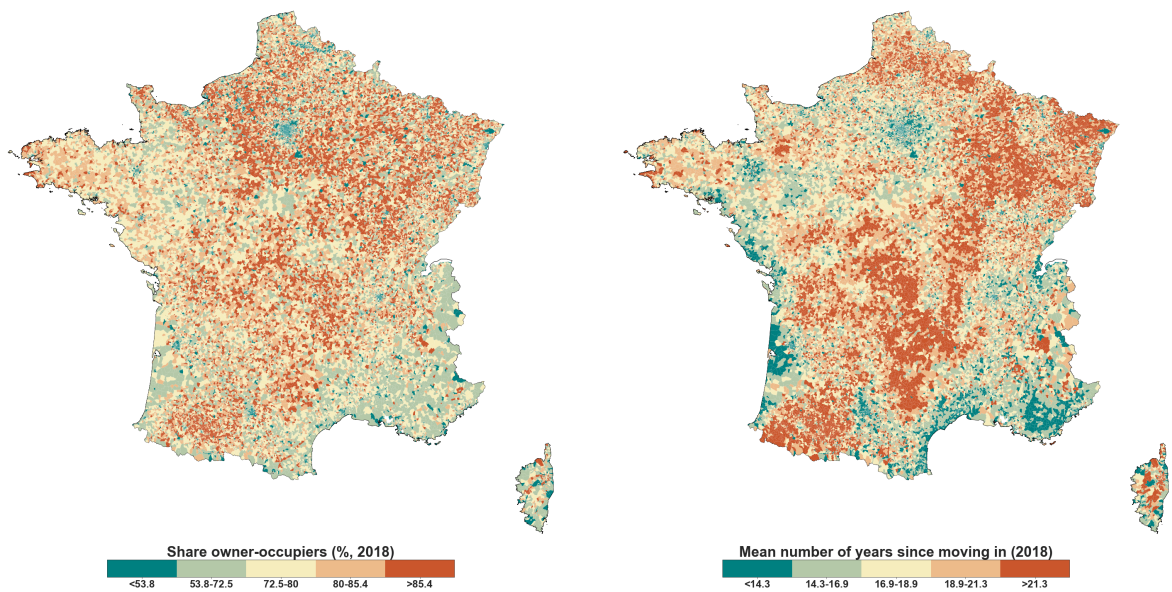
Collective heating infrastructures are also mostly found in cities. As expected, there are more dwellings equipped with electric heating systems in areas belonging to higher electricity consumption quintiles (Figure 4.3.11, left), while there is no significant difference in the last three gas consumption quintiles (Figure 4.3.11, right). There are also relatively more dwellings equipped with individual heating systems in high-consumption areas.Census data provides further information on households characteristics. The majority of residents are owner-occupiers in 80% of IRIS areas (Figure 4.3.12, left). The share of owner-occupiers in main residences is significantly smaller in the Paris urban area and in the South-East, which is in line with higher property prices. The number of years since moving in is expectedly lower in these areas (Figure 4.3.12, left). The turnover is lower in rural areas, where ownership is more accessible. Mobility remains rather low overall, as the bottom quintile threshold was set at 14 years in 2018. Other household characteristics used in the controls include household size, local age structure, mean square meters per dwellings, local unemployment rate, etc.



Sources: Author's computations from ENEDIS, GRDF and French census data.

Note: Quintiles are derived from the whole sample of IRIS-level observations.

Figure 4.3.11 – Energy consumption and heating systems

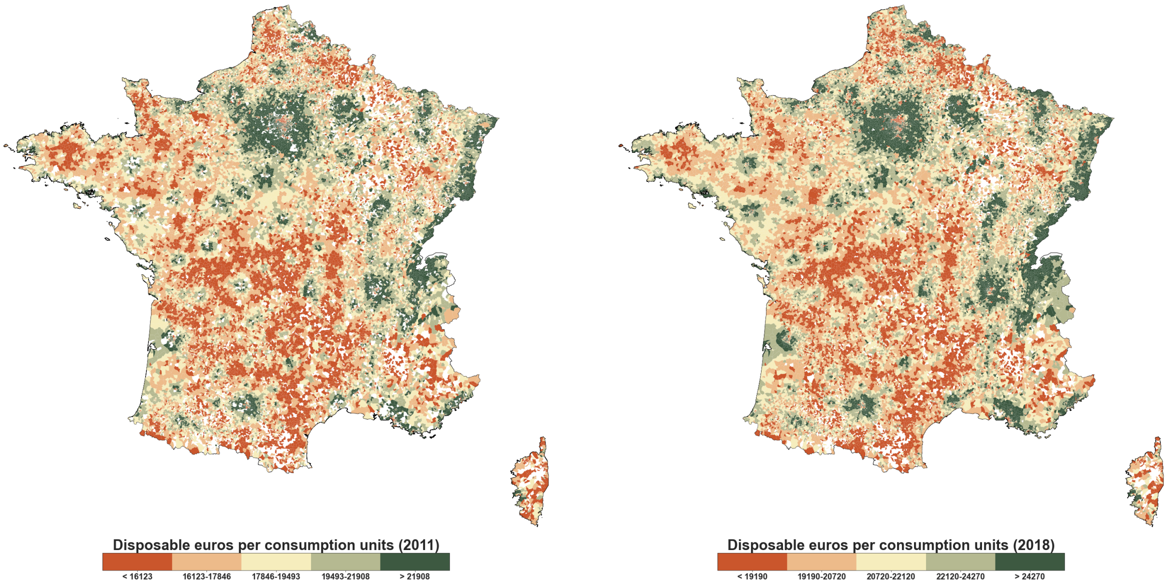


Source: Author's computations from French census data.

Note: Data is presented by quintiles. For instance, the share of owner-occupiers was below 53.8% in 20% of IRIS zones in 2018.

Figure 4.3.12 – Main residences

Information on income is not directly available from the census, but found in the "*Fichier Localisé Social et Fiscal*" (Filosofi) [18] database. It is also produced by the Insee and gathers several indicators measuring living standards, fiscal incomes and post-tax disposable revenues at different geographic levels. It is derived from the annual "*Enquête Revenus Fiscaux et Sociaux*" (ERFS) [19], and replaced the "*Revenus Fiscaux Localisés*" (RFL) [20] module in 2012. The RFL survey provides income information for the years 2010 and 2011, but it is less exhaustive. Contrary to previous studies, income is not self-declared by households, but derived from their tax forms, which is both more precise and more reliable.



Sources: Author's computations from RFLM and Filosofi data.

Note: Data is presented by quintiles. For instance, median living standards were below 16 123 €/CU in 20% of IRIS zones in 2011, while that threshold rose to 19 190 €/CU in 2018.

Figure 4.3.13 – Median living standards

Median living standards were used to control for households' purchasing power. They are computed by the Insee as a household's disposable income divided by the number of consumption units (CU), and are equal for all household members. Consumption units are computed following a modified OECD scale: the first adult represents 1 unit, every person older than 14 counts as 0.5 unit and every child under 14 counts as 0.3 unit.

18. "*Localized disposable income system*".
19. "*Tax and social income survey*".
20. "*Localised tax revenues*".

Median living standards are the indicator that was available for the most amount of IRIS zones, and they have the advantage of not being distorted by extreme revenues, contrary to the mean. There are significant spatial disparities, but the evolution over time is not drastic (Figure 4.3.13). Cities are again clearly identifiable, with an interesting and somewhat surprising distribution: the very center of urban areas seems to be characterized by low living standards, and they increase in the greater periphery.

4.4 Estimation results

4.4.1 Estimation procedure and endogeneity issues

Variable	Mean	Standard deviation	Max	Min
Elec. consumption (total)	50416.43	3451.87	0.00	3268.13
Elec. consumption (per capita)	436.58	6.41	0.00	2.74
Gas consumption (total)	408770.12	7730.36	0.00	6122.00
Gas consumption (per capita)	152459.45	13.43	0.00	587.37
RGE firms (20 KM)	3932.00	240.70	0.00	570.53
Construction firms (20 KM)	128625.00	9054.72	10.00	23932.70
Eco loan	26.92	8.76	0.00	4.95
ANAH	22.46	9.06	2.90	4.12
Tax credits	43.43	19.57	0.00	8.76
Reduced VAT	79.91	59.47	46.53	12.19
White certificates	17.91	7.65	2.58	5.86
Average temperature (°C)	24.20	12.13	-6.76	2.38
Dwellings	29584.48	698.90	0.00	754.48
Sh. main residences (%)	100.00	81.21	0.00	15.09
Sh. owner-occupiers (%)	100.00	69.36	0.00	20.94
Sh. flats (%)	100.00	23.95	0.00	31.60
Sh. coll. heating (%)	100.00	10.11	0.00	20.26
Sh. elec. heating (%)	100.00	24.67	0.00	14.42
Sh. families (%)	100.00	42.29	0.00	11.10
Med. living std. (€ /CU)	67153.00	20675.60	2124.00	4244.66
Unemployment rate (%)	100.00	12.05	0.00	6.68

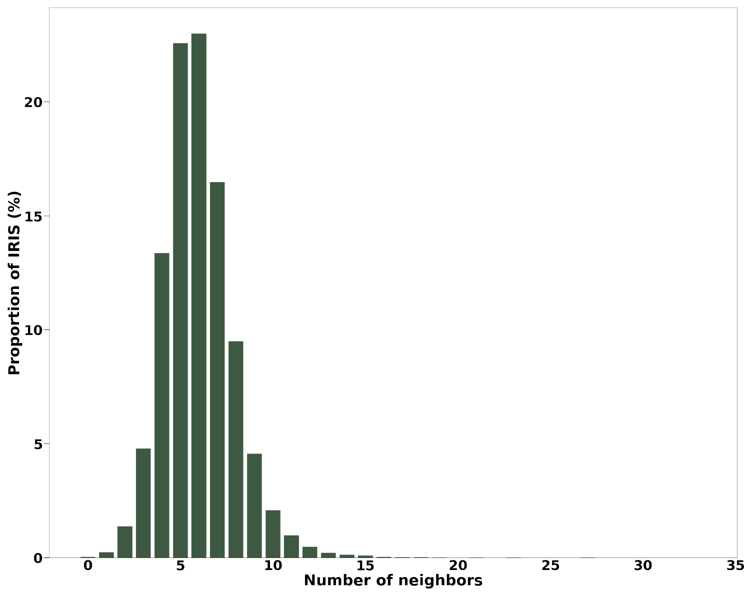
Values are computed on the entire panel.

Table 4.4.1 – Summary statistics

This section presents and discusses several regression results to identify the impact each policy had on firms' labeling decisions and households' energy consumption over time. Table 4.4.1 displays summary statistics for the total sample, with public spending expressed in euros per capita and energy consumption given in megawatts per hour (MWh). Estimations are run using the random effect spatial error model developed by Kapoor, Kelejian, and Prucha (2007). The main assumptions are that unobserved heterogeneity is uncorrelated to the independent variables. The non constant part of the error term is modeled following a normal distribution. Contrary to other specifications, the KPP estimator allows for a spatial diffusion effect in both the idiosyncratic part of the error term and the individual effect. In other words, observations can be correlated both spatially and time-wise. The KPP approach to spatial dependence for each period takes after Cliff and Ord (1981), which they extended to a panel specification. Formally, denoting the spatial autoregressive parameter λ, the $(n \times 1)$ outcome vector y_t and the $(n \times k)$ independent variable matrix x_t for each time period t:

$$\begin{cases} y_{it} = x_{it}\beta + \alpha + u_{it} \\ u_{it} = \lambda \sum_{j \neq i} \omega_{ij} u_{jt} + v_{it} \\ v_{it} = \alpha_i + \epsilon_{it} \qquad \text{where:} \quad \epsilon_{it} \overset{i.i.d.}{\sim} \mathcal{N}\left(0, \sigma^2\right) \end{cases} \tag{4.4.1}$$

The weight matrix ω was computed using queen continuity, meaning two IRIS zones were considered to be neighbors if their borders shared a common edge. Each zone had 6 neighbors on average and 15 IRIS were "islands" in the statistical sense, which means that they did not have any neighbor (Figure 4.4.1).



Source: Author's computations from Insee data.

Note: Queen continuity was used to match neighbors on the whole sample.

Figure 4.4.1 – Distribution of IRIS zones per number of neighbors

The parameters were estimated through a generalized method of moments (GMM) procedure. As the presence of RGE firms may be affected by public policies, they were instrumented by the overall number of construction firms in the same buffer. The rationale behind this instrument is that the number of firms does not impact residential energy consumption directly, but skilled firms may choose to get the label to differentiate themselves from their competitors, meeting the exclusion restriction. First stage results will assess the stenght of the instrument, as well as the impact each policy had on the the number of RGE firms. Second-stage results will review their impact on energy consumption. Policy spendings are expressed in euros per capita, energy consumption is measured in megawatt per hour (MWh) and the number of observations are given per year. The intercept was included in the regressions but is not displayed in the tables. The regression results presented in this section only account for the 2014-2018 period, meaning after the eco-conditionality law, but estimations run on the entire period can be found in the appendix.

4.4.2 First stage : RGE firms

Table 4.4.2 presents regression results for the first stage regressions, each column corresponding to a different buffer size. Regressions run on the reduced time-period are overall a better fit (see Appendix 4.D for estimation results run on the 2011-2018 period), which suggests that the eco-conditionality law had the escompted effect. Further, the pseudo-R^2 increases up to the 20km buffer and decreases for larger buffers, hence this 20km buffer was used in second-stage regressions. The instrument performed well, since the number of construction firms in the same buffer had a significantly positive effect on the number of RGE firms in all specifications. This is consistent with labels being a strategic choice for firms, allowing them to stand out in competitive markets, using the RGE certification as to signal quality workmanship to households.

Further, there is clear link between policy spending and RGE diffusion, which supports the need for an instrument. Focusing on the 20 km buffer, all policies have a positive effect on the number of RGE firms, except spending related to the reduced VAT measure. This further supports the idea that getting the label is a strategic choice for firms, as the only type of aid non-labelled firms can benefit from is reduced VAT. Firms may strategically choose to either get the costly RGE label, or differentiate themselves by selling at a lower price using the reduced VAT rate. There are also signs of heterogeneity between aid schemes. For instance, at the regional level, one euro spent per capita on ANAH spending seems to have generated double the number of RGE firms than one euro spent on tax credits. Using IRIS zones'

	Number of RGE firms										
	Within IRIS	5KM buffer	10KM buffer	15KM buffer	20KM buffer	25KM buffer	30KM buffer	35KM buffer	40KM buffer	45KM buffer	50KM buffer
Eco loan	-0.0302***	0.6723***	2.5586***	4.9538***	6.3035***	8.9975***	10.2691***	11.0386***	11.7316***	12.1674***	12.0171***
	(0.0014)	(0.0452)	(0.1191)	(0.181)	(0.2313)	(0.3279)	(0.3849)	(0.4342)	(0.4789)	(0.5189)	(0.5571)
ANAH	0.0042**	1.4855***	4.1803***	6.2786***	6.8401***	17.1678***	20.2138***	22.3271***	23.7522***	24.3388***	23.8544***
	(0.0018)	(0.0492)	(0.1253)	(0.1862)	(0.2363)	(0.3931)	(0.4612)	(0.5202)	(0.5737)	(0.6214)	(0.667)
Tax credits	0.0333***	0.3414***	0.6189***	1.8298***	3.4941***	-18.7464***	-21.6286***	-23.391***	-24.2714***	-24.485***	-23.7398***
	(0.0004)	(0.0213)	(0.0623)	(0.1028)	(0.138)	(0.2085)	(0.2438)	(0.2742)	(0.302)	(0.3273)	(0.3517)
White Certificates	0.0377***	1.9576***	6.0752***	11.021***	16.2678***	15.031***	18.8439***	22.746***	26.8669***	31.1498***	35.3024***
	(0.0005)	(0.0283)	(0.0896)	(0.1594)	(0.2259)	(0.4983)	(0.5723)	(0.6345)	(0.6966)	(0.7594)	(0.8218)
Reduced VAT	-0.0412***	-2.803***	-9.1181***	-15.9518***	-22.5296***	-51.6915***	-62.8887***	-72.7888***	-82.1687***	-91.3988***	-99.6065***
	(0.0011)	(0.0648)	(0.2052)	(0.3645)	(0.5157)	(1.1151)	(1.2808)	(1.4198)	(1.5586)	(1.6987)	(1.8378)
Construction firms	0.0229***	0.0139***	0.0185***	0.022***	0.0242***	0.1169***	0.1224***	0.1265***	0.1298***	0.1326***	0.135***
	(0.0003)	(0.00005)	(0.00004)	(0.00004)	(0.00004)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Average temperature	-0.0043***	0.724***	1.7314***	2.2642***	2.0439***	0.9112***	0.8393***	0.6245***	0.3566	-0.0909	-0.4531*
	(0.0014)	(0.0331)	(0.0887)	(0.1454)	(0.1965)	(0.1496)	(0.1757)	(0.1982)	(0.2185)	(0.2364)	(0.2536)
Households	0.0019***	0.0159***	0.0338***	0.043***	0.0422***	0.0782***	0.0882***	0.1075***	0.1218***	0.1386***	0.1626***
	(0.00004)	(0.0006)	(0.0014)	(0.0019)	(0.0023)	(0.0135)	(0.0158)	(0.0178)	(0.0197)	(0.0213)	(0.0229)
Dwellings	0.0001***	-0.0082***	-0.0173***	-0.0188***	-0.0159***	-0.0292**	-0.0463***	-0.0714***	-0.091***	-0.1122***	-0.1371***
	(0.00003)	(0.0004)	(0.001)	(0.0013)	(0.0016)	(0.0114)	(0.0134)	(0.0151)	(0.0166)	(0.018)	(0.0193)
Med. living std. (log)	-0.0725*	16.0329***	59.6925***	100.1244***	119.8548***	-78.8409***	-88.8411***	-122.5602***	-138.0256***	-148.3644***	-144.3522***
	(0.0425)	(0.7827)	(1.9038)	(2.7152)	(3.372)	(7.2478)	(8.5092)	(9.5991)	(10.5835)	(11.4557)	(12.2867)
Sh. vacant dwellings	0.0136***	-0.3794***	-1.4884***	-2.4581***	-2.8273***	-1.0405***	-0.8068***	-0.5325**	-0.218	-0.0394	0.1372
	(0.0013)	(0.0244)	(0.0607)	(0.0891)	(0.1122)	(0.1842)	(0.2163)	(0.244)	(0.269)	(0.2912)	(0.3123)
Sh. main residences	0.0026***	0.2802***	0.7722***	1.2083***	1.7119***	-2.224***	-2.1494***	-2.0796***	-1.8048***	-1.5974***	-1.426***
	(0.0007)	(0.0119)	(0.0281)	(0.0391)	(0.0479)	(0.2239)	(0.2629)	(0.2966)	(0.3271)	(0.354)	(0.3797)
Sh. owner-occupiers	-0.002***	0.0228*	0.1436***	-0.0641	-0.3457***	-0.0306	0.0508	0.0807	0.1106	0.1703	0.2149
	(0.0007)	(0.0123)	(0.0299)	(0.0428)	(0.0532)	(0.1094)	(0.1284)	(0.1449)	(0.1597)	(0.1729)	(0.1854)
Sh. flats	-0.0275***	0.7286***	1.3592***	1.3743***	1.1969***	0.714***	0.6553***	0.5032***	0.329*	0.2998	0.3886*
	(0.0005)	(0.0086)	(0.0206)	(0.029)	(0.0359)	(0.1289)	(0.1514)	(0.1708)	(0.1884)	(0.204)	(0.2188)
λ	0.152772	0.689531	0.733698	0.744395	0.747073	0.935319	0.933439	0.931914	0.93153	0.932138	0.932898
Observations	40727	40727	40727	40727	40727	40727	40727	40727	40727	40727	40727
Pseudo R-squ.	0.35496	0.779207	0.833786	0.863236	0.875198	0.842041	0.837298	0.827892	0.815308	0.800136	0.782634

Standard errors in parentheses.

$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4.4.2 – RGE firms : estimations results for years 2014-2018

average population in 2018, it means that increasing ANAH grant spending by 1 334 € in an IRIS led to the certification of 7 more firms within 20km, against 3 if the same amount was spent in tax credits. This difference holds even when considering variations in amounts perceived by households through each policy. The average ANAH grant was 8 101 € per dwelling in 2018 (ANAH 2018), meaning that retrofitting one dwelling in an IRIS area induced on average 42 new certifications within 20 km. The average tax rebate obtained in 2018 was 1 242 €, hence one retrofit in an IRIS would lead to almost 3 new certifications.

IRIS zones' characteristics also affected the presence of RGE contractors. The number of dwellings has a negative effect on all dependent variables for buffers larger than the IRIS itself. This is consistent with the idea that a larger potential market decreases the need to get the certification. Turning to household characteristics, log median standards of living and the share of main residences seem to drive the implantation of RGE firms. This may reflect a higher willingness to pay, as hiring RGE contractors is usually more expensive. The share of flats has a positive impact, while the share of owner-occupiers seems to affect the number of RGE firms negatively. These results may indicate that RGE firms are primarily located in city centers.

ù Overall, these first stage results not only support the instrumental strategy, but also suggest that aid schemes have a heterogeneous impact on RGE certifications. Heterogeneous access to RGE companies seems to have led to inequalities in policy attributions across the territory. Obtaining the certification is currently up to the companies, which make strategic decisions based on their local market conditions. From the firms' perspective, there seems to be an arbitrage between getting the certification and resorting to reduced VAT rates. ANAH grants, eco-loans and white certificates also seem to have a larger effect on certifications than tax credits. These findings call for a better monitoring of the diffusion of the label, as a lack of RGE firms could seriously hinder the effectiveness of the policies in some areas.

4.4.3 Second stage: energy consumption

Tables 4.4.3 and 4.4.4 display coefficients from the regressions on residential electricity and gas log-consumption respectively, run on the 2014-2018 period. Coefficients from estimations run on the 2011-2018 period can be found in Appendix 4.E. Again, regressions run on the reduced time period have better overall fit, suggesting the eco-conditionality law did increase retrofit quality and efficiency. Specifications (1) and (2) are included as baselines, since they respectively do not include RGE firms, and do not treat endogeneity. Focusing first on electricity, the pseudo R-squared is higher for per-capita consumption than for total consumption within the IRIS. All policies have a significantly negative impact on per capita consumption, except tax credits. At the national level, the effect of reduced VAT spending is on average larger in magnitude than white certificate spending - similar results hold for total consumption. These policies do seem to be efficient to decrease energy consumption, even if their cost-effectiveness is heterogeneous.

	Consumption per capita (log)			Total consumption (log)		
	(1)	(2)	(3)	(1)	(2)	(3)
Eco loan	-0.0035***	-0.0036***	-0.0035***	-0.0034***	-0.0034***	-0.0033***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
ANAH	-0.0042***	-0.0041***	-0.0042***	-0.0044***	-0.0042***	-0.0043***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Tax credits	0.0009***	0.0009***	0.0009***	0.001***	0.001***	0.001***
	(0.00004)	(0.00004)	(0.00004)	(0.00004)	(0.00004)	(0.00004)
Reduced VAT	-0.0026***	-0.0028***	-0.0033***	-0.0032***	-0.0033***	-0.0035***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
White certificates	-0.0017***	-0.0016***	-0.0012***	-0.0005***	-0.0004***	-0.0003***
	(0.00005)	(0.00005)	(0.00005)	(0.00005)	(0.00005)	(0.0001)
Average temperature	0.0005***	0.0005***	0.0006***	0.0004***	0.0004***	0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Dwellings	-0.0001***	-0.0001***	-0.0001***	0.0006***	0.0006***	0.0006***
	(0.000001)	(0.000001)	(0.000001)	(0.000002)	(0.000002)	(0.000002)
Sh. main residences	-0.0079***	-0.0079***	-0.0078***	0.0093***	0.0092***	0.0093***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Sh. owner-occupiers	0.0024***	0.0024***	0.0024***	-0.000009	-0.00001	-0.00001
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Sh. flats	-0.0056***	-0.0056***	-0.0053***	0.0019***	0.0019***	0.002***
	(0.00006)	(0.00005)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Sh. elec. heating	0.0064***	0.0065***	0.0065***	0.005***	0.005***	0.005***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Sh. coll. heating	-0.0007***	-0.0006***	-0.0005***	-0.0001	-0.0001	-0.0001
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Sh. families	0.0018***	0.0019***	0.002***	0.0004***	0.0004***	0.0004***
	(0.00005)	(0.00005)	(0.00005)	(0.0001)	(0.0001)	(0.0001)
Med. living std. (log)	0.2604***	0.2659***	0.2806***	0.2026***	0.2041***	0.2067***
	(0.0044)	(0.0044)	(0.0044)	(0.006)	(0.006)	(0.0061)
Unemployment rate	-0.0011***	-0.0012***	-0.0013***	-0.0002*	-0.0002*	-0.0002**
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
RGE firms		-0.000005***	-0.00003***		-0.000004***	-0.00002***
		(0.0000007)	(0.000002)		(0.0000007)	(0.000003)
λ	0.005803	0.157132	0.125519	0.007584	0.139615	0.13802
2SLS		No	Yes		No	Yes
Observations	36303	36303	36303	36303	36303	36303
Pseudo R-squ.	0.780358	0.782815	0.783327	0.694378	0.694332	0.694803

Standard errors in parentheses. "RGE" refers to RGE firms within 20km of the IRIS of residence.
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4.4.3 – Residential electricity consumption (2014-2018)

The positive coefficient associated with tax credits does however raise concern. This echoes criticism made towards this policy, as rebates are obtained through a declarative form, and very few audits have been undertaken. Another drawback of grants is that as the perceived cost of the renovation diminishes for the household, they may become less attentive to the contractor they hire or to the overall renovation process. This is typically not a problem in the case of loans, which rely on their own funds, and could explain the differences in signs. The design of this tax credit also favored partial renovations, which have raised questions regarding their efficiency. Turning to control variables, the impact of the total number of dwellings and the share of main residences is positive on total consumption but negative on per-capita consumption, which is consistent with the literature on density effects, as individual heating needs are lower in denser areas. This result is also consistent with the positive coefficient associated with the share of flats, as they are mostly found in city centers. The shares of owner-occupiers, electric heating and families are increasing energy consumption, conforming with the literature on energy demand. Income indicators are also in line with previous papers, as energy is a normal good and demand should increase with revenue.

Results are somewhat different for gas consumption (Table 4.4.4). The pseudo R^2 is much lower than for electricity consumption. One should keep in mind that gas is not accessible everywhere, hence there might be a selection bias. It is mostly available in urban areas (Appendix 4.B), where dwellings are typically older. Contrary to electricity, not all households in an IRIS may choose to use gas, which may also be an issue. As 39% of households have a primary heating system requiring gas, it is however important to consider how policies affect gas consumption.(Grandclément et al. 2018). The coefficients associated to tax credits remain significantly positive in all specifications, as well as eco-loans. Coefficients associated with controls also remain in line with previous results on energy demand and density effects. White certificates, reduced VAT and ANAH grants have the most consistent negative effects on consumption throughout all specifications. The ANAH's target is substandard housing, hence it is not surprising that there is a significant impact. Those dwellings are so unfit that any improvement would provoke a drastic change in their energy efficiency. In the case of reduced VAT, it could be explained by the fact that the eligible type of renovations have a more substantial impact on energy consumption than the ones suitable for eco-loans and tax credits. Namely, only boiler replacement, wall insulation and the installation of sustainable energy production technologies qualify for the reduced TVA rate. These measures are known to produce much more noticeable changes to a dwelling's energy efficiency than double glazing or swapping out lights.

	Consumption per capita (log)			Total consumption (log)		
	(1)	(2)	(3)	(1)	(2)	(3)
Eco loan	0.006***	0.006***	0.0061***	0.0076***	0.0076***	0.0076***
	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)
ANAH	-0.0024***	-0.0024***	-0.0025***	-0.0032***	-0.003***	-0.0033***
	(0.0007)	(0.0008)	(0.0007)	(0.0008)	(0.0008)	(0.0007)
Tax credits	0.0086***	0.0086***	0.0086***	0.0087***	0.0087***	0.0086***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Reduced VAT	-0.0081***	-0.0081***	-0.0074***	-0.0083***	-0.0084***	-0.0076***
	(0.0004)	(0.0004)	(0.0004)	(0.0003)	(0.0004)	(0.0004)
White certificates	-0.0085***	-0.0085***	-0.009***	-0.008***	-0.0079***	-0.0084***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Average temperature	-0.0052***	-0.0052***	-0.0054***	-0.0045***	-0.0045***	-0.0048***
	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0005)
Dwellings	-0.0001***	-0.0001***	-0.0001***	0.0006***	0.0006***	0.0006***
	(0.000006)	(0.000006)	(0.000006)	(0.000006)	(0.000006)	(0.000006)
Sh. main residences	-0.0042***	-0.0042***	-0.0044***	0.013***	0.0131***	0.0129***
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)
Sh. owner-occupiers	-0.0005**	-0.0005**	-0.0005*	-0.001***	-0.001***	-0.001***
	(0.0002)	(0.0002)	(0.0002)	(0.0003)	(0.0003)	(0.0003)
Sh. flats	0.0057***	0.0057***	0.0054***	0.0081***	0.0082***	0.0078***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Sh. elec. heating	-0.0128***	-0.0128***	-0.0128***	-0.01***	-0.01***	-0.01***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Sh. coll. heating	-0.011***	-0.011***	-0.0111***	-0.0096***	-0.0096***	-0.0097***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Sh. families	-0.0012***	-0.0012***	-0.0014***	-0.0021***	-0.0021***	-0.0022***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Med. living std. (log)	0.5674***	0.5681***	0.539***	0.5355***	0.5392***	0.5072***
	(0.0183)	(0.0184)	(0.019)	(0.0195)	(0.0196)	(0.0202)
Unemployment rate	0.0008*	0.0008*	0.0009**	0.0006	0.0006	0.0007
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)
RGE firms		-0.0000005***	0.00003***		-0.000002	0.00003***
		(0.000002)	(0.000005)		0.000002)	(0.000006)
λ	0.045641	0.147145	0.139403	0.045846	0.129728	0.116159
2SLS		No	Yes		No	Yes
Observations	18577	18577	18577	18577	18577	18577
Pseudo R-squ.	0.257211	0.257192	0.262431	0.450066	0.450159	0.452863

Standard errors in parentheses. "RGE" refers to RGE firms within 20km of the IRIS of residence.
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4.4.4 – Residential gas consumption (2014-2018)

Table 4.4.5 provides an estimation of the energy savings induced by an increase of policy spending of 1000€ per capita - which corresponds to a 1.3 million€ increase at the IRIS level given their average population. These figures should be interpreted with caution, as the estimates are based on aggregate and imperfect data. In particular, the coefficients presented in tables 4.4.3 and 4.4.4 are the results of estimations run on different samples. They do however illustrate the differences between each policy: an increase of white certificates would induce an annual saving of 47 305€ in an IRIS area's total consumption, while the same amount spent on tax credits could increase total household expenditure by 51 889€. The last column translates the total energy saving achieved in terms of dwelling consumption, given that the 2014-2018 average annual consumption of electricity and gas in a dwelling were 4.5MWh and 10.4MWh respectively. Based on these numbers, increasing spending related to VAT reduction would lead to an overall energy saving equivalent of removing 75 dwelling from an IRIS area, which corresponds on average to 10% of its housing stock. These extrapolations highlight the large differences in policy impact, as well as the importance of not limiting the analysis to one source of energy.

Policy	Electricity			Gas			Total	
	%	MWh	€	%	MWh	€	€	Dwelling
Eco loan	-3.3	-106	-16467	7.6	564	41445	24978	28
ANAH	-4.3	-138	-21458	-3.3	-245	-17996	-39454	-52
Tax credits	1.0	32	4990	8.6	638	46899	51889	65
Reduced VAT	-3.5	-112	-17465	-7.6	-564	-41445	-58911	-75
White certificates	-0.3	-10	-1497	-8.4	-623	-45808	-47305	-58

Note: These figures are inferred from the coefficient displayed in Tables 4.4.3 and 4.4.4 and the average IRIS-level consumption of gas and electricity over the 2014-2018 period. Household energy prices are aggregated from the DIDO database, which is updated monthly by the French Ministry of Ecological Transition.

Table 4.4.5 – Extrapolated annual impact of a 1000€ per capita increase of policy spending

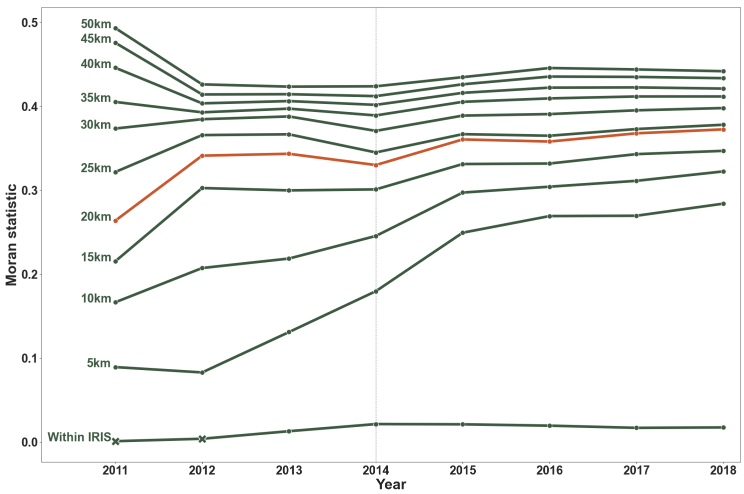
Observed consumption	Energy used for heating	Primary energy consumption	Energy label
148	Electricity	382	F
	Gas	148	C

Note: Energy consumption is expressed in kWh/m^2. Energy label refers to the French DPE scale, as it was computed between 2012 and its 2020 revision.

Table 4.4.6 – Conversion of energy consumption into energy label

The number of RGE firms within 20km also has a differentiated effect depending on the energy source. It has a significant negative impact on electricity consumption, but a positive one on gas consumption. Contrary to household determinants, this effect can only transit through actual energy retrofits. Though counter-intuitive, this result can be explained by looking into how energy performance was measured in France during that period. Beyond comfort issues, energy retrofits are undertaken to increase a dwelling's energy label, which is measured by the DPE scale, going from A to G depending on the dwelling's energy consumption and the type of energy used for heating. In practice, the type of energy was included in the formula by attaching a 2.58 coefficient to households with electric heating systems, versus 1 for any other type of heating (JORF 2012). It was meant to account for losses due to energy conversion: gas can be used to heat a dwelling directly, but also to produce electricity. Electricity is thus seen as a less efficient heating source, since there are losses when it is produced. The goal was also to incentivize households to get rid of old and inefficient electric heaters, which were very commonly found in France. Taking a practical example, Table 4.4.6 provides the energy label of a dwelling with an annual consumption of 148 kWh/m^2 depending on its primary heating system. Introducing this primary energy coefficient may have created a bias towards gas-powered heating systems for households who had access to the gas network, especially knowing that dwellings with an F label will not be allowed to be rented out as of 2028. Hence the negative impact of eco-loans and access to RGE firms on electricity consumption could translate into an increase of gas consumption. These results further suggest that access to RGE firms in itself seems to boost energy retrofits, which have a consistent effect on the efficiency of dwellings locally. Controlling for the quality of retrofits should hence be at the heart of aid programs, independently of their design.

4.4.4 Robustness and alternative specifications

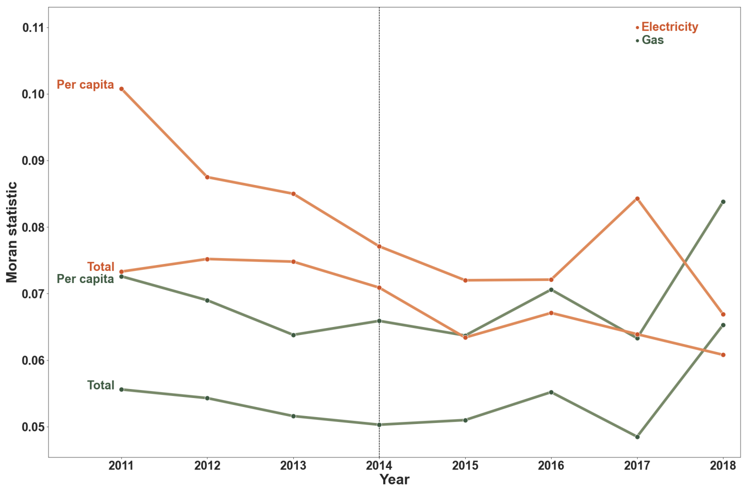


Source: Author's computations.

Note: Each point corresponds to the Moran statistic obtained from cross-section regressions for each year. Non-significant results are indicated by crosses.

Figure 4.4.2 – First stage results from cross-section Moran tests

Moran tests were performed to check the validity of the spatial error model against a simple OLS specification. Figure 4.4.2 displays the Moran statistics obtained from cross-section first-stage regressions. Everything else equal, the value of the Moran statistic increases with buffer size and converges over time. The difference between them decreases over time, all values being close to 0.3 in 2018. It is significant for almost all specifications, except when using RGE firms within the IRIS in 2011 and 2012, which strongly supports the use of a spatial error model. Results are less clear-cut for the second-stage regressions, but the statistic remains significant across all regressions (Figure 4.4.3). Statistics are positive in all cases, which indicates a positive spatial autocorrelation. It means that neighbor areas tend to be characterized by similar parameter values, generating local clusters. This is consistent with the positive λ values found in the main results.



Source: Author's computations.

Note: Each point corresponds to the Moran statistic obtained from cross-section regressions for each year. RGE firms are instrumented.

Figure 4.4.3 – Second-stage results from cross-section Moran tests

Tables 4.4.7 and 4.4.8 display second-stage results with alternative specifications. Columns (1) correspond to the specification discussed in the previous section and columns (2) include cross variables between the number of RGE firms in the 20km buffers and non eco-conditional policies. The negative coefficient associated with the presence of RGE firms still holds for electricity consumption per capita. The effect is reinforced by ANAH grants, and mitigated by spendings related to reduced VAT. The positive impact of RGE firms on gas consumption still holds, even if it is reduced by the interaction with ANAH grants. It means that the effect of having access to RGE firms does not only transit through eco-conditional schemes. The implantation of more certified firms locally impacts the overall quality of retrofits. It can be due to more renovations being conducted by RGE firms, or to an increase of competition on quality due to their presence. Columns (3) include a proxy for revenue dispersion, namely the relative interquartile coefficient $\frac{Q_1-Q_3}{Q_2}$. Dividing the interquartile range by the median revenue provides a measure of the relative distance to the median.

	Consumption per capita (log)			Total consumption (log)		
	(1)	(2)	(3)	(1)	(2)	(3)
Eco loan	-0.0055***	-0.0058***	-0.0054***	-0.0041***	-0.0042***	-0.004***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
ANAH	-0.0054***	-0.0048***	-0.0054***	-0.0024***	-0.0024***	-0.0023***
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0005)	(0.0004)
Tax credits	0.0007***	0.0005***	0.0007***	0.0012***	0.001***	0.0012***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Reduced VAT	-0.0023***	-0.0028***	-0.0024***	-0.003***	-0.0034***	-0.0032***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
White certificates	-0.0019***	-0.0018***	-0.0018***	-0.0017***	-0.0016***	-0.0014***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Average temperature	0.0009***	0.001***	0.0009***	0.0008***	0.0008***	0.0009***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Dwellings	-0.00004***	-0.00004***	-0.00004***	0.0004***	0.0004***	0.0004***
	(0.000003)	(0.000003)	(0.000003)	(0.000003)	(0.000003)	(0.000003)
Sh. main residences	-0.0113***	-0.0112***	-0.0111***	0.0021***	0.0023***	0.0024***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Sh. owner-occupiers	0.0013***	0.0013***	0.0014***	0.0008***	0.0007***	0.0008***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Sh. flats	-0.0059***	-0.0059***	-0.006***	-0.0038***	-0.0038***	-0.004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Sh. elec. heating	0.0053***	0.0053***	0.0053***	0.0043***	0.0043***	0.0043***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Sh. coll. heating	-0.0005***	-0.0005***	-0.0005***	-0.0015***	-0.0015***	-0.0014***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Sh. families	0.002***	0.002***	0.0021***	0.0005***	0.0005***	0.0006***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Med. living std. (log)	0.2631***	0.2681***	0.2528***	0.3928***	0.4014***	0.3816***
	(0.0078)	(0.0078)	(0.0079)	(0.0093)	(0.0093)	(0.0092)
Unemployment rate	-0.0006***	-0.0006***	-0.0007***	-0.002***	-0.002***	-0.002***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
RGE firms	-0.00001***	-0.00002***	-0.00001***	-0.00002***	-0.00003***	-0.00002***
	(0.000002)	(0.000003)	(0.000002)	(0.000002)	(0.000003)	(0.000002)
RGExANAH		-0.000004***			–0.000003***	
		(0.0000005)			(0.0000005)	
RGExVAT		0.0000006***			0.0000005***	
		(0.0000001)			(0.0000001)	
(Q3-Q1)/Q2			0.0779***			0.1419***
			(0.0108)			(0.0117)
λ	0.152882	0.161414	0.154398	0.137729	0.168763	0.141468
2SLS	Yes	Yes	Yes	Yes	Yes	Yes
Observations	11103	11103	11103	11103	11103	11103
Pseudo R-squ.	0.732826	0.734719	0.733947	0.75587	0.757165	0.758264

Standard errors in parentheses. "RGE" refers to RGE firms within 20km of the IRIS of residence.
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4.4.7 – Alternative specifications for electricity consumption (2014-2018)

	Consumption per capita (log)			Total consumption (log)		
	(1)	(2)	(3)	(1)	(2)	(3)
Eco loan	0.0062***	0.0044***	0.0067***	0.0071***	0.0053***	0.0076***
	(0.0009)	(0.0009)	(0.0009)	(0.0009)	(0.0009)	(0.0009)
ANAH	0.0007	0.0095***	0.0013	0.002*	0.0102***	0.0028**
	(0.0011)	(0.0012)	(0.0011)	(0.0011)	(0.0012)	(0.0011)
Tax credits	0.0077***	0.0082***	0.0077***	0.008***	0.0084***	0.008***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Reduced VAT	-0.0074***	-0.01***	-0.0084***	-0.0082***	-0.0107***	-0.0093***
	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0005)
White certificates	-0.0079***	-0.0068***	-0.0068***	-0.0074***	-0.0064***	-0.0062***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Average temperature	-0.0079***	-0.007***	-0.0078***	-0.0072***	-0.0064***	-0.0072***
	(0.0008)	(0.0008)	(0.0008)	(0.0008)	(0.0008)	(0.0008)
Dwellings	-0.0001***	-0.0001***	-0.0001***	0.0004***	0.0004***	0.0003***
	(0.000008)	(0.000008)	(0.000008)	(0.000009)	(0.000009)	(0.000009)
Sh. main residences	-0.0094***	-0.0096***	-0.0083***	0.0041***	0.0039***	0.0052***
	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0005)
Sh. owner-occupiers	0.0006**	0.0006**	0.0008***	0.00005	0.00002	0.0002
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Sh. flats	0.0006**	0.0004*	0.0001	0.0018***	0.0016***	0.0012***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Sh. elec. heating	-0.0123***	-0.0125***	-0.0125***	-0.0109***	-0.0111***	-0.0112***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Sh. coll. heating	-0.0107***	-0.0108***	-0.0106***	-0.0108***	-0.0108***	-0.0106***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Sh. families	-0.0008*	-0.0009**	-0.0004	-0.0017***	-0.0018***	-0.0014***
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)
Med. living std. (log)	0.5459***	0.5403***	0.4962***	0.6543***	0.6488***	0.604***
	(0.0244)	(0.0244)	(0.0244)	(0.0251)	(0.0252)	(0.0251)
Unemployment rate	-0.0006	-0.0005	-0.0009	-0.0021***	-0.002***	-0.0024***
	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)
RGE firms	0.00002***	0.0001***	0.000005	0.000006	0.00005***	-0.00001**
	(0.000006)	(0.000008)	(0.000006)	(0.000006)	(0.000009)	(0.000006)
RGExANAH		-0.00002***			-0.00002***	
		(0.00001)			(0.000001)	
RGExVAT		0.000002***			0.000002***	
		(0.0000002)			(0.0000002)	
(Q3-Q1)/Q2			0.4989***			0.5661***
			(0.0323)			(0.0328)
λ	0.123613	0.113782	0.122447	0.119983	0.110497	0.118343
2SLS	Yes	Yes	Yes	Yes	Yes	Yes
Observations	10900	10900	10900	10900	10900	10900
Pseudo R-squ.	0.34022	0.345891	0.350059	0.388365	0.394023	0.400528

Standard errors in parentheses. "RGE" refers to RGE firms within 20km of the IRIS of residence.
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

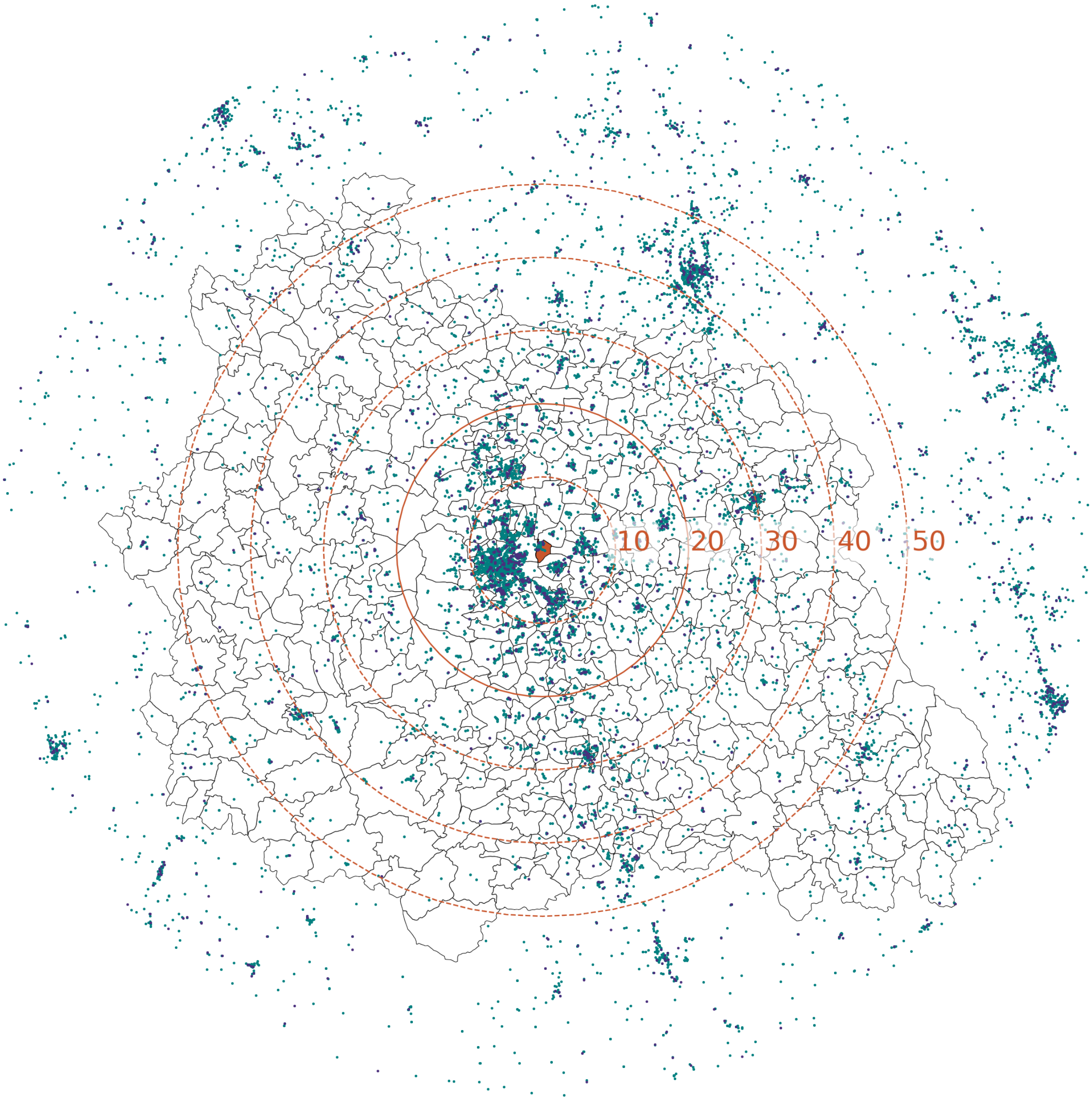
Table 4.4.8 – Alternative specifications for gas consumption (2014-2018)

The coefficient is significant and positive in all cases, meaning larger revenue disparities in an IRIS lead to higher consumption, everything else equal. A possible explanation is that inequalities are tilted towards higher income households, who consume relatively more energy.

4.5 Conclusion

In France, the residential sector accounts for roughly a third of total energy consumption. The current 50% consumption reduction target set for 2050 implies that 2% of the existing buildings needs to be efficiently retrofitted every year. This paper provides insights on the impact of the 5 national-scale policies implemented to achieve this goal, while controlling for access to skilled companies. First-stage estimation results using the KPP estimator indicate that the number of RGE firms is driven by both the number of competing firms and financial aid to households. This supports the idea that the label is used as a differentiation strategy on the quality of service in a competitive context. This is further reinforced by the fact that there are less RGE firms when spending for reduced VAT rates increase. The heterogeneous distribution of RGE firms is a concerning result in itself, since it has had a direct consequence in terms of access to public aid schemes for households since 2014. The instrumented second-stage results are consistent with previous papers on density effects and on residential energy demand, and reveal differences in the determinants of gas and electricity consumption. With the exception of tax credits, all policies seem to contribute to a decrease of electricity consumption, but with different magnitudes. This is consistent with previous results on the cost-effectiveness of different policy designs. Results on gas consumption however suggest that part of the decrease in electricity consumption induced by eco-loans may be compensated by a shift to gas heating. This would likely be due to a bias induced in the computation of energy label and further analysis would be needed to see the total impact on households' overall energy consumption. A more alarming result is the significantly positive coefficient associated with tax credits across all specifications, which signals a design issue with this scheme. The available data does not allow to differentiate between a rebound effect and phony installations, but recent audit of the systems have revealed severe flaws in the way retrofits were handled. Overall, these results further support the need to improve the oversight of this policy.

Like any empirical analysis, these results however have limitations. First, the data does not include information on the number of renovations and the actual work done. It is solely inferred from aggregated policy spending and the localization of labeled firms. Household and dwelling characteristics are also not observed at the individual level. Even if the



Source: Author's computations from ADEME data.

Note: Only the 571 IRIS zones located in the Puy-de-Dôme department (63) are displayed. Firms are restricted to the 11 540 firms that were active in 2018 and located within 75km of Aulnat - among which 1 889 had the RGE label.

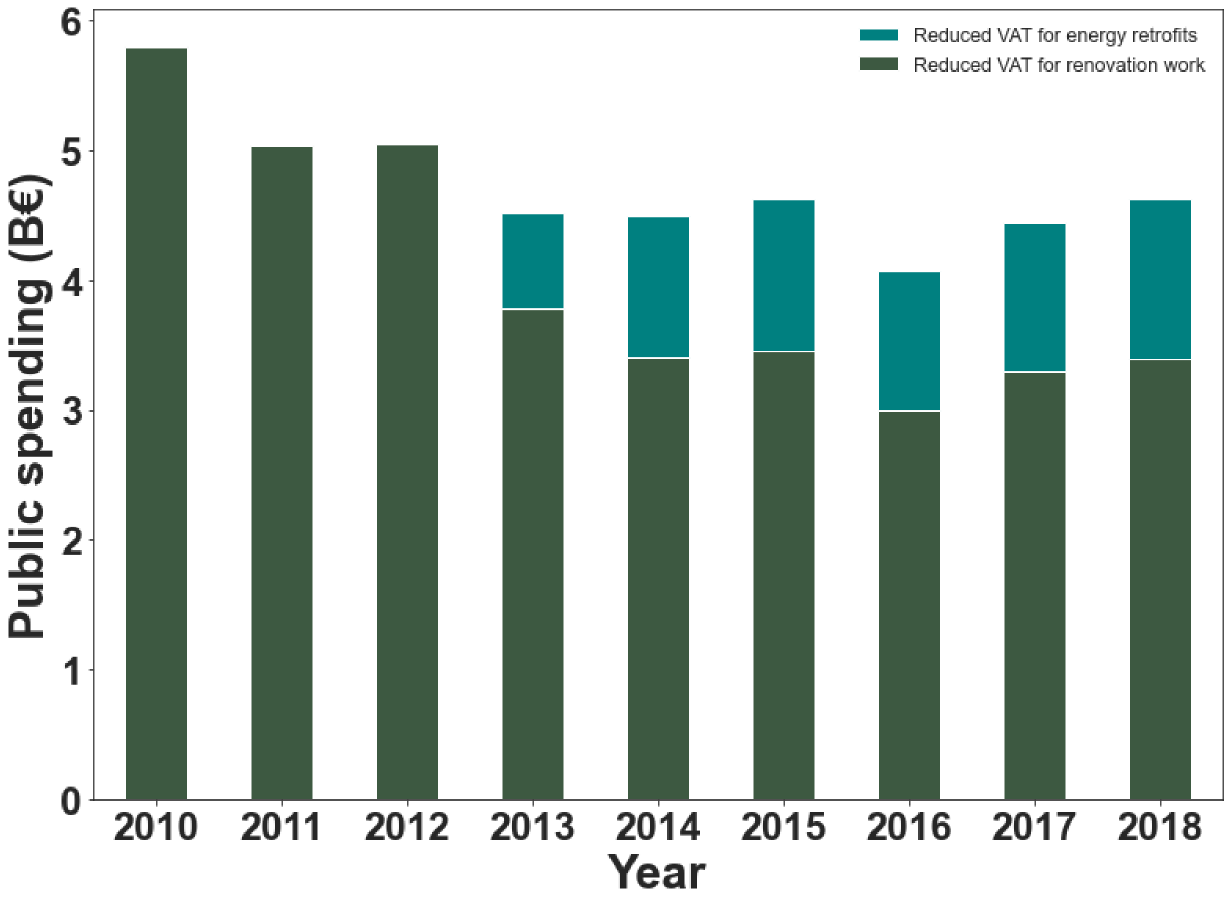
Figure 4.5.1 – Buffers around the IRIS of Aulnat

aggregation scale is the smallest possible, the results are valid only if there is not too much heterogeneity among households in the same IRIS zone, which is supposed to be the case but cannot be checked. Any estimation relying on aggregated data is however subject to the Modifiable Areal Unit Problem (MAUP) raised in Briant, P.-P. Combes, and Lafourcade (2010). Organizing the data in discrete units is sensitive to zoning, meaning changing how the borders of these units are drawn and the scale of aggregation may alter the results. As it is a nonrandom spatial classification, using IRIS-aggregated data might bias the results in unpredictable ways. This holds true for any analysis using aggregated geographical zoning and is not an issue that is specific to this work. This is however less constraining regarding the firm count variables. Figure 4.5.1 illustrates how the number of firms around IRIS zones were computed, taking the example of Aulnat, located in a central French department. This methodology has the advantage of going beyond administrative borders, and the actual IRIS contours become less and less relevant as the buffers get larger.

Despite these drawbacks, this paper brings an interesting perspective on policy design for energy retrofits. These policies come with a non-negligible cost, and their effect has to be more clearly measured and monitored. There is room for improvement when it comes to including firms in the implementation of these programs. They are key actors of the retrofitting process, yet the RGE label is the only measure directly involving them. Further, there are virtually no barriers to entry for most trades in the construction sector. Degrees are thus less valued than in other markets, as they can be honorarily obtained with three years of experience in a trade. Since this sector is now at the forefront of the French plan to transition to a low-carbon economy, it is more important than ever to ensure a baseline quality of the final product. Smaller-scale ethnographic papers have already highlighted the need for continuous training of contractors, as it is a very labor-intensive market (eg. Killip 2012). Moreover, though green certifications for firms are not a new concept, their application to the construction sector remains limited in the EU. It would be interesting to see it implemented its impact in countries with a similar supply-side structure (ESCSO 2020). There is also room for improvement when it comes to both monitoring retrofits and the list of eligible renovations. There is growing criticism towards small-scale renovation projects, which were particularly favored by the tax credit scheme, regarding their effectiveness to improve energy efficiency. Finally, the results presented in this paper raise questions around the multiplicity of aid schemes, and suggests a more unified approach could be more impactful given the heterogeneity of their effect. Overall, the French policy mix seem to foster energy savings, but these key points should be more carefully looked at, especially considering the cost of these programs and the future ban on renting out dwellings with an label F and G.

Appendices of Chapter 4

4.A Evolution of VAT reduction measures

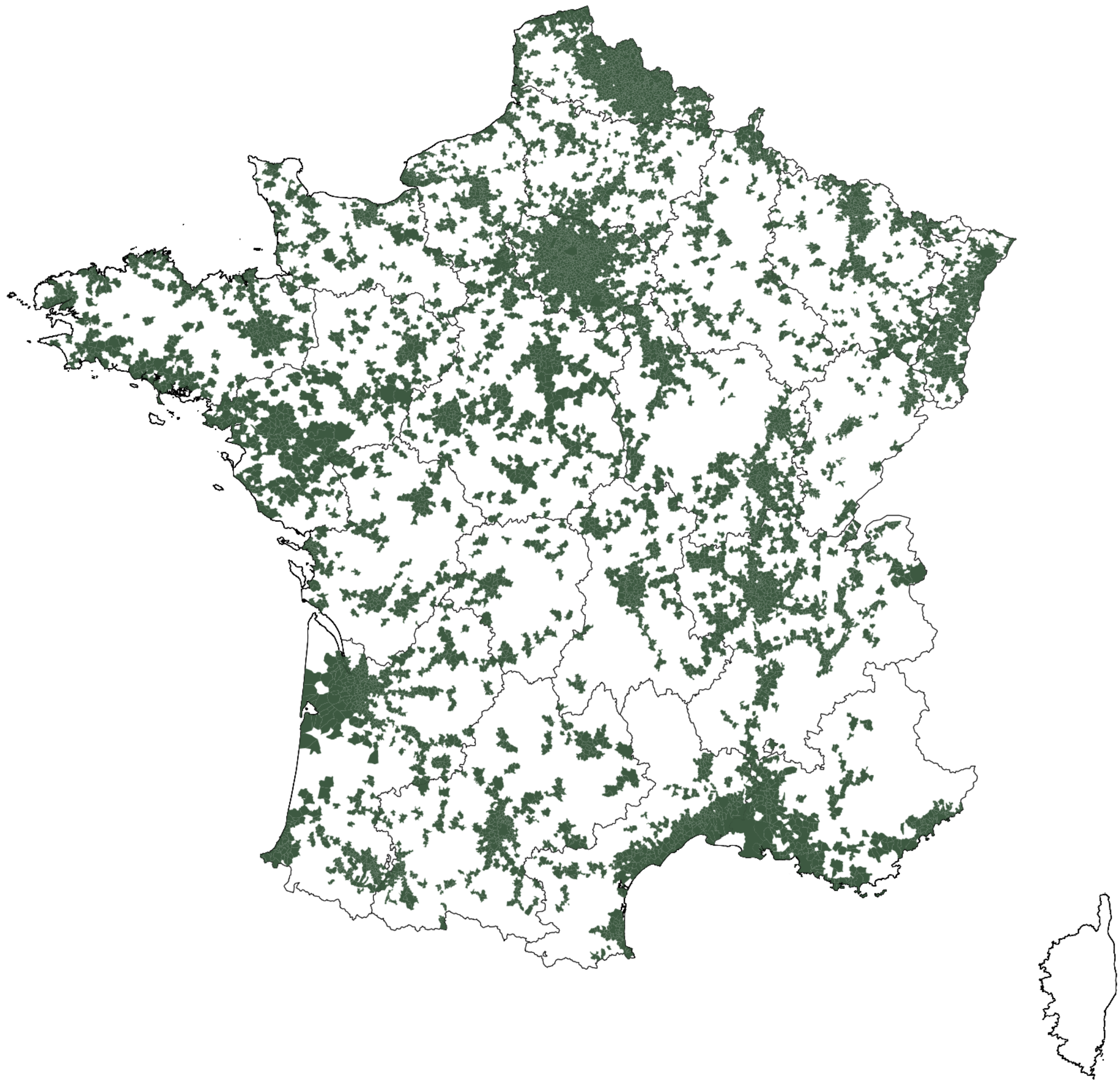


Sources: Author's computations from annual French Finance Acts.

Note: Public spending refers to what households actually received during each given year.

Figure 4.A.1 – Public spending related to VAT reduction measures since 2010

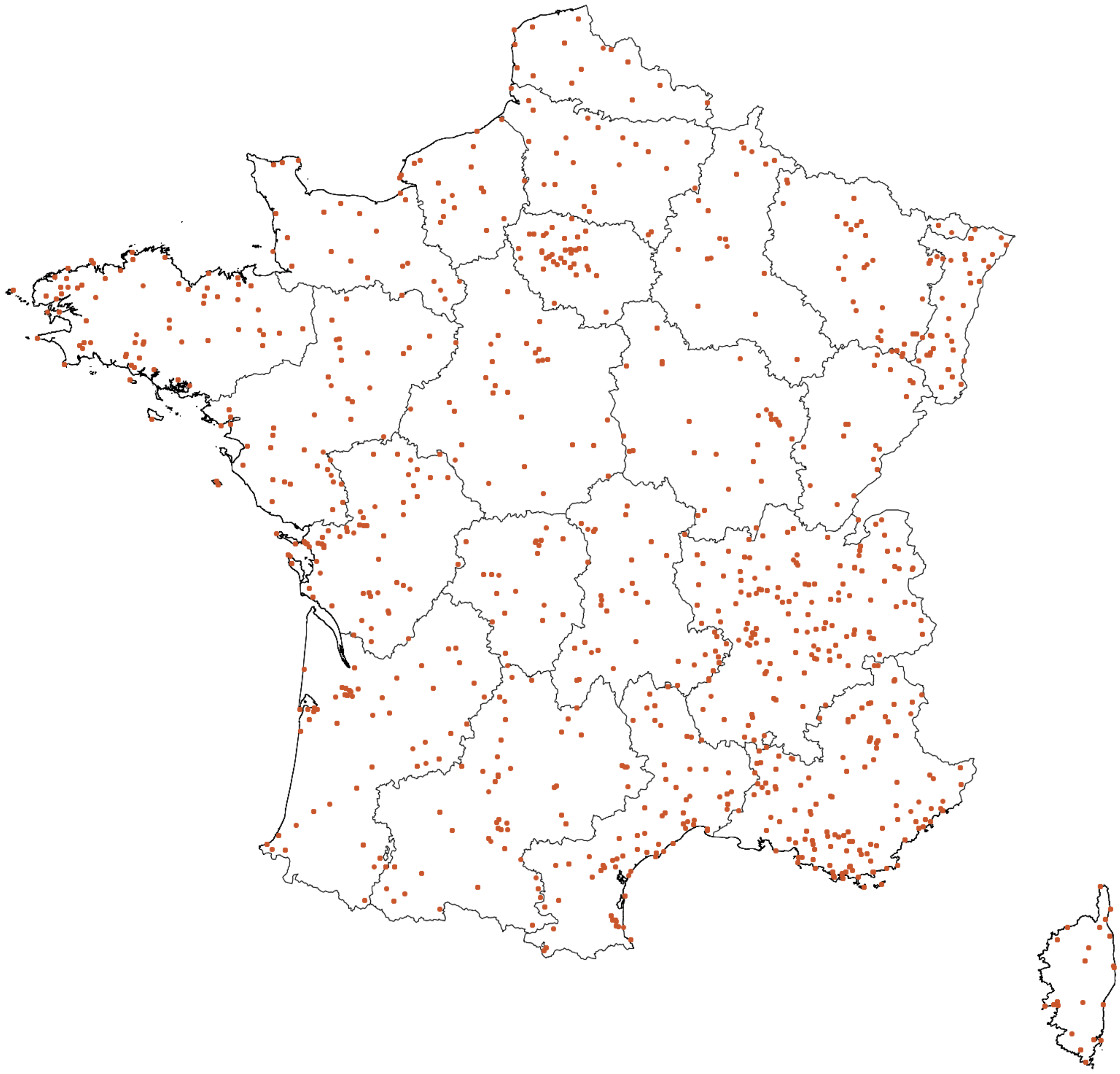
4.B Metropolitan France gas distribution network



Source: Author's computations from Cerema data.

Figure 4.B.1 – Cities with access to gas in metropolitan France (2018)

4.C Weather stations



Source: Author's computations from Infoclimat data.

Figure 4.C.1 – Weather stations in metropolitan France

4.D First stage results for the 2011-2018 time period

	Number of RGE firms										
	Within IRIS	5KM buffer	10KM buffer	15KM buffer	20KM buffer	25KM buffer	30KM buffer	35KM buffer	40KM buffer	45KM buffer	50KM buffer
Eco loan	-0.0224***	1.6188***	5.369***	8.9621***	7.628***	9.9486***	11.5237***	12.4398***	13.2158***	13.7635***	13.6005***
	(0.0011)	(0.0319)	(0.0842)	(0.1285)	(0.227)	(0.2741)	(0.3178)	(0.3594)	(0.401)	(0.4404)	(0.4799)
ANAH	0.0093***	-2.0375***	-5.7795***	-8.7781***	2.7166***	3.0897***	3.7418***	3.8083***	3.0765***	2.1987***	1.8214***
	(0.001)	(0.036)	(0.0971)	(0.1539)	(0.1708)	(0.2067)	(0.2404)	(0.2727)	(0.305)	(0.3356)	(0.3664)
Tax credits	0.038***	0.3921***	0.9343***	2.5919***	-6.2598***	-8.1381***	-8.9269***	-8.6576***	-7.5276***	-5.6297***	-2.58***
	(0.0004)	(0.02)	(0.0585)	(0.0969)	(0.1271)	(0.1532)	(0.1771)	(0.1998)	(0.2226)	(0.2444)	(0.2662)
White Certificates	0.0436***	2.5915***	8.0843***	14.3051***	13.9455***	18.7148***	23.3878***	27.977***	32.7994***	37.7744***	42.3793***
	(0.0006)	(0.0361)	(0.1156)	(0.2067)	(0.4596)	(0.5488)	(0.6234)	(0.691)	(0.7624)	(0.8365)	(0.9116)
Reduced VAT	-0.0187***	-1.2963***	-3.9678***	-6.7481***	-4.8663***	-6.7571***	-8.5131***	-10.4259***	-12.5549***	-14.8002***	-16.8599***
	(0.0003)	(0.0186)	(0.0583)	(0.1031)	(0.2232)	(0.2666)	(0.3031)	(0.3362)	(0.371)	(0.4071)	(0.4438)
Construction firms	0.0155***	0.0102***	0.0136***	0.016***	0.1033***	0.1098***	0.115***	0.1187***	0.1216***	0.1239***	0.1258***
	(0.0002)	(0.00003)	(0.00003)	(0.00003)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Average temperature	-0.0128***	0.3788***	0.7301***	0.5322***	0.3115***	0.0252	-0.4039***	-0.8234***	-1.3187***	-1.8244***	-2.1101***
	(0.0013)	(0.031)	(0.082)	(0.1319)	(0.1079)	(0.1303)	(0.1512)	(0.171)	(0.1909)	(0.2095)	(0.2282)
Households	0.0016***	0.0105***	0.0221***	0.0279***	0.1122***	0.1507***	0.1835***	0.2258***	0.2619***	0.305***	0.3548***
	(0.00003)	(0.0004)	(0.001)	(0.0014)	(0.0082)	(0.0099)	(0.0115)	(0.013)	(0.0145)	(0.0159)	(0.0173)
Dwellings	0.00003*	-0.0053***	-0.0107***	-0.0111***	-0.0192***	-0.044***	-0.0748***	-0.1173***	-0.1523***	-0.1888***	-0.2305***
	(0.00002)	(0.0003)	(0.0007)	(0.001)	(0.0067)	(0.0081)	(0.0094)	(0.0107)	(0.0119)	(0.0131)	(0.0142)
Med. living std. (log)	-0.3772***	6.0794***	23.3559***	41.8776***	-102.9945***	-93.6586***	-89.868***	-93.832***	-89.3637***	-83.1481***	-73.8116***
	(0.0281)	(0.523)	(1.2987)	(1.8997)	(3.9166)	(4.7308)	(5.4888)	(6.2113)	(6.9314)	(7.6094)	(8.2911)
Sh. vacant dwellings	0.0059***	-0.357***	-1.181***	-1.7659***	-2.4108***	-2.2094***	-1.7226***	-1.143***	-0.4379**	0.1146	0.6003**
	(0.001)	(0.0186)	(0.0466)	(0.0694)	(0.1174)	(0.1418)	(0.1645)	(0.1861)	(0.2077)	(0.228)	(0.2483)
Sh. main residences	-0.0011**	0.1583***	0.4384***	0.6802***	-3.5829***	-3.365***	-2.9266***	-2.6736***	-2.2672***	-2.0231***	-1.7972***
	(0.0005)	(0.008)	(0.0196)	(0.0282)	(0.1342)	(0.162)	(0.188)	(0.2128)	(0.2374)	(0.2606)	(0.2839)
Sh. owner-occupiers	0.0021***	0.0356***	0.1727***	0.0526*	-0.3761***	-0.1281	0.0807	0.1817*	0.2142*	0.2452*	0.2986**
	(0.0005)	(0.0087)	(0.0216)	(0.0315)	(0.0683)	(0.0825)	(0.0957)	(0.1083)	(0.1208)	(0.1326)	(0.1445)
Sh. flats	-0.0188***	0.4444***	0.7967***	0.7533***	1.5714***	1.7954***	1.6982***	1.4509***	1.1336***	0.9714***	0.9164***
	(0.0003)	(0.006)	(0.0146)	(0.0212)	(0.0812)	(0.0981)	(0.1139)	(0.1289)	(0.1439)	(0.158)	(0.1721)
λ	0.133211	0.675134	0.727075	0.741058	0.9332	0.932236	0.93039	0.92854	0.927507	0.927444	0.927465
Observations	40727	40727	40727	40727	40727	40727	40727	40727	40727	40727	40727
Pseudo R-squ.	0.342667	0.598615	0.6466	0.675768	0.591844	0.589618	0.581654	0.569889	0.555558	0.539326	0.521829

Standard errors in parentheses.

$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4.D.1 – RGE firms : estimations results for years 2011-2018

4.E Second stage results for the 2011-2018 time period

	Consumption per capita (log)			Total consumption (log)		
	(1)	(2)	(3)	(1)	(2)	(3)
Eco loan	-0.0037***	-0.0035***	-0.003***	-0.0052***	-0.0046***	-0.0039***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
ANAH	-0.0073***	-0.0074***	-0.0085***	-0.0066***	-0.0071***	-0.0079***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Tax credits	-0.0014***	-0.0014***	-0.0012***	-0.0014***	-0.0014***	-0.0012***
	(0.00003)	(0.00003)	(0.00003)	(0.00003)	(0.00003)	(0.00003)
Reduced VAT	-0.0004***	-0.0005***	-0.0011***	-0.0008***	-0.0011***	-0.0017***
	(0.00003)	(0.00003)	(0.00003)	(0.00003)	(0.00003)	(0.00004)
White certificates	-0.0021***	-0.0019***	-0.0007***	-0.0009***	-0.0004***	0.0008***
	(0.00004)	(0.00005)	(0.0001)	(0.00004)	(0.00005)	(0.0001)
Average temperature	-0.0021***	-0.0019***	-0.0019***	-0.0024***	-0.0023***	-0.0023***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Dwellings	-0.0001***	-0.0001***	-0.0001***	0.0004***	0.0004***	0.0004***
	(0.000001)	(0.000001)	(0.000001)	(0.000002)	(0.000002)	(0.000002)
Sh. main residences	-0.0078***	-0.0078***	-0.0076***	0.0072***	0.0071***	0.0073***
	(0.00005)	(0.00005)	(0.00005)	(0.0001)	(0.0001)	(0.0001)
Sh. owner-occupiers	0.002***	0.002***	0.002***	0.0002***	0.0001**	0.0001**
	(0.00005)	(0.00005)	(0.00005)	(0.0001)	(0.0001)	(0.0001)
Sh. flats	-0.005***	-0.005***	-0.0046***	0.0023***	0.0024***	0.0027***
	(0.00004)	(0.00004)	(0.00004)	(0.0001)	(0.0001)	(0.0001)
Sh. elec. heating	0.0051***	0.0052***	0.0052***	0.0036***	0.0035***	0.0036***
	(0.00005)	(0.00004)	(0.00004)	(0.00005)	(0.00005)	(0.00005)
Sh. coll. heating	-0.0011***	-0.0011***	-0.001***	0.0001	0.0001	0.0001**
	(0.00005)	(0.00005)	(0.00005)	(0.0001)	(0.0001)	(0.0001)
Sh. families	0.0012***	0.0012***	0.0013***	0.0003***	0.0004***	0.0003***
	(0.00004)	(0.00004)	(0.00004)	(0.00004)	(0.00004)	(0.00004)
Med. living std. (log)	0.2004***	0.2015***	0.2154***	0.1304***	0.1273***	0.1364***
	(0.0028)	(0.0028)	(0.0029)	(0.0033)	(0.0033)	(0.0033)
Unemployment rate	-0.0012***	-0.0013***	-0.0014***	-0.0003***	-0.0004***	-0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
RGE firms		-0.00001***	-0.00009***		-0.00002***	-0.00001***
		(0.0000006)	(0.000003)		(0.0000006)	(0.000004)
λ	0 0.006322	0.250783	0.226586	0.009173	0.208066	0.207433
2SLS		No	Yes		No	Yes
Observations	36303	36303	36303	36303	36303	36303
Pseudo R-squ.	0.750292	0.754551	0.75528	0.666134	0.665958	0.671299

Standard errors in parentheses. "RGE" refers to RGE firms within 15km of the IRIS of residence.
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4.E.1 – Residential electricity consumption (2011-2018)

	Consumption per capita (log)			Total consumption l(og)		
	(1)	(2)	(3)	(1)	(2)	(3)
Eco loan	0.0002	0.0008**	0.001**	-0.0001	0.0008*	0.0009**
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)
ANAH	-0.015***	-0.0154***	-0.0161***	-0.0148***	-0.0153***	-0.016***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Tax credits	0.002***	0.0021***	0.0021***	0.002***	0.0021***	0.0022***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Reduced VAT	-0.0012***	-0.0014***	-0.0019***	-0.0014***	-0.0017***	-0.0021***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
White certificates	-0.009***	-0.0085***	-0.0077***	-0.0085***	-0.008***	-0.0071***
	(0.0001)	(0.0002)	(0.0002)	(0.0001)	(0.0001)	(0.0002)
Average temperature	-0.0099***	-0.0096***	-0.0096***	-0.0096***	-0.0093***	-0.0094***
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)
Dwellings	-0.0002***	-0.0002***	-0.0002***	0.0004***	0.0004***	0.0004***
	(0.000004)	(0.000004)	(0.000004)	(0.000005)	(0.000005)	(0.000005)
Sh. main residences	-0.0074***	-0.0075***	-0.0073***	0.007***	0.0068***	0.0071***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Sh. owner-occupiers	0.0001	0.0001	0.0001	-0.0004**	-0.0004**	-0.0004**
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Sh. flats	0.0032***	0.0033***	0.0035***	0.0058***	0.0059***	0.0062***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
Sh. elec. heating	-0.0074***	-0.0075***	-0.0074***	-0.0056***	-0.0057***	-0.0056***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Sh. coll. heating	-0.0072***	-0.0071***	-0.0071***	-0.006***	-0.006***	-0.0059***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Sh. families	-0.0018***	-0.0017***	-0.0016***	-0.0022***	-0.0021***	-0.0021***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Med. living std. (log)	0.196***	0.1972***	0.2081***	0.1664***	0.1675***	0.1787***
	(0.0098)	(0.0098)	(0.0099)	(0.01)	(0.01)	(0.0101)
Unemployment rate	0.0002	0.00003	-0.00005	0.0002	0.000009	-0.00004
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
RGE firms		-0.00002***	-0.00007***		-0.00002***	-0.00008***
		(0.000002)	(0.000008)		(0.000002)	(0.000008)
λ	0.045457	0.186302	0.183609	0.04741	0.176865	0.170375
2SLS		No	Yes		No	Yes
Observations	18577	18577	18577	18577	18577	18577
Pseudo R-squ.	0.142418	0.140766	0.136884	0.405422	0.404171	0.402785

Standard errors in parentheses. RGE" refers to RGE firms within 15km of the IRIS of residence.
$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4.E.2 – Residential gas consumption (2011-2018)

* * *

«The solid world exists, its laws do not change. Stones are hard, water is wet, objects unsupported fall towards the earth's centre. With the feeling that he was speaking to O'Brien, and also that he was setting forth an important axiom, he wrote:

> *Freedom is the freedom to say that two plus two make four. If that is granted, all else follows.»*

George Orwell – *1984*.

* * *

General Conclusion

1 Discussion of main findings and transversal policy implications

1.1 National policies, local markets

The residential sector is currently at the forefront of environmental and energy policies. It is responsible for about 30% of the final energy consumption in France (CGEDD 2020), and the retrofit of existing buildings is necessary to close the energy efficiency gap between old and new builds. The four chapters in this thesis explored the role construction firms play in improving the residential sector's energy efficiency and discussed implications in terms of public policies to address various issue: how to upskill the construction sector, how new technical innovations could affect the market, and how effective public policies have been in reducing households' energy consumption.

Of particular note, and a major intervention of this thesis, is the significant role that regional variations play in determining the construction sector's successes and failures in terms of its potential to drive forward-thinking energy policies. The high fragmentation of the sector was identified as a common source of inefficiency for these three aspects. The construction sector is characteristically very localized, as dwellings can, by nature, not be moved and firms are not particularly mobile. Additionally, differences in regional climates affect the architecture and materials used to build these dwellings. These disparities induce differences in regulations, most notably in the performance requirements defined in thermal regulations. Policy emphasis put on insulation against cold weather, in order to reduce heating needs, led to a clear North-South divide in France when it came to the number of retrofits achieved and the amount of public aid received by households. As described in Chapter 4, this is particularly visible in the distribution of RGE contractors on the metropolitan territory. Summer comfort and air conditioning needs have remained somewhat overlooked and will raise increasing challenges for designing policies to reduce energy consumption. The impact of the energy efficiency policies developed during the 2010-2020 decade was thus limited by these local disparities. Further, the RGE certification, failed to meaningfully address upskilling challenges, since it is still not widely adopted due to its voluntary nature. Worse, given the unequal spatial distribution of the label, the 2013 eco-conditionality law of public aid created inequalities in households' access to retrofit grants and tax rebates, since their successful applications for these funds depended on how easily they could hire a RGE contractor.

The market penetration of innovative products was also found to be dependent on local market factors per Chapter 2. As materials are in most cases picked out by contractors, this may in turn create disparities in the quality of the renovation services households are able to purchase. Overall, the French construction market seems to be scarred with these spatial disparities generating differences in supply-side quality, which have been further reinforced by the national governance of public policies. The local nature of construction markets has yet to be addressed by policymaker, as regulations and public aid were mostly designed based on technical requirements. The implication and integration of actors at the local level would be a way to overcome these limitations and increase the efficiency of both household policies and supply-side regulations.

1.2 Push factors: understanding actors' incentives

Beyond these spatial disparities, global structural obstacles hinder the potential of mass take-up of energy retrofits. Housing and construction policies have historically targeted new builds and public policy efforts have only recently been reoriented towards renovations. From households' perspective, the main barrier to actually renovating their dwellings is the uncertainty regarding the return on their investments. There are no strong signals for the *ex ante* skills of contractors, and they might fear hidden costs related to completion times and wrongful installation. As illustrated in Chapter 1, the RGE label does not seem to be the appropriate solution to efficiently alter the skill distribution on the market. There is a persistent uncertainty with respect to contractors' trustworthiness, as unskilled firms are known to be present on the market. Given contractors' lack of barriers to entry, leading some to undertake projects they may not have the skills to follow through, customers may rightfully be reluctant to hire contractors. Households also might be subject to credit constraints, as the upfront costs of retrofit investments are usually high, while savings in terms of energy expenses will only be achieved in the long run. The retrofit aid policies implemented in France are a good illustration of the European policy package to incentivize households to undertake retrofits. Their evaluation thus provides relevant insights in terms of global policy design.

Costs aside, there are indeed outstanding questions about the efficiency of retrofits *ex post*. In practical terms, the French eco-conditionality law further provides a unique opportunity to assess the impact of contractors' skills on the effectiveness of the retrofits that were undertaken from 2013 to 2018. The lack of precise and publicly available data on retrofits makes the evaluation of these policies difficult, but the results in Chapter 4 suggest that making the RGE label mandatory did increase the impact of public spending on residential energy consumption. However, there were also important disparities in efficiency depending on the type of policy considered and the energy source (electricity or gas). There was evidence of a larger rebound effect for gas consumption, which could be linked to the computation of dwellings' energy labels (DPE) during that period. Recent micro-level reports have made the same reservations and drawn attention to potential fraud, which can take the form of non-completed work, false declarations or the installation of the wrong equipment or materials. In the case of white certificates, an estimated 59 MWhc were effectively saved for every predicted 100 MWhc (ADEME 2019a). The missing 41% of these predicted energy savings were attributed to an initial overestimation of the gains from renovations (23%), the energy poverty bonuses not inducing extra energy savings (11%), and wrongful installation (4%). Similar observations were made in the case of CITE tax rebate, as estimated *ex post* savings were below the initial projections (CGDD 2018). There were overall less retrofits undertaken than the objectives set by the government, and they led to smaller energy savings than the initial projections. This could be attributed to governance issues, namely the frequent amendments made to the eligibility conditions and grant levels which may deter households from applying. The multiplicity of aid programs, even excluding the grants offers at the region or department-level, adds additional red-tape costs for households which may discourage retrofits. A single-channel aid program could be both easier to understand for households and more straightforward to evaluate for observers.

On the other hand, firms do not necessarily have incentives to specialize in energy retrofits, nor do they all have the skills to provide these services. Contractors face a high competitive pressure and their main business model is to keep their prices low in order to win projects. The RGE label was also established as a way for skilled tradesmen to set themselves apart, with the hope of upskilling the sector in the long run. Theoretical insights from Chapter 1 highlighted important limitations to this certification scheme, specifically regarding its lack of effectiveness to deter the entry of low-skilled professionals. It does however seem to work well in signaling firms' attitude towards innovation: RGE firms had a higher probability to adopt the new drywall in Chapter 2, and their workers were found to have stronger preferences for green innovative attributes in Chapter 3. However, take-up of the label could simply reflect that innovation-oriented firms apply for the label, rather than the certification providing incentives for them to turn to state-of-the-art materials. There is virtually no diffusion policy set up to promote the diffusion of innovations - beyond research and development funding -, despite the low uptake rates observed on the sector. Given the cost of uncertainty perceived by contractors and the low valuations attributed to green materials found in Chapter 3, there is a need to further push these products in order to increase the sector's decarbonization efforts. Promoting continuous professional training could encourage contractors generate new skills, but if degrees and training cannot be used to set higher prices, it is likely contractors' enrollment will remain low. However, setting barriers to entry in the form of minimal degree requirement to become a contractor of any trade could allow skilled professionals to fully take advantage of their expertise and increase the quality of the retrofits provided on the market. It could effectively remove the uncertainty around skills for households, which from a theory standpoint would in turn increase their willingness to pay per Chapter 1.

1.3 Pull factors: regulations and upskilling

Regulatory requirements can prove to be more efficient than incentive-based policies considering the stakes and the insufficient number of retrofits these policies led to so far. A number of requirements are already in place to regulate the construction and retrofit activity, and the results from this thesis are useful to discuss their effectiveness. First, dwelling owners were not directly targeted by regulations during the 2010-2020 decade. Households' main constraint stemmed from the eco-conditionality law to ensure a baseline quality of the retrofits. There is growing concern regarding the effectiveness of this measure, as the label on its own may not be sufficient to ensure that minimal quality given the low number of worksite audits performed (CGEDD 2017). Chapter 4 estimates did show a significant effect to having more access to certified firms on the quality of the retrofits, but it remained small. An alternative to the RGE requirement to access grants and zero-interest loans could be the undertaking of mandatory audits once renovations are complete, or during the process. It would reduce the probability of fraud, while ensuring public funds are well directed.

Second, firms are in general much more impacted by regulations than households. Construction activities have always been subject to strict guidelines, with an emphasis on thermal performance since the 1970s. Retrofit regulation was introduced in 2007 as an add-on to the existing thermal regulations and worked following the same principle, by setting minimal energy efficiency requirement and constraining professional practices, notably regarding what materials can be used. Given the results presented in Chapter 3, it could be argued that regulatory efforts should be more heavily directed towards promoting green products - for instance by setting standards in terms of materials' carbon footprint, as these innovations are the least likely to be adopted spontaneously by contractors. Again, contrary to the materials they use, there is however no requirement regarding their skill level or degree, with the exception of plumbers and electricians who have to be licensed. This is particularly significant in light of the difficulties in upskilling underlining previously. Moreover, RGE-type labels have not proven effective in excluding unskilled firms from the market, per Chapter 1, which calls for stricter barriers to entry in order to prevent wrongful practices. Overall, as the construction sector is set to play a leading part in the energy transition, there needs to be higher requirements and access to professional training. Finally, one type of regulation is conspicuously absent: residential carbon externalities are not directly taxed. A carbon tax could efficiently send a price signal to both firms and households, and further affirm the role the construction sector is expected to play in environmental policies. It would increase the cost of energy inefficiency, meaning a higher return on a retrofit investment. A carbon-tax type of regulation, however, needs to be carefully designed, as it could be regressive for low-income households if energy poverty issues are not taken into account.

2 Future policy and research perspectives

2.1 Paving the way to global retrofits

This thesis provided insights on the state of retrofits in France using policies and observations from the 2010-2020 decade. Some aspects were beyond the scope of this thesis, but could be rewarding to further explore. A key factor contributing to the limited impact retrofits have had on residential energy consumption is the lack of global renovations. A large majority of retrofits were only partial, focusing on single tasks such as window replacement, wall insulation, etc. Tackling these issues one at a time reduces their efficiency and increases the chance of thermal bridges, as each task can be undertaken by a different contractor with no consideration for coordination. Global retrofits are however much more costly and take more time, which can pose additional constraints for households. The French 2020 Environmental Regulation, which is set to replace the previous thermal regulations for both existing and new buildings, has set ambitious targets in terms of global retrofits. This should translate into a modification of the eligibility conditions for grants and loans in the upcoming years. The CITE tax credit was already re-designed and the updated version, "*MaPrimeRénov'*"[1], was allocated a higher budget. This reform was effective in reaching low-income households, as they accounted for two thirds of the applications in 2021 while the CITE went mainly to high-income households (I4CE 2021). Additionally, dwellings with an energy consumption higher than 450 kWh/m^2 cannot be rented out anymore as of January 2023, which provides extra incentives for owners to undertake these large-scale retrofits. Comparative results on the efficiency of global and partial retrofits would help better direct public funds, which is essential since these schemes represent a large part of the government's climate investments. Further research could also address renovation issues that are unrelated to energy performance. In particular, given the demographic transition, more and more dwellings will have to be accommodated for individuals with reduced mobility in addition to increasing their energy performance (Trésor 2020).

Additionally, the aftermath of the COVID crisis and the recent conflict in Ukraine will have uncertain effects on construction activities despite this surge in demand for retrofits. On one hand, higher energy prices may lead households to invest in better heating equipment and insulation to reduce their expenses. On the other hand, higher material prices and longer shipment times have increased the prices of these retrofits, and the current global inflation crisis may relegate renovations to a secondary plan for households. These new regulations and market conditions open interesting research perspectives regarding their impact on retrofitting.

2.2 Towards developing new trades

Promoting retrofits also means reducing the share of new builds in the general construction activity. This will lead to a major reconfiguration of traditional trades in the years to come, starting with individual home builders. These contractors have already experienced a decrease in activity due to the shift of public aid schemes towards retrofit grants, which is set to be reinforced: the 2021 *"Climat-résilience"*[2] law has set a zero net land artificialization objective for 2050, which will drastically limit the number of building permits granted. Further, the Pinel law establishing tax incentives to invest in the construction of new rental housing is set to be abrogated by 2024. These recent evolutions drastically contrast with the way the construction sector was governed in the past, reflecting the transition to a more sustainable model taking into account the growing scarcity of energy resources, as well as impact of human activity on local ecosystems.

1. It can be translated to "*MyRetrofitGrant*".
2. "*Climate resilience*".

Home builders are not the only trade that will be affected by these deep changes to the construction sector. Virtually every trade has been impacted by technological advances, and will continue to be following the development of smart devices and more complex "*system*" solutions. Offsite construction and modular assembly have already changed the nature of a majority of contractors' day-to-day jobs. Offiste production processes range from the conception of small-scale elements like windows, which is already a fairly mainstream solution, to the prefabrication of entire rooms or houses. This development of standardized solution has been cited as a potential solution to the skill shortage on the market, since installers would have less of an impact on the final product (ECSO 2020b). The increasing demand for energy retrofits should create new trades in itself, since the traditional ones do not cover some key aspects. Insulation, for instance, has always been relegated as a secondary skills for masons, carpenters or plasterers. Given the recent development of new materials and more complex insulation systems, it is likely that it will become its own specialty in the future, in the same way that drywalling emerged as a trade during the 20$^{\text{th}}$ century.

Finally, the upcoming decades are likely to witness the emergence of intermediation platforms between households and contractors. As established in Chapter 1, trust is a central issue for households and the lack of quality signals may deter investments. This provides ground for intermediation, and there are already some initiatives launched by private actors in France, such as the *Maison Saint-Gobain*[3] or Leroy Merlin and Quotatis' *Frizbiz* platform. These platforms are typically linked to a preexisting hardware store brand and offer to put households and contractors in relation, for a small price paid by either side depending on the platform. This intermediation aims to both provide household with skilled contractors and speed up the retrofit process, for instance with additional on-site material delivery services. These deep changes to contractors' business model are set to have a significant impact on the structure of the construction market.

2.3 French results, European challenges

Although this thesis focused on France, its conclusions have a more global reach. France accounts for 15% of the European Union's citizens and 17% of its GDP (Insee 2019), and as such has a large impact on the EU. The construction activity takes place on an integrated market, which raises additional issues to take into consideration. As living standards and wages vary between member states, there are migration flows of skilled workers from less economically mature regions to richer countries (ECSO 2020b). This contributed to reduce

3. "*Saint-Gobain Home*".

the skill shortage for Western countries, but could cause a skill shortage for the countries of departure in the long run.

Further, the France has exceeded the European Union's expectation, making it a leading case studies for further research in other national contexts. Indeed, the European Union's 2011 "*Roadmap to a Resource Efficient Europe*" established that a more efficient use of resources in the construction and residential sectors could help reduce the EU's final energy consumption by 42%, and it would cut its greenhouse gas emissions by 35%. The resulting regulatory framework set an energy consumption reduction target of 20% for 2020, letting member states establish their individual "National Energy Efficiency Action Plan" (NEEAP). France had surpassed that goal as of 2018 (ECSO 2018a), which makes its NEEAP an interesting case study for policy design. In particular, the limitations highlighted throughout this thesis are interesting to consider when designing similar measures in other national contexts. Similar public aid schemes, thermal regulations and labels already exist in the United Kingdom and in Germany, but Peñasco and Anadón's (2023) recent evaluation of the UK aid scheme established a pessimistic vision of the long-run energy savings actually achieved *ex post*, which is consistent to the results presented in this thesis. A more comprehensive review of the performance of these policies depending on national contexts would help set more efficient policies and achievable targets.

* * *

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Abstract

Residential construction accounts for roughly 40% of final energy use and greenhouse gas emissions within the European Union. Consequently, since the 1970s, public policy has aimed to improve the energy efficiency of dwellings, through regulation and public aid schemes. While these programmes were initially intended to reduce energy import dependency, beginning in the 2000s, environmental challenges started becoming an increasing focus, with energy poverty becoming an additional area of concern in the 2010s. These three objectives translated into increasingly ambitious regulatory and incentive programs regulating new constructions and renovations. In practice, they encouraged industrial actors to improve building materials, and tried to stimulate households into commissioning renovations through financial aid.

This dissertation examines the web of economic relations these programmes have drawn between these different actors, and how they've impacted policy objectives, by focusing specifically on the role of construction firms. Indeed, construction firms occupy a crucial intermediary position between households who rely on their labor and expertise, industrial actors developing technical solutions, and the governmental institutions seeking to deploy policies. The construction sector thus stands out as a locus of problems and opportunities when it comes to bettering Europe's construction sector's energy efficiency along the three priorities outlined above: energy efficiency, sovereignty, and poverty.

The construction market is both highly fragmented and competitive: very small firms represent 99% of the firms in the market, and strikingly account for more than 2/3rds of full-time equivalent jobs and value added. Regulating this market, however, can prove surprisingly difficult, not least because it is difficult for consumers to assess whether they are receiving quality services or not: in most cases households cannot precisely identify their needs, nor implement the appropriate technical solution themselves, creating information asymmetries augmented by the lack of quality signals. These market failures can lead to fraud and poor workmanship that can undermine the effectiveness of energy renovations. This thesis explores how renovations are supplied to the market, focusing on European and French policy from 2010 to 2020, underlining the role of upskilling, promoting innovations and removing financial barriers for households. The first chapter presents theoretical insights on the impact of information asymmetries. The second and third chapters explore the dynamics of innovation diffusion among contractors with contrasting approaches. The fourth and final chapter evaluates the efficiency of retrofits, relying on panel data on French policies and households.