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Les obstacles à la baisse des consommations énergétiques dans le secteur résidentiel.

Une analyse empirique du cas français.

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Résumé

La réduction de la consommation énergétique du secteur résidentiel constitue un enjeu majeur dans un contexte de transition énergétique et de lutte contre le changement climatique. Pourtant, malgré les politiques publiques en place, la consommation énergétique sectorielle française peine à baisser. À travers quatre essais empiriques, cette thèse s'intéresse aux obstacles à la baisse des consommations énergétiques dans le secteur résidentiel français en se focalisant sur le rôle des facteurs individuels. Dans le *premier chapitre*, qui s'inscrit dans la littérature sur le les barrières à l'investissement en efficacité énergétique et le « paradoxe énergétique » (Jaffe and Stavins, 1994), nous utilisons la méthode des choix discrets pour mettre en évidence le rôle de l'incertitude sur la qualité des travaux de rénovation et le prix de l'énergie comme barrière à l'investissement en efficacité énergétique. Le *second chapitre* fournit un éclairage empirique sur le rôle des facteurs socio-économiques, des préférences individuelles pour le confort et de la performance énergétique du logement pour expliquer la consommation énergétique résidentielle. Le *troisième chapitre* est l'occasion d'étudier l'écart de performance énergétique à l'échelle du logement (consommation énergétique réelle vs théorique) et ses déterminants individuels et socio-économiques, via la régression quantile. Enfin, le *quatrième chapitre* s'intéresse aux interactions dynamiques entre efficacité énergétique et consommation énergétique en traitant la question de l'effet rebond direct pour l'usage de chauffage résidentiel en France.

Mots clé : consommation énergétique, secteur résidentiel, comportement énergétique, efficacité énergétique, effet rebond, préférences individuelles

Abstract

Reducing the energy consumption of the residential sector is a major stake in the context of the energy transition and the fight against climate change. However, despite the implementation of several dedicated public policies, the energy consumption of the sector has barely decreased in France. Through four empirical articles, this thesis aims to identify some of the barriers to the decrease of the French residential energy consumption with a focus on the role of individual determinants. In the first chapter, we wish to contribute to the literature on the barriers to energy efficiency investment (Sutherland, 1991) and the "energy efficiency gap" (Jaffe and Stavins, 1994). We use the methodology of the discrete choice experiment to assess the role of perceived risk and uncertainty on retrofit quality and energy price as barrier to the energy renovation decision. In the second chapter, we provide an empirical contribution on the role of individual preferences for comfort, other individual determinants and energy performance of dwellings in explaining energy consumption. In the third chapter, we study the *energy performance gap* (gap between theoretical and real energy consumption at dwelling level) and its drivers by using the quantile regression. Finally, in the fourth chapter, we test the assumption of the existence of a rebound effect for the heating energy consumption in France.

Key words: energy consumption, residential sector, energy behaviour, energy efficiency, rebound effect, individual preferences.

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Introduction générale

En France, le secteur résidentiel représente 30% de la consommation énergétique finale nationale française et émet 20% des émissions de gaz à effet de serre nationales[1]. Depuis longtemps déjà, de par son potentiel d'économies d'énergie significatif (80% du potentiel d'efficacité énergétique du secteur du bâtiment serait non-réalisé[2]), la réduction des consommations énergétiques sectorielles a été désignée comme enjeu majeur pour la transition énergétique, la lutte contre le changement climatique et pour la sécurité énergétique, en France, mais aussi dans d'autres pays européens. Dès 1975 est née la première réglementation thermique française mettant en place des normes de construction visant la meilleure efficacité énergétique des bâtiments. Les politiques publiques qu'elles soient de types réglementaires ou incitatives se sont ensuite succédées et complétées dans le but de permettre l'atteinte des objectifs énergétiques et climatiques prévus par les cadres législatifs français, européens et les accords internationaux. Pourtant, aujourd'hui, le constat est le suivant : la consommation énergétique du secteur résidentiel français peine à décroître. Entre 1999 et 2015, soit en 15 ans, la consommation finale d'énergie du secteur a diminué seulement de 8 %.[3] Par ailleurs, en 2016, la France n'a pas respecté ses objectifs de réduction d'émissions des gaz à effet de serre, en partie à cause du secteur du bâtiment qui a démontré une hausse d'émissions de +11%[4] (venant en partie des consommations de gaz ou de fioul domestique pour le chauffage). Ainsi, à politique inchangée, il semble que les trajectoires énergétiques et climatiques devraient être en deçà des objectifs[5].

La question se pose alors : Existerait-il des obstacles à la baisse des consommations énergétiques découlant des spécificités du secteur ?

Pour répondre à cette question, il est nécessaire de revenir sur les modalités d'action qui permettraient la réduction de la consommation énergétique finale du parc de logements. Il existe

[1] Le rapport du Commissariat Général au Développement durable est disponible sur le lien suivant : http://www.carbone4.com/wp-content/uploads/2016/08/Revue_-_Renovation_thermique.pdf

[2] Plus d'information sur le potentiel d'économie d'énergie de différents secteurs sont présentés dans le rapport de l'International Energy Agency, voir : https://www.iea.org/media/training/eetw2016/buildings/A.2_Energy_efficiency_potential.pdf

[3] Plus de détails sur les statistiques nationales : http://www.statistiques.developpement-durable.gouv.fr/lessentiel/ar/340/1207/consommation-denergie-emissions-co2-lhabitat.html

[4] Des chiffres clés sur tendances énergétiques françaises sont disponibles ici : https://www.actu-environnement.com/ae/news/strategie-bas-carbone-reduction-emissions-investissements-transport-batiment-30508.php4

5 La LETCV fixe la réduction de 50% la consommation énergétique entre 2012 et 2050 (LTECV et PPE) tous secteurs confondus. Les orientations de la Stratégie Bas Carbone 2015-2028 identifient le secteur du bâtiment comme principal levier d'action.

deux leviers. Le premier est l'efficacité énergétique, qui permet d'agir sur la consommation de chauffage ou des équipements, en conduisant par exemple à la réduction du besoin de chauffage du bâti ou des intensités énergétiques des appareils. Ainsi, la meilleure isolation, ou l'installation de systèmes de chauffage performants via la rénovation énergétique peut permettre des gains d'énergie considérables dans le secteur résidentiel (particulièrement sur l'usage chauffage qui représente environ 60% de la consommation d'un logement). En France, ce potentiel est très important compte tenu de l'état général peu performant du parc de logements et a été la cible de la majorité des politiques publiques mises en place jusqu'à présent. En effet, outre la mise en place de réglementations thermiques ciblant avant tout la construction neuve, d'importants moyens financiers ont été mobilisés pour inciter les ménages à rénover.
Le second levier est la sobriété énergétique, i. e. consommer l'énergie avec modération, et concerne tous les usages énergétiques (chauffage, électricité spécifique, eau chaude sanitaire, etc.) ; la mise en œuvre volontaire de ce levier relève de considérations idéologiques et de préférences individuelles. Les travaux de recherche ont montré que jusqu'à 30% d'économies d'énergie pouvaient découler d'un changement vers des comportements plus économes en énergie (Lopes et al., 2012).

Ainsi, une des spécificités de la transition énergétique du secteur résidentiel est qu'elle reposerait *in fine* sur un ensemble de décisions individuelles concomitantes des usagers, que ce soit pour la mise en œuvre de comportements économes en énergie ou de solutions d'efficacité énergétique. Les caractéristiques des ménages et notamment leur capacité économique, idéologique, etc. à assumer les choix énergétiques nécessaires posent les conditions de la transition énergétique du secteur résidentiel. De ce fait, bien qu'à première vue le potentiel d'économie d'énergie du secteur résidentiel existe et est important, la réduction de la consommation d'énergie du secteur semble être un challenge car elle se joue au niveau de décision le plus désagrégé possible avec un grand nombre d'acteurs aux comportements potentiellement hétérogènes et complexes. Confirmant cette intuition, la littérature académique foisonnante sur le sujet a mis en évidence que les ménages et leurs caractéristiques constituent un facteurs explicatif essentiel pour comprendre la consommation énergétique sectorielle (Belaïd, 2017; Newell and Siikamaki, 2015; Qiu et al., 2014).

Ainsi, nous prenons ici le pari que la meilleure compréhension des comportements énergétiques individuels peut aider à identifier et à lever les obstacles à la baisse des consommations énergétiques dans le secteur résidentiel français. Cette démarche pourrait aussi permettre

d'apporter des éléments d'éclairage pour la décision publique. Pour atteindre cet objectif, les travaux de recherche empiriques ont ici toute leur importance.

La présente thèse propose quatre contributions empiriques originales pour répondre à la question suivante : quels sont certains des obstacles à la baisse des consommations énergétiques dans le secteur résidentiel ? Les travaux ont pour objectif d'apporter un éclairage empirique aux décideurs publics sur les schémas de la décision énergétique et les facteurs qui pourraient limiter la réduction de la consommation énergétique résidentielle du point de vue des ménages. Ils se focalisent sur le cas français.

I. Les apports de la littérature académique passée pour la définition de la problématique de thèse et des questions de recherche traitées.

Depuis plusieurs décennies, face au constat de la difficulté du secteur résidentiel à réduire sa consommation énergétique et/ou ses émissions de gaz à effet de serre, la littérature académique apporte un éclairage actif indispensable aux décideurs publics. Sur le sujet, plusieurs champs de recherche académique se croisent ; certains sont particulièrement pertinents pour enrichir notre problématique de thèse ainsi que pour élaborer des pistes de recherche en vue d'y apporter des éléments de réponse. Ces champs de la littérature mettent notamment en évidence et/ou justifient la difficulté de mise en œuvre des deux moyens d'action identifiés pour la réduction de la consommation énergétique résidentielle –i.e l'efficacité énergétique et la maîtrise des consommations énergétiques- et contribuent à l'élaboration de recommandations adressées aux décideurs publics pour mobiliser les gisements d'économie d'énergie ciblés.

Tout d'abord, les enjeux liés à la difficulté de mise en œuvre du levier de l'efficacité énergétique sont approchés par la vaste littérature sur les barrières à l'investissement en efficacité énergétique (Sutherland, 1991), dont la littérature sur le « paradoxe énergétique » ou « energy efficiency gap » (« écart d'efficacité énergétique »)(Jaffe and Stavins, 1994) fait partie. La littérature fait état du constat du sous-investissement dans les solutions d'efficacité énergétique dans le secteur résidentiel malgré leur apparente rentabilité. Le paradoxe énergétique en particulier est justifié par l'existence de défaillances de marché, de barrières de marché et de défaillances comportementales (Gillingham et al, 2018 ; Jaffe and Stavins, 1994). Les barrières de marché englobent par exemple des problématiques de risque et d'incertitude, d'hétérogénéité des agents ou l'existence de coûts cachés. La littérature sur le sujet est très active aujourd'hui avec notamment l'essor d'analyses empiriques pour appuyer le rôle des différentes barrières.

D’autre part, la littérature a par ailleurs montré que l’efficacité énergétique est loin d’être le seul facteur déterminant de la consommation énergétique. Le rôle des usagers et de leur hétérogénéité pour expliquer la consommation énergétique finale est tout aussi crucial et a été l’objet d’une recherche empirique active jusqu’à aujourd’hui. Les enjeux liés à la sobriété énergétique et plus largement ceux liés à la maîtrise des consommations énergétiques sont abordés par une littérature très riche visant à identifier les déterminants de la consommation énergétique ou des comportements économes en énergie (Belaïd, 2017; Harold et al., 2015; Hori et al., 2013; Yue et al., 2013). Cette littérature montre notamment qu’il est nécessaire d’intégrer plusieurs niveaux de décision dans les modèles de consommation énergétique pour mieux apprécier le rôle des déterminants socio-économiques et individuels. Aujourd’hui, intégrer l’ensemble des recommandations académiques et participer à l’amélioration des connaissances sur le sujet en vue d’éclairer la décision publique requiert la mobilisation de données toujours plus riches pour mieux apprécier l’importance de l’hétérogénéité individuelle. Finalement, au croisement de ces deux pans de la littérature se trouve un autre champ d’investigation aux enjeux significatifs pour notre problématique, celui de l’effet rebond (Jevons, 1965). Cet effet fait référence au fait que les économies d’énergie issues de la mise en œuvre de l’amélioration de l’efficacité énergétique sont moins importantes qu’attendu ; ceci serait justifié par une augmentation de la demande pour le service énergétique ciblé suite à la baisse du coût de ce service. La théorie économique a fourni une littérature très riche sur le sujet ; cependant les applications et les estimations de l’effet rebond pour le secteur résidentiel sont peu nombreuses et très dépendantes des méthodologies mobilisées et des périmètres considérés.

Les principaux résultats et apports de la littérature à la construction de notre problématique et de nos questions de recherche sont présentés ci-dessous.

1. ***Le paradoxe énergétique et les barrières à l'efficacité énergétique dans le secteur résidentiel, de la théorie à l'évidence empirique***

La mise en œuvre des solutions d'efficacité énergétique dans les logements résidentiels est un levier d'action incontournable pour la réduction des consommations énergétiques du secteur. Cependant, il n'est aujourd'hui que très peu mobilisé par les ménages[6]. En allant dans le sens de ce constat qui ne se limite pas qu'au territoire national, la littérature en économie de l'énergie a mis en exergue la potentielle existence d'un « paradoxe énergétique » ou « energy efficiency gap » (Jaffe and Stavins, 1994a) dans le secteur résidentiel, justifié par la prévalence de barrières à l'investissement en efficacité énergétique (Sutherland, 1991). Le constat est le suivant : malgré l'apparente rentabilité des investissements en efficacité énergétique, on observe un sous-investissement dans ces technologies. Dans le secteur résidentiel, de nombreuses barrières sont fréquemment citées et investiguées par les académiques pour justifier le sous-investissement en efficacité énergétique (cf Tableau 1) (Gillingham and Palmer, 2014a; Sutherland, 1991).

La littérature sur les barrières aux investissements en efficacité énergétique distingue trois types de barrières : *les imperfections de marché*, les *barrières de marché ou barrières économiques* et *les défaillances comportementales* (Brown, 2001 ; Gillingham, 2018 ; Jaffe and Stavins, 1994).

Tout d'abord, les imperfections ou défaillances de marché se définissent par des conditions du marché qui aboutissent à une allocation inefficace des ressources. Elles correspondent à des conditions du marché qui violent une ou plusieurs des hypothèses néoclassiques d'économie comme l'absence de coûts de transaction et l'information parfaite. La présence d'imperfections de marché est considérée comme une justification pour l'intervention publique relative à l'efficacité économique (Brown, 2001). Dans le domaine de l'efficacité énergétique résidentielle, on peut citer les défaillances de marché suivantes : la non prise en compte par le marché de l'externalité négative de pollution liée à l'usage intensif d'énergie, l'asymétrie d'information (par exemple illustré par l'aléa moral entre maitre d'ouvrage et maître d'œuvre quant à la qualité des travaux de rénovation énergétique réalisés), l'existence d'incitations divergentes entre propriétaires et locataires (le propriétaire n'a aucun intérêt économique à investir dans des travaux dont les bénéfices économiques ne lui reviendront pas), etc.(Davis,

[6] Les résultats de l'enquête OPEN sur les travaux énergétiques réalisés par les ménages français est disponible sur le lien suivant : http://www.alec-saint-brieuc.org/2016/06/08/les-chiffres-de-la-renovation-en-france-letude-open-2015/

2010; Gillingham et al., 2016; Giraudet et al., 2018; Jessoe et al., 2017; Giraudet & Houde, 2014; Myers, 2013).

L'autre grande famille de barrières est constituée des barrières de marché ou barrières dites économiques. Ces barrières correspondent à des conditions de marché qui découragent l'investissement en efficacité énergétique relativement à un niveau estimé coût-efficace, contribuant alors à la diffusion lente des technologies efficaces en énergie (Jaffes and Stavins1994 ; Brown, 2001). On peut notamment citer les barrières suivantes (Brown, 2001). Tout d'abord, *la faible priorité* donnée par certains consommateurs aux questions énergétiques: par exemple, certains consommateurs peuvent ne pas percevoir la nécessité d'investir en efficacité énergétique (ou même d'adopter des comportements énergétiques modérés). Cela peut s'expliquer, par exemple, par le fait que la facture énergétique n'a pas la même importance dans le budget de tous les consommateurs (par exemple, pour les ménages à faibles et hauts revenus). Ainsi, l'hétérogénéité des agents et des situations peut constituer un facteur explicatif au faible taux d'adoption des technologies d'efficacité énergétique. Par ailleurs, pour ceux qui perçoivent l'intérêt d'un investissement en efficacité énergétique, d'autres barrières de marché peuvent intervenir. Ainsi, la rénovation énergétique a un coût élevé et *l'accès au capital* n'est pas le même pour tous ; cela peut se traduire par des taux d'intérêt plus élevés pour certains consommateurs les dissuadant/ empêchant d'emprunter des capitaux et de passer à l'acte en matière de rénovation énergétique. D'autre part, *l'incertitude sur la rentabilité de l'investissement* en efficacité énergétique peut aussi rentrer dans la catégorie des barrières de marché ; parmi les éléments entrant en jeu, l'incertitude de court terme sur les prix futurs de l'énergie peut être un frein à l'investissement (Brown, 2001). L'incertitude économique et technologique, l'irréversibilité peuvent favoriser des comportements d'inertie et d'attentisme par rapport à l'investissement en efficacité énergétique, les ménages préférant alors patienter pour améliorer leurs connaissances sur les paramètres (prix, type de technologie, etc.) intervenant dans le choix à réaliser (Gerarden et al., 2015; Kevin A Hassett and Metcalf, 1992; Newell and Siikamaki, 2015). Finalement, *l'existence d'un marché incomplet relativement à l'efficacité énergétique* peut constituer un obstacle supplémentaire à l'adoption des investissements en efficacité énergétique (Brown, 2001). Cela est le cas quand l'efficacité énergétique est un attribut constitutif d'un bien plus global destiné à fournir un autre service (par exemple, dans notre cas, le service de logement). Alors, le choix du niveau d'efficacité énergétique n'est pas forcément possible, car contraint par certaines circonstances (localisation, taille, coût du logement). Enfin, l'existence de coûts cachés relativement à la mise en œuvre de

solutions d'efficacité énergétique (coût de la recherche d'information sur les solutions d'efficacité énergétique, coût du dérangement, etc.) pourraient, rationnellement, fortement limiter leur intérêt pour les ménages (Fowlie, 2015).

Par ailleurs, la littérature évoque aussi l'existence de « biais comportementaux » côté ménage, faisant référence à des phénomènes individuels comportementaux qui peuvent amener à « déformer » la vision de la réalité économique et à violer l'hypothèse de rationalité des consommateurs posée dans les modèles économiques néo classiques. Ces « défaillances » peuvent conduire à une forme de « rationalité limitée » dans le comportement d'investissement des ménages dans les solutions d'efficacité énergétique et justifient une intervention publique corrective. Par exemple, on trouve dans cette catégorie les comportements suivants : le biais du statu quo (le ménage surévalue le bien-être apporté par la situation actuelle), l'inattention, l'effet de l'irréversibilité (le fait de ne pas pouvoir revenir en arrière peut réduire l'envie de changer de situation), l'aversion à la perte (liée au coût d'investissement considérable des solutions d'efficacité énergétique et au long temps de retour sur investissement, etc.) (Sexton, 2014; Tsvetanov and Segerson, 2014).

Parmi les trois types de barrières citées précédemment, nous intéressons dans les différents chapitres de ce travail de thèse principalement aux barrières de marché. Tout naturellement en effet, la perspective « ménage », empirique et à visée opérationnelle choisie dans ce travail de thèse, visant à mieux comprendre les schémas de la décision énergétique dans le secteur résidentiel français s'inscrit dans le second type de barrières. Notamment, le rôle de l'hétérogénéité des agents y est central. Celle-ci peut s'exprimer de différentes façons, que ce soit, par exemple, par la perception qu'ont les individus de l'environnement et des conditions du marché, en lien avec les choix de rénovation énergétique, ou par les préférences individuelles pour le confort ou les caractéristiques socio-économiques des individus en lien avec le choix du logement et du niveau d'intensité énergétique. Bien qu'elles ne constituent pas en elles-mêmes une justification en faveur de l'intervention publique relativement au critère d'efficacité économique, mettre en évidence certaines de ces barrières de marché est utile pour aider la décision publique. Par exemple, cela est nécessaire pour mieux comprendre l'origine de certains dysfonctionnements des politiques publiques passées (par exemple, l'efficacité des politiques énergétiques de subvention en termes de réduction de la consommation énergértique), ajuster les dispositifs actuels pour mieux accompagner les ménages aux ressources limitées (notion de justice sociale), identifier des mesures d'accompagnement du marché qui peuvent aider l'atteinte des objectifs énergétiques et aider à la prévision plus précise des effets des futures

politiques publiques, via la meilleure connaissance des comportements énergétiques et de leur intégration dans des modèles.

Dans le premier chapitre de cette thèse, nous nous intéressons tout d'abord à deux barrières de marché qui s'insèrent directement dans la littérature de l'energy efficiency gap susmentionnée : le rôle de l'incertitude sur les bénéfices de la rénovation dans la décision de rénovation énergétique et de l'hétérogénéité des agents.

Une très riche littérature théorique suggère que l'incertitude et le risque perçus peuvent être des freins à l'investissement non négligeables dans le domaine de l'efficacité énergétique (Dixit and Pindyck, 1994; Gollier, 2007; Neumann and Morgenstern, 2007; Sutherland, 1991). Cependant, les contributions de la littérature empirique sur ce sujet sont rares. Quelques travaux empiriques ont mis en évidence le rôle de l'aversion au risque pour expliquer le sous-investissement en efficacité énergétique dans le secteur résidentiel (Qiu et al., 2014; Volland, 2017 ; Fischbacher et al., 2015); d'autres travaux suggèrent que l'incertitude pourrait être un frein à l'investissement et se reflèteraient dans des hauts taux d'actualisation pour ces investissements (Anderson and Newell, 2004; Gerarden et al., 2015; Hassett and Metcalf, 1992). Cependant, à notre connaissance, aucun travail de recherche ne cherche à identifier, distinguer et mesurer le rôle des différentes sources d'incertitude ou de risque perçues par les ménages qui jouent sur la décision d'investissement en efficacité énergétique. Un des seuls travaux empiriques de référence est celui d'Alberini (2013) dans lequel il est mis en évidence précisément le rôle de l'incertitude sur le prix futur de l'énergie comme un frein à l'adoption des ménages via la méthodologie de l'expérience de choix discrets. Cependant, la question de l'hétérogénéité des préférences est peu abordée faute de taille d'échantillon adéquat et le périmètre est restreint au rôle de l'incertitude sur les prix de l'énergie. Cet article fournit des indications précieuses : l'intérêt de réaliser une enquête dédiée à la problématique et notamment la pertinence de l'utilisation de méthodologies des préférences déclarées dans le domaine de l'efficacité énergétique (méthode de choix discret). Dans cette thèse, nous nous intéresserons donc à tester la réalité de la barrière du risque et de l'incertitude liés à la qualité des travaux et au prix futur de l'énergie comme frein à l'investissement en efficacité énergétique chez les ménages français. Cette analyse fera l'objet du chapitre un. Compte tenu des challenges identifiés, ce travail sera réalisé grâce à l'élaboration et l'analyse d'une enquête innovante utilisant la méthodologie de l'expérience de choix discret.

Tableau 1. Les barrières à l'investissement en efficacité énergétique dans le secteur résidentiel, adapté de (Cagno et al., 2013; Sorrell and O'Malley, 2004; Sutherland, 1991)

Type	**Domaine**	**Description des barrières**	**Littérature récente**
Imperfections de marché	*Information*	Information incomplète	(Giraudet & Houde, 2014) (Giraudet 2018) (Myers, 2013)
		Aléa moral (maîtrise d'œuvre/maîtrise d'ouvrage)	
	Organisation	Incitations divergentes (propriétaire /locataire)	(Charlier, 2015; Jessoe et al., 2017; Melvin, 2018)
Barrières de marché	*Economique*	Coûts cachés	(Fowlie et al., 2015)
	Economique	Incertitude (prix de l'énergie, qualité des travaux , etc.), irréversibilité	(Alberini, 2013)
	Economique	Accès au capital	
	Préférences et hétérogénéité	Faible priorité	
		Aversion au risque	(Farsi, 2010; Fischbacher et al., 2015; Greene, 2011)
		Préférence temporelle	(Fischbacher et al., 2015; Newell and Siikamaki, 2015)
Imperfections comportementales		Biais de status quo, aversion à la perte	

2. ***L'usager, déterminant majeur de la consommation énergétique résidentielle.***

L'efficacité énergétique n'est pas le seul moteur de la réduction des consommations énergétiques résidentielles. En effet, le rôle de l'usager est central pour comprendre la consommation énergétique. Certains comportements et facteurs individuels découlant de l'hétérogénéité des agents (préférences individuelles, caractéristiques socio-économiques) peuvent conduire à des écarts importants entre consommation énergétique réelle et consommation énergétique théorique (liée à l'efficacité énergétique du logement) à l'échelle d'un logement et ainsi conduire à mésestimer ou sous-estimer les gisements d'économie d'énergie mobilisables.

Les déterminants de la consommation énergétique résidentielle.

Dans ce champ de la littérature, les travaux de recherche empiriques passés se sont beaucoup intéressés au sujet des déterminants de la consommation énergétique résidentielle. Par des études avant tout économétriques, les chercheurs de ce domaine ont notamment montré que la consommation d'énergie finale dépendait, certes, de multiples facteurs externes (climatique, efficacité énergétique du logement, prix de l'énergie) mais aussi largement des caractéristiques individuelles des occupants comme le niveau de revenu, les croyances personnelles (le niveau d'information), le statut d'occupation, la place dans le cycle de vie, etc. (Ayres et al., 2013; Belaïd, 2017; Harold et al., 2015). Les approches statistiques de type bottom-up ont pu estimer que 40% de la consommation d'énergie était déterminée par les facteurs techniques caractérisant le bâtiment d'habitation ; ainsi, la part restante est dépendante d'un ensemble d'autres variables, pour la plupart de l'ordre des facteurs individuels. Par exemple, les ménages aux revenus élevés consommeraient plus d'énergie que les ménages plus pauvres, ce qui pourrait traduire un besoin de confort exagéré et laisse envisager une marge de manœuvre positive pour l'action publique en vue de la meilleure maîtrise des consommations énergétiques. Cependant, les effets revenus sont parfois ambigus et peuvent capter les effets de variables non observées parfois contradictoires (Cayla et al. 2011; Labandeira et al. 2006; Nesbakken 2001; Santamouris et al. 2007). Par ailleurs, les préférences pour le confort sont rarement l'objet d'évaluation (qualitative ou quantitative). Les variables socio-économiques sont en effet souvent les seuls indicateurs utilisés pour expliquer la consommation énergétique par l'hétérogénéité individuelle. Ainsi, de futures contributions sont nécessaires pour approfondir la connaissance des schémas de décision énergétique en faisant intervenir des variables individuelles plus ciblées : préférences pour les économies d'énergie, sensibilité environnementale, etc.

La littérature empirique a réaffirmé le besoin d'intégrer l'ensemble de ces déterminants (socio-économiques, individuels, techniques, environnementaux, etc.) mais aussi de prendre en compte leurs interactions et corrélations (Estiri, 2015; Ewing and Rong, 2008) pour estimer plus justement leur poids dans la consommation énergétique finale. Considérer les corrélations entre caractéristiques techniques et individuelles du ménage revient à considérer que la consommation énergétique finale résulterait de plusieurs niveaux de décision : le choix de l'équipement énergétique (équipements électro-ménagers, système de chauffage, logement, etc.) et le choix de l'intensité d'utilisation du service énergétique (Estiri, 2014; McLoughlin et

al., 2012; Stolyarova, 2016). Pour investiguer la pertinence de ce cadre d'analyse à l'échelle du logement, des données relatives à la caractérisation objective de l'entité « logement » (dont la performance énergétique) sont nécessaires pour isoler son effet sur la consommation énergétique de celui d'autres facteurs d'ordre économique ou individuels. Or, ces données sont rarement disponibles compte tenu de leur nature technique qui nécessite l'intervention d'un expert (donc, réalisable à un certain coût). Jusqu'à présent, seule des variables descriptives et facilement observables du logement (surface, statut d'occupation, type de logement) ont été mobilisées dans ce cadre d'analyse à plusieurs niveaux.

Ainsi, la structure du parc de logements, les caractéristiques individuelles et comportements associés des ménages les occupant sont cruciaux pour comprendre la consommation énergétique finale du parc de logements, les obstacles à sa réduction et les leviers potentiels. Contribuer à ce champ de la recherche nécessite des données toujours plus riches (données à la fois techniques et individuelles) pour intégrer au mieux les dernières avancées académiques et pouvoir répondre à notre question de thèse.

Dans ce contexte et grâce à la disponibilité d'une enquête ménages très riche sur la consommation énergétique et l'efficacité énergétique du parc français (enquête PHEBUS[7], présentée plus en détail dans la section I.3), nous nous intéresserons dans le chapitre deux de cette thèse à comprendre les déterminants de la consommation énergétique française en prenant en compte l'existence d'une double décision énergétique : le choix du logement, décrit par sa performance énergétique, et le choix de consommation énergétique finale. Nous intéresserons particulièrement au rôle de l'hétérogénéité des préférences individuelles pour le confort et aux effets revenus pour expliquer ces choix.

Mesurer et comprendre les déterminants de la sobriété énergétique

Dans une moindre mesure, la littérature académique s'est aussi intéressée à l'étude des déterminants des comportements dits « économes en énergie »[8] ou « sobres en énergie »[9]. La sobriété énergétique est définie par une démarche volontaire et organisée de réduction des consommations d'énergie par des changements de modes de vie, de pratiques[10], etc. ; elle

[7] Voir la description de l'enquête en suivant le lien : https://www.cnis.fr/enquetes/performance-de-lhabitat-equipements-besoins-et-usages-de-lenergie-phebus-enquete-sur-la/

[8] Sont exclus ici les comportements d'investissement en efficacité énergétique.

[9]Pour une définition de la sobriété énergétique plus approfondie, consulter par exemple la page internet suivanthttp://www.appanpc.fr/_docs/7/fckeditor/file/Revues/AirPur_Env_Sante/numero_09/HTML/files/assets/common/downloads/page0008.pdf

[10] Pour une définition de la sobriété énergétique, suivre le lien suivant : http://www.virage-energie-npdc.org/imaginer-le-futur/la-sobriete-energetique

s'évalue par rapport à un référentiel (par exemple, une pratique énergétique « standard »). Dans cette littérature, les comportements énergétiques ne sont pas observés via la quantité d'énergie finale consommée mais par un indicateur capable de cerner et d'évaluer plus précisément les habitudes ou intensités énergétiques et les usages concernés. Il y a un réel enjeu à mieux comprendre l'ampleur et l'origine des comportements économes ou non en énergie. Notamment, cela pourrait permettre d'améliorer le ciblage des politiques publiques en faveur de la réduction des consommations énergétiques individuelles (qui consomme plus que les autres, plus que la norme, sur quels usages énergétiques ?) ainsi que les prédictions des trajectoires énergétiques. Les travaux de recherche de ce deuxième champ de la littérature sont plus rares mais non moins nécessaires. En effet, les économies d'énergie atteignables par la mise en œuvre de comportements économes en énergie ne seraient pas négligeables, jusqu'à 30% (Lopes et al., 2012).

L'enjeu ici est de caractériser les comportements énergétiques en définissant une échelle commune d'évaluation pour les usages énergétiques ciblés. Cela peut se révéler être une tâche ardue. Une partie de la littérature sur le sujet repose sur des travaux issus du domaine de la psychologie (Blake, 1999; Steg and Vlek, 2009). Quelques études empiriques contribuent aujourd'hui aussi à cette problématique de recherche (Belaïd, 2015; Hori et al., 2013; Yue et al., 2013). Ces dernières utilisent majoritairement des indicateurs de « sobriété » énergétique basés sur les habitudes énergétiques déclarées par les ménages, parfois agrégées en un seul indicateur, relevés au cours d'enquêtes ménages. Les travaux démontrent que les bénéfices économiques, la performance énergétique du logement, la sensibilité environnementale peuvent expliquer dans un sens ou dans l'autre les comportements économes en énergie.

Cependant, il existe un manque de contributions de recherche mobilisant des données quantitatives pour évaluer la nature des comportements (sobres ou non en énergie) sur données mesurées réelles. Certains ménages consomment-ils plus d'énergie ou moins d'énergie que « prévu » ? Si oui, pourquoi, sur quel usage ? Répondre à ces questions pourrait pourtant permettre de mieux identifier et évaluer les catégories de consommateurs d'énergie au regard de leurs caractéristiques et d'améliorer significativement les prédictions des modèles énergétiques ingénieurs utilisés dans le bâtiment résidentiel en intégrant des facteurs « correctifs » (Allibe, 2012; Delzendeh et al., 2017; Galvin, 2013). Pour ce faire, la disponibilité de données adéquates est souvent le facteur limitant. En effet, d'une part, des données techniques et fiables sur les logements, leur consommation énergétique, leur performance énergétique sont nécessaires pour établir l'indicateur de comportement énergétique ; d'autre part, des données individuelles comme les données socio-économiques,

les préférences, etc. et des données environnementales comme le climat réel, le prix de l'énergie, etc. sont nécessaires pour comprendre sa variabilité.

Quelques premiers résultats existent cependant et ont démontré une intensité d'utilisation de l'énergie[11] croissante avec la performance énergétique du logement et l'existence d'un écart entre consommation énergétique réelle et théorique[12] sur le périmètre du chauffage et de l'usage eau chaude sanitaire allant dans les deux sens (existence de situations de sur- ou sous-consommation d'énergie par rapport à la référence de consommation théorique) (Galvin 2013) ; il est fait l'hypothèse que le sens de l'écart reflèterait les préférences pour le confort et la contrainte économique des ménages en relation avec la qualité énergétique du logement. Tester cette hypothèse pourrait constituer une piste intéressante pour notre problématique puisque cela peut faire émerger explicitement les raisons des écarts/dysfonctionnement entre la consommation énergétique réelle et les attentes théoriques, notamment les raisons qui relèveraient de l'hétérogénéité des ménages et de facteurs individuels. Cette dernière piste d'étude fera l'objet de notre chapitre trois. Grâce aux riches données de l'enquête PHEBUS, nous avons en effet la possibilité d'investiguer les déterminants de *l'écart de performance énergétique* chez les ménages français via la caractérisation de l'intensité d'usage énergétique à l'échelle du logement (ratio consommation énergétique réelle/ consommation énergétique théorique). Notamment, nous nous focaliserons sur le rôle des déterminants socio-économiques et les préférences individuelles pour le confort pour expliquer cet écart.

L'effet rebond direct dans le secteur résidentiel français, quand l'amélioration de l'efficacité énergétique entraîne un changement de comportement énergétique.

Le dernier volet de la littérature laissant suspecter de potentiels obstacles individuels à la réduction des consommations énergétiques du secteur résidentiel est celui traitant de l'effet rebond.

Ce phénomène comportemental fait référence à une augmentation de la demande du service énergétique après l'amélioration de son efficacité énergétique et donc la baisse du son coût (Alcott, 2005). L'effet rebond direct a fait l'objet de nombreux travaux académiques appliqués au secteur résidentiel (Berkhout et al., 2000; Khazzoom, 1980; Thomas and Azevedo, 2013a).

[11] Calculée à partir du ratio consommation énergétique réelle / consommation énergétique théorique (issue d'un modèle ingénieur)

[12] La consommation énergétique théorique est basée sur la prédiction de consommation énergétique calculée à partir des besoins de chauffage du bâtiment et d'utilisation de l'eau chaude sanitaire (issus du Diagnostic de Performance Energétique). Le logement est supposé être occupé et utilisé selon des « conditions standards » dépendant de sa surface, de sa qualité énergétique, du climat, etc.

Pour l'usage chauffage, l'augmentation de la consommation énergétique serait justifiée par une amélioration du confort thermique.

La conséquence inhérente de l'effet rebond est que les économies d'énergie réalisées après la mise en œuvre d'une solution d'efficacité énergétique sont moins importantes qu'attendu : mesurer l'effet rebond est donc d'un intérêt premier pour mieux anticiper l'effet des politiques d'efficacité énergétique sur la réduction des consommations énergétiques. Dans la littérature, les approches pour mesurer l'effet rebond direct sont de deux types (Sorrell and Dimitropoulos, 2008): la première est la comparaison des gains énergétiques réels entre les situations avant et après rénovation énergétique avec les gains théoriquement attendus ; cette méthode est exigeante car elle nécessite un suivi précis et temporel sur de nombreux ménages et logements et requiert un proxy de l'efficacité énergétique du logement. L'autre approche est l'estimation de l'élasticité prix de la consommation énergétique par une approche économétrique (données de panel, séries temporelles). Comme un gain d'efficacité énergétique correspond à une baisse du coût du service énergétique[13], il est fait l'hypothèse qu'estimer l'effet rebond reviendrait à étudier la réaction de la consommation énergétique à la baisse du coût de l'énergie (élasticité prix). Cependant, l'approche ne fait pas toujours consensus parmi les micro-économistes (Chan et Gillingham, 2015) dont les travaux suggèrent des cas où cette méthodologie pourrait conduire à un biais dans l'estimation de l'effet rebond. Par ailleurs, d'autres critiques viennent du fait beaucoup de travaux ignorent l'asymétrie de la réaction de la consommation énergétique aux hausses puis baisses successives du prix de l'énergie (Thomas and Azevedo, 2013). Dans la réalité en effet, cette réaction est bien asymétrique puisque les solutions d'efficacité énergétiques installées en réponse à une hausse du coût de l'énergie ne peuvent être retirées ensuite lorsqu'celui-ci baisse à nouveau. Au regard de cette critique, quelques académiques ont intégré une décomposition du prix de l'énergie à cette deuxième approche. Compte tenu des dernières contributions académiques et au regard des données disponibles, le dernier chapitre de thèse sera l'occasion de tester l'hypothèse d'un effet rebond pour l'usage chauffage (principale cible des politiques de réduction des consommations énergétiques en France).

[13] Par exemple, après travaux d'isolation, moins d'énergie est requise pour obtenir le même service de chauffage qu'avant les travaux, le service de chauffage coûte alors moins cher

3. Un besoin de recherche empirique confronté au challenge de la donnée disponible

La synthèse de la littérature présentée dans la section précédente a mis en exergue l'existence d'un besoin important de recherche empirique pour contribuer à la validation empirique de la théorie sur le sujet des obstacles à la réduction des consommations énergétiques résidentielles Notamment, des travaux empiriques questionnant la réalité du paradoxe énergétique et de certaines barrières à l'investissement en efficacité énergétique, de l'effet rebond et la justesse du cadre d'analyse des déterminants de la consommation énergétique, semblent particulièrement pertinents.

La recherche empirique est d'autant plus pertinente pour notre problématique puisque l'objectif est d'étudier le cas français avec pour vocation d'éclairer la décision publique sur les comportements énergétiques observés dans le secteur résidentiel à l'échelle nationale et leurs implications. Cependant, la disponibilité de données adaptées au traitement des différentes questions est un facteur limitant clairement identifié dans la littérature. La question se pose aussi dans notre cas : quelle source de données utiliser ? Il est clair que si la littérature fait état d'un besoin de recherche du fait du challenge de la donnée, cela signifie qu'il faut faire preuve d'imagination et/ou de moyens pour faire avec les ressources disponibles dans le cadre d'un travail de thèse.

Aujourd'hui, la recherche empirique mobilise de façon croissante l'économie expérimentale via des expérimentations de terrain essentiellement, parfois en réalisant des essais randomisés contrôlés, pour comprendre les comportements énergétiques et les leviers du changement (Ayres et al., 2013; Fowlie et al., 2015; Frederiks et al., 2015; Gillingham et al., 2018). Cependant, le coût et le temps incombant à la mise en œuvre de ces méthodologies sont des obstacles majeurs à leur mobilisation pour répondre même en partie à notre problématique. De plus, la plupart de ces méthodes et de ces travaux visent à tester, en situation, l'influence de la provision d'information ou de programmes sur les comportements énergétiques (comportements de maîtrise des consommations énergétiques ou de mise en œuvre de l'efficacité énergétique). Or, comprendre les comportements énergétiques avant de les changer nous semble une première étape indispensable, qui peut déjà fournir malgré tout des idées sur les leviers potentiels et les marges d'action.

En cohérence avec ces derniers points, l'autre option, largement utilisée jusqu'à présent, est la mobilisation de données d'enquêtes. Dans notre cas, les données d'enquêtes ménages, si possibles représentatives du parc ou de segments de la population d'intérêt, semblent être des vecteurs d'information à privilégier compte tenu des ressources disponibles (coût, temps) dans

le cadre d'un travail de thèse. Par ailleurs, l'exploitation d'enquêtes (si représentatives) répond bien aux vocations d'amélioration de la connaissance sur les pratiques existantes et d'aide à la décision publique que portent ce projet. En outre, elles peuvent permettre une certaine flexibilité pour la mise en évidence des comportements énergétiques et de leurs déterminants par l'analyse de préférences révélées (observation des comportements réels) ou déclarées (réponses issues de la mise en situation de choix hypothétiques). L'analyse des préférences déclarées (comme les expériences de choix ou Discrete Choice Experiment) a connu un intérêt croissant ces dernières années pour l'aide à la décision (Hoyos, 2010) (malgré certaines limites connues), et notamment pour comprendre les déterminants et freins à l'investissement en efficacité énergétique (Alberini et al., 2013; Galassi and Madlener, 2017; Kwak et al., 2010).

Dans le cadre de cette thèse, deux enquêtes riches et originales ont été utilisées : l'enquête PHEBUS[14] (Enquête sur la performance de l'habitat, équipements, besoins et usages de l'énergie (Phébus) et une seconde enquête financée par le CSTB pour mon projet de thèse.

L' enquête PHEBUS est une enquête complète réalisée en 2012 par le SOes (sous-direction des statistiques de l'énergie et sous-direction des statistiques du logement et de la construction, ministère de l'écologie, du développement durable et de l'énergie.) ; elle inclut un échantillon représentatif des logements composants le parc résidentiel français, des données sur la performance énergétique des logements (audit complet DPE, consommation énergétique théorique) très peu exploitées jusqu'à présent, des données complètes et innovantes sur les caractéristiques socio-économiques et individuelles des ménages qui les occupent (préférences individuelles pour le confort pour différents usages énergétiques, température de chauffage, revenu, etc.) ainsi que leur consommation énergétique réelle. L'exploitation de ces données donne lieu à deux des travaux de cette thèse (cf chapitres 2 et 3) en cohérence avec les gaps identifiés dans la littérature.

La seconde enquête a été élaborée pour cette thèse ; son objectif principal est de tester l'hypothèse de barrières à l'investissement en efficacité énergétique chez les propriétaires français. Adressée à près de 3000 propriétaires occupants français représentatifs du parc, j'ai utilisé la flexibilité de la méthodologie de l'expérience de choix inspiré par la littérature (Alberini, 2013) pour faire révéler le rôle de l'incertitude sur le prix futur de l'énergie et la qualité des travaux de rénovation comme frein à la rénovation énergétique. En plus de cette

[14] Voir la description de l'enquête en suivant le lien : https://www.cnis.fr/enquetes/performance-de-lhabitat-equipements-besoins-et-usages-de-lenergie-phebus-enquete-sur-la/

section originale, l'enquête incorpore aussi de nombreuses questions de contrôle sur les pratiques énergétiques actuelles et passées, la perception de la rénovation énergétique par les ménages (en vue de tester la cohérence avec les préférences élicitées via la méthode de choix discret), des données socio-économiques ainsi que l'évaluation de l'aversion au risque des ménages dans un environnement contextualisé. Conduite entre décembre 2017 et janvier 2018, cette enquête ouvre des perspectives de recherche prometteuses. Son exploitation a fait l'objet du premier chapitre de cette thèse.

Finalement, sur la question de l'effet rebond, la question de la donnée est aussi pertinente. Comme mentionné précédemment, l'estimer sur données réelles revient à disposer d'un suivi des consommations énergétiques des ménages dans le temps, de comparer la situation avant et après travaux de rénovation énergétique puis de comparer les gains énergétiques réels avec les gains théoriques (Sorrell and Dimitropoulos, 2008). Cette approche est donc consommatrice de temps (notamment, il faut compter le temps de réalisation des travaux et celui nécessaire avant et après travaux pour mesurer la consommation énergétique sur des bases comparables) et de ressources financières (il faut pouvoir mesurer les gains énergétiques théoriques, ce qui peut nécessiter l'intervention d'un expert ; par ailleurs, il faut pouvoir disposer d'un échantillon suffisamment important pour l'analyse). Se référant aux dernières contributions méthodologiques de la littérature sur le sujet, nous avons choisi dans cette thèse d'utiliser des séries temporelles nationales (voir chapitre 4) ; ceci nous a permis d'apporter une réponse rigoureuse dans un délai et coût compatibles avec le projet de thèse.

Grâce à ces deux enquêtes et à l'exploitation de séries temporelles nationales, quatre travaux de recherche ont été conduits dans le cadre de cette thèse. En s'appuyant sur l'exploitation de données réelles françaises et les apports de la littérature académique, ils permettent d'apporter des réponses crédibles à la question posée initialement, c'est-à-dire, comprendre le rôle de certains facteurs individuels comme obstacles à la réduction des consommations du secteur résidentiel français.

Dans la suite de ce chapitre introductif, nous rappelons d'abord les spécificités du secteur résidentiel français et le cadre politique. Puis, les quatre chapitres de la thèse sont présentés plus en détail.

II. Le secteur résidentiel, enjeu majeur pour la lutte contre le changement climatique et la transition énergétique

Le secteur du bâtiment représenterait jusqu'à 20.1% de la demande mondiale d'énergie finale, faisant du secteur l'un des plus énergivores (International Energy Outlook 2016[15]) ; il serait aussi responsable d'un tiers des émissions annuelles de Gaz à Effet de Serre. Dans le cadre des derniers travaux des experts internationaux sur le climat (Rapport du GIEC, 2018[16]), la réduction de la demande finale globale d'énergie a été identifiée comme un des éléments clés pouvant contribuer fortement à l'atteinte des objectifs climatiques. Pour les auteurs, limiter le réchauffement climatique à 1.5 °C requiert la participation de tous les secteurs en faveur d'une transition énergétique « rapide et de grande ampleur » et notamment celui du bâtiment. L'Agence Internationale de l'Energie a identifié ce même secteur comme ayant le potentiel d'économies d'énergie non-réalisé le plus important de tous les secteurs d'activité : 80% des économies d'énergie pouvant être théoriquement attendues suite à la mise en place de différents leviers dans le secteur ne sont encore réalisées.

Dans l'Union Européenne, les secteurs tertiaires et résidentiels représentent 40% de la consommation finale d'énergie, dont 25.4% pour le secteur résidentiel en 2016 (source : Commission Européenne[17]) et 36% des émissions de CO2 (émissions de la phase d'exploitation des bâtiments). La structure des bâtiments, le mix énergétique utilisé pour leur consommation finale et les besoins en énergie varient selon plusieurs facteurs comme la disponibilité des ressources énergétiques, le climat, les standards de vie, les facteurs démographiques, etc. Le chauffage résidentiel est l'usage énergétique le plus important en termes de quantité d'énergie finale consommée (68% de l'énergie résidentielle en 2009 et 74% en 1990). Par ailleurs, le parc de bâtiments est de faible qualité énergétique : 35% des bâtiments de plus de 50 ans de l'UE répondent à de faibles normes énergétiques voire même à aucune norme.

1. ***Caractérisation du secteur résidentiel français***

En France, le secteur résidentiel est composé d'environ 33 millions de logements dont plus de 26 millions de résidences principales. En 2013, la consommation du parc représentait près de 30% de la consommation d'énergie française et en 2014, le secteur émettait 20% des émissions

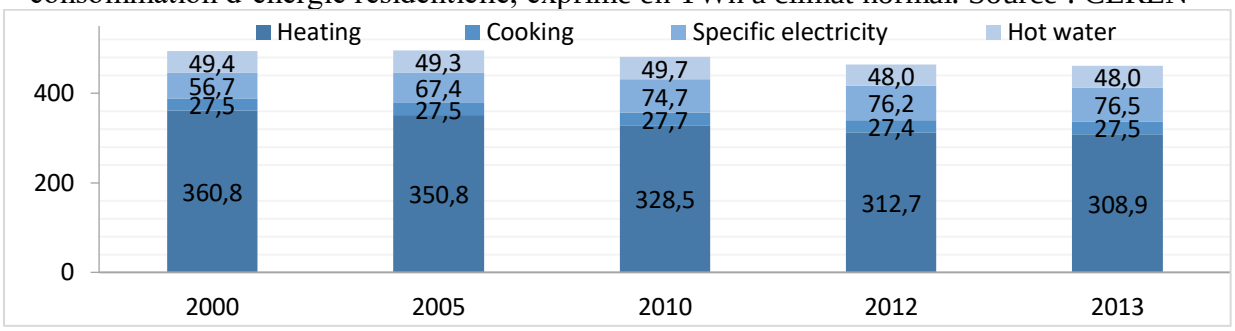
[15] Les données mentionnées sont consultables en suivant le lien : https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf

[16] Le rapport du GIEC et le résumé à l'attention des décideurs sont disponibles en suivant le lien : https://www.ipcc.ch/sr15/

[17] Les données de statistiques sur l' énergie sont consultables en ligne : https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Consumption_of_energy/fr&oldid=322013

de gaz à effet de serre nationales (CGDD, 2015). L'usage de chauffage contribue à plus de 60% des consommations énergétiques du secteur résidentiel (voir Fig. 2). Concernant les énergies utilisées, le gaz est utilisé comme source d'énergie de chauffage principale chez plus de 40% des ménages français, l'électricité est la seconde énergie majoritaire (31%) suivie par le fioul domestique (16%) puis le chauffage urbain (5%)[18].

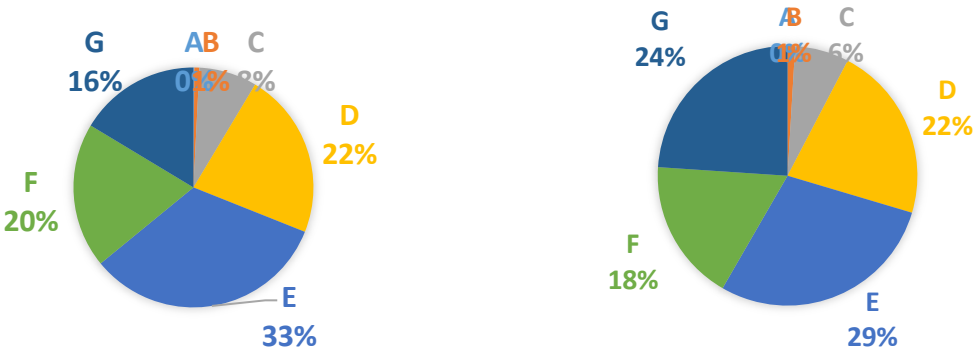
Figure 2. Part de chaque usage énergétique dans le résidentiel Français et évolution de la consommation d'énergie résidentielle, exprimé en TWh à climat normal. Source : CEREN



De gauche à droite : chauffage, cuisine, électricité spécifique, eau chaude

La performance énergétique du parc résidentiel français a été caractérisée plus finement en 2012 grâce à l'enquête PHEBUS[19]. Les données ont mis en évidence que plus de la moitié du stock de résidences principales était très énergivore, leur étiquette énergétique DPE[20] étant inférieure à la classe énergétique D, soit des consommations de plus de 150 kWh/m2/an (voir Fig. 3). Cette faible qualité énergétique est due à la faible isolation thermique de ces bâtiments construits en grande partie avant toute réglementation thermique, la première datant de 1975, et/ou à la faible efficacité des systèmes de chauffage.

Figure 3. Performance énergétique du parc résidentiel français (Maisons à gauche, Appartements à droite). Source : Phebus 2012



[18] Données PHEBUS : http://www.statistiques.developpement-durable.gouv.fr/sources-methodes/enquete-nomenclature/1541/0/enquete-performance-lhabitat-equipements-besoins-usages.html
[19] Voir le descriptif de l'enquête Phebus sur le site internet du ministère : http://www.statistiques.developpement-durable.gouv.fr/sources-methodes/enquete-nomenclature/1541/0/enquete-performance-lhabitat-equipements-besoins-usages.html
[20] Diagnostic de Performance Energétique

Finalement, le parc résidentiel français se caractérise aussi par les ménages qui l'occupent. Le parc compte 64% de propriétaires. Par ailleurs, 5 millions de ménages seraient en situation de précarité énergétique (source : ONPE[21]). Pour mémoire, la loi du 12 juillet 2010 définit une personne en situation de précarité énergétique comme « 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 conditions d'habitat ». Les ménages en situation de précarité énergétique ont une probabilité plus importante d'habiter dans des logements peu performants d'un point de vue de l'efficacité énergétique et donc des logements énergivores (Belaïd, 2018). Ainsi, l'urgence de l'action énergétique est fortement liée à des enjeux sociaux.

2. ***Engagements énergétiques sectoriels***

En cohérence avec le contexte européen (Conseil européen d'octobre 2014), les objectifs nationaux de réduction de la consommation énergétique ont été traduits dans la loi française (Loi pour la Transition Energétique Et la Croissance Verte, 2015). Au niveau global, la LTECV fixe les engagements de (1) la réduction de 50% la consommation énergétique entre 2012 et 2050 (LTECV et PPE) tous secteurs confondus ainsi que (2) la baisse des émissions de gaz à effet de serre (GES) de 40% d'ici 2030 et de 75 % d'ici 2050 par rapport au niveau de 1990

Des engagements plus précis ont été définis au niveau sectoriel par la loi TECV, notamment des engagements sur le nombre et la performance de rénovations énergétiques à mettre en œuvre dans le parc résidentiel. À échéance proche, on peut citer l'engagement de la réalisation d'au moins une rénovation énergétique pour tous les bâtiments privés résidentiels dont la consommation en énergie primaire est supérieure à 330 kWhep/m2.an (étiquettes énergétiques G et F, soit environ 30% du parc) d'ici 2025 et celui de la réalisation de 500 000 rénovations énergétiques par an à partir de 2017 parmi lesquels 120 000 doivent concerner des ménages à faible revenu, pour réduire de 15% la précarité énergétique à l'horizon 2020. Finalement, la Stratégie Nationale Bas Carbone, vise une réduction des émissions de GES de 54% dans ce secteur entre 2013 et 2028.

Des dispositifs de politiques publiques ont été mis en place pour accompagner l'atteinte des objectifs énergétiques. Ils sont présentés dans la section suivante.

[21] Site de l'observatoire de la précarité énergétique en France :http://onpe.org/

3. ***Politiques publiques en place***

Réglementations et incitations économiques sont les deux types d'outils de politiques publiques qui co-existent actuellement en France pour atteindre ces engagements.

Concernant le bâtiment neuf, le secteur résidentiel a été ciblé par les réglementations européennes ayant pour but l'amélioration de la performance énergétique. Les directives européennes de 2010[22] et 2012[23] (révisée en 2016) transposées dans les réglementations pays fixent des mesures contraignantes pour aider les pays membres à atteindre l'objectif de 30% d'efficacité énergétique en 2030. En France, des réglementations thermiques sont régulièrement renouvelées depuis 1975 avec des exigences de plus en plus contraignantes. Les réglementations thermiques n'ont d'effet que sur la réduction des consommations de chauffage des bâtiments neufs (et eau-chaude sanitaire). Or, le taux de renouvellement du parc est très bas, moins d'1% par an.

Des outils incitatifs de type subventions ou taxes ont été déployés par les pouvoirs publics pour réduire la consommation énergétique résidentielle.
Des aides financières et subventions à la rénovation énergétique ont été mises en place comme le CITE (Crédit d'Impôt pour la Transition Energétique), l'Eco-prêt à taux zéro, les aides de l'ANAH, aides régionales, etc. L'ensemble des dispositifs publics nationaux de soutien à la rénovation énergétique des logements a représenté un coût pour l'état de 3, 2 Mds€[24]. Un autre dispositif, financé par les fournisseurs d'énergie, est connu sous le nom de « certificats d'économie d'énergie » (CEE)[25]. Mis en place par la loi POPE (Programme fixant les Orientations de la Politique Energétique, juillet 2005), ces dispositifs constituent un mécanisme d'innovation en matière de fiscalité écologique : l'Etat oblige les fournisseurs d'énergie à réaliser un certain quota d'économies d'énergie soumis à pénalité financière si non respecté. Pour respecter ce quota, les fournisseurs proposent à leurs clients de réaliser leurs travaux de rénovations énergétiques eux-mêmes ou ils peuvent déléguer leurs actions au marché de CEE faisant ainsi réaliser les économies d'énergie par d'autres acteurs. Les subventions à la rénovation énergétique sont ainsi financées par les fournisseurs d'énergie, qui les répercutent en partie sur le prix consommateur de leur produit.

[22] Energy Performance of Buildings Directive
[23] Energy Efficiency Directive
[24] Source et plus d'information : https://www.actu-environnement.com/media/pdf/news-29861-rapport-IFG-CGEDD-aides-publiques-renovations-energetiques.pdf
[25] Pour la présentation du dispositif, plus d'informations en suivant le lien : https://www.chaireeconomieduclimat.org/wp-content/uploads/2018/03/CEE-Creti-Cruz.pdf

Par ailleurs, le relèvement de la fiscalité énergétique ou taxe carbone, initialement introduite en 2014, a été mis en place en automne 2017 [26]pour accélérer les changements de comportement par le biais d'un signal prix. La fiscalité énergétique vise à la modération des consommations d'énergie des usages concernés et l'incitation économique à la mise en place de mesures d'efficacité énergétique dans le domaine de la mobilité et de l'habitat. Cette fiscalité imposait des hausses régulières du tarif des énergies, dont le gaz et le fioul domestique qui sont utilisés pour le chauffage des logements. Aujourd'hui, la fiscalité écologique est cependant suspendue en réponse à la contestation virulente des ménages français aux revenus modestes face à l'augmentation des coûts du carburant (exacerbés par la hausse du cout du pétrole). Ces ménages ont été largement impactés économiquement par cette hausse, car très dépendants de ces énergies pour leurs déplacements. Les futures hausses de la fiscalité prévues pour le 1 janvier 2019 ont été annulées.

En 2014, seulement 288 000 logements ont été rénovés « efficacement » ou « très efficacement » au regard de la performance énergétique atteinte (OPEN, 2016) et les travaux de rénovation énergétique auraient été peu dynamiques sur 2015-2016. Par ailleurs, entre 1999 et 2015, soit en 15 ans, la consommation finale d'énergie du secteur résidentiel a diminué de 8 %[27]. Ainsi, à politique inchangée et malgré la trajectoire de contribution climat-énergie prévue[28], il semble que les économies d'énergie devraient être nettement en deçà de l'objectif sectoriel fixé pour le secteur du bâtiment.

III. Présentation des chapitres de la thèse

Les travaux réalisés dans cette thèse ont pour but l'identification des obstacles à la baisse des consommations énergétiques résidentielles en France principalement via une approche par les ménages. Chacun des chapitres tente d'apporte des éléments d'éclairage aux décideurs publics sur les facteurs intervenant dans les décisions énergétiques (consommation énergétique ou efficacité énergétique) chez les ménages français. Les quatre chapitres s'inscrivent principalement dans la littérature sur les barrières de marché relatives à la réduction des consommations énergétiques. Le chapitre un traite du rôle de l'incertitude sur les bénéfices de

[26] Plus d'information sur la taxe carbone française : https://www.chaireeconomieduclimat.org/wp-content/uploads/2018/11/2018-04-POLICY-BRIEF-2.pdf
[27] Plus de détails sur les tendances énergétiques du secteur résidentiel: http://www.statistiques.developpement-durable.gouv.fr/lessentiel/ar/340/1207/consommation-denergie-emissions-co2-lhabitat.html
[28] Plus de détails : https://www.actu-environnement.com/media/pdf/news-29861-rapport-IFG-CGEDD-aides-publiques-renovations-energetiques.pdf

la rénovation énergétique dans la décision de rénovation ; les chapitres un, deux et trois mettent en évidence le rôle de l'hétérogénéité des individus (préférences et caractéristiques socio-économiques) comme facteur de compréhension des consommations et comportements énergétiques ; le chapitre quatre s'intéresse plus particulièrement à l'effet des préférences pour le confort sur la consommation énergétique après une rénovation énergétique, i.e l'effet rebond.

Chapitre 1 : Investissements en efficacité énergétique dans le secteur résidentiel français : le rôle des incertitudes contextuelles dans la décision de rénovation énergétique[29]

La littérature sur le paradoxe énergétique ou « energy efficiency gap » mis en lumière par Jaffe et Stavins (1994) et, plus largement, sur les barrières à l'efficacité énergétique (Sutherland, 1991) a mis en exergue le fait que les solutions d'amélioration de l'efficacité énergétiques de l'habitat, bien qu'apparemment rentables, sont sous-déployées par les ménages. Pour justifier ce sous-investissement, le rôle de l'incertitude sur les économies effectivement réalisées et plus largement, le rôle de l'incertitude contextuelle comme frein à la rénovation énergétique a été soulevé par la littérature académique théorique (barrière de marché). Cependant, peu de travaux empiriques se sont penchés sur la réalité de cette hypothèse (Alberini, 2013). Dans cet article, nous tentons d'apporter des éléments d'éclairage sur cette question grâce à l'élaboration et l'analyse d'une expérience de choix discrets réalisées chez 3000 propriétaires occupants français. Nous nous focalisons sur deux types d'incertitude auxquelles l'investisseur fait face : l'incertitude sur la qualité effective de l'opération de rénovation énergétique, l'incertitude sur le prix futur de l'énergie.

Les expériences de choix discret permettent de faire révéler les préférences des agents par des mises en situation de choix répétées. Dans l'enquête élaborée dans le cadre de notre analyse, les ménages ont fait face à 8 situations de choix relatif à l'amélioration de l'isolation des murs de leur logement. Les alternatives sont définies par 5 attributs qui décrivent les conditions/ caractéristiques de l'opération de rénovation. Les compromis réalisés par les ménages entre les différents attributs au cours des situations de choix permettent d'évaluer ensuite l'importance relative accordée à chaque attribut. Outre des attributs classiques (coût de l'opération, économies d'énergie espérées, amélioration de la température intérieure) qui se déclinent selon plusieurs valeurs ou modalités, nous avons choisi d'ajouter dans les offres la possibilité de s'assurer contre le risque de non-qualité des travaux énergétiques et celle de souscrire à un

[29] Le travail présenté dans ce chapitre a été conduit en collaboration avec Fateh Belaïd (CSTB) et avec la participation financière du CSTB.

contrat garantissant un prix de l'énergie constant sur 5 ans. En choisissant ces garanties, le ménage a la possibilité de réduire l'incertitude contextuelle liée à la mise en œuvre de travaux de rénovation énergétique. L'enquête a été réalisée auprès de 3000 propriétaires sur un échantillon représentatif du parc des logements résidentiels des propriétaires occupants. Cette enquête a été réalisée entre décembre 2017 et janvier 2018.

Pour analyser les données d'enquête ainsi récoltées, nous avons mobilisé des modèles de choix discrets permettant la prise en compte de l'hétérogénéité des préférences individuelles (le modèle de logit mixte et modèle de classes latentes).

Nos résultats montrent que les incertitudes sur la qualité des travaux et sur le prix futur de l'énergie ont un rôle significatif dans le processus de décision de rénovation énergétique. Dans la mesure où ils constituent une barrière au passage à l'acte, le développement de garanties de performance ou de contrats de fourniture de gaz ou électricité à tarif fixe de long terme favoriseraient l'investissement en efficacité énergétique. Par ailleurs, le coût d'investissement, l'amélioration du confort thermique et le potentiel d'économie d'énergie sont aussi des attributs qui expliquent fortement la décision de rénovation énergétique. L'importance de l'ensemble de ces facteurs pour expliquer le choix d'investissement varie selon les individus, il y a une forte hétérogénéité des préférences au sein de notre échantillon. Cette hétérogénéité s'explique en partie par des perceptions différentes sur les paramètres économiques (prix de l'énergie), et l'aversion au risque des individus.

Par un exercice de simulation, ces résultats montrent les outils et schémas de type assurantiels peuvent jouer un rôle significatif sur l'augmentation du taux de rénovation énergétique dans le parc des propriétaires français. Par exemple, l'introduction d'une garantie de performance énergétique sur les travaux de rénovation pourrait entraîner une augmentation de 15% du taux de rénovation (dans le contexte présenté ici). Ces résultats questionnent les modalités de développement et de généralisation des deux garanties et le rôle des pouvoirs publics. Par exemple, il pourrait s'agir de faire émerger une mesure de la performance énergétique intrinsèque pour favoriser le développement de marchés assurantiels ou mise en œuvre d'une responsabilité décennale pour la réduction de l'incertitude liée à la qualité des travaux. Sur les contrats prix fixes de l'énergie, il pourrait s'agir d'une politique d'accompagnement des marchés.

Chapitre 2 : Consommation énergétique dans le secteur résidentiel : quel est le poids des préférences individuelles ? [30]

Dans cet article, nous cherchons à identifier les déterminants de la consommation énergétique dans le secteur résidentiel. Nous nous intéressons particulièrement au rôle des préférences individuelles pour le confort pour différents usages énergétiques pour expliquer la quantité d'énergie finale annuelle consommée par le ménage.

L'intérêt de ce papier est double. Tout d'abord, l'analyse menée repose sur des donnée originales (base PHEBUS[31]) puisque nous disposons à la fois d'éléments techniques sur les logements (classe énergétique, consommation énergétique théorique), de données environnementales (localisation), socio-économiques (caractéristiques des ménages, revenu, âge, composition familiale, etc) ainsi que des données sur les préférences des ménages en termes d'usage énergétique (température de chauffage, préférence pour le confort, etc) pour plus de 2000 ménages. Ensuite, notre cadre d'analyse s'inscrit dans les tendances académiques récentes : Nous faisons l'hypothèse que la consommation énergétique résulte d'un double choix : le choix du logement (et de sa performance énergétique) et le choix de la consommation énergétique compte tenu du logement habité. Jusqu'à présent, peu de données étaient disponibles pour intégrer correctement cette endogénéité.

Grâce aux données de l'enquête Phébus, nous avons pu tester notre hypothèse sur le secteur résidentiel français. Nous avons tenté de comprendre et d'expliquer la double décision du choix du logement et du choix de la consommation d'énergie en intégrant parmi les facteurs explicatifs les préférences individuelles pour le confort pour différents usages énergétiques.

Notre procédure économétrique repose sur une méthode d'estimation conjointe. D'une part nous estimons un probit ordonné, par lequel nous souhaitions déterminer le rôle des caractéristiques du ménage, de ses préférences en matière d'usage énergétique et des caractéristiques environnementales et économiques sur le fait d'habiter dans un logement de plus ou moins grande efficacité énergétique. D'autre part, nous réalisons une régression linéaire

[30] Ce chapitre a été publié en tant que working paper co-écrit avec Dorothée Charlier sur les sites de la FAERE et de la Chaire Economie du Climat : https://www.chaireeconomieduclimat.org/publications/energy-consumption-in-the-french-residencial-sector-how-much-do-individual-preferences-matter/. Cet article a été accepté à l'Energy Journal et sera publié début 2019 sous le titre *Energy consumption in the residential sector: how much do individual preferences matter?*

[31] Plus de détails sur l'enquête Phebus sont disponibles en suivant ce lien : http://www.statistiques.developpement-durable.gouv.fr/sources-methodes/enquete-nomenclature/1541/0/enquete-performance-lhabitat-equipements-besoins-usages.html

multiple avec variable instrumentales (pour corriger l'endogénéité liée au prix de l'énergie) pour étudier les déterminants de la consommation énergétique et notamment le rôle des facteurs individuels. Nos premiers résultats nous ont conduits à différencier l'analyse sur deux échantillons composés des ménages appartenant aux trois premiers déciles de revenu d'une part et aux trois derniers déciles de revenu d'autre part.

Les principaux résultats sont les suivants. Tout d'abord, différents schémas de consommation énergétique se dégagent de nos résultats, ils se manifestent par le biais des préférences individuelles liées à l'énergie et les caractéristiques économiques des ménages. En moyenne, préférer le confort aux économies d'énergie pour deux ou trois usages énergétiques (chauffage et/ou électricité spécifique et/ou eau chaud sanitaire) entraîne une consommation énergétique de dix pour cent supérieure. Nos résultats montrent que pour les ménages aux revenus importants, cette surconsommation peut atteindre 22%. Nos résultats soulignent aussi que les préférences pour le confort et le revenu jouent aussi sur le choix du logement, surtout pour les ménages aisés. Les ménages aux revenus faibles sont doublement impactés : ils habitent dans les logements les plus énergivores, de mauvaise qualité et leur consommation d'énergie est ensuite contrainte par leur revenu ; cela se traduit par la plus faible élasticité-prix de l'énergie de leur consommation d'énergie par rapport aux ménages aux revenus plus importants.

À partir de ces résultats qui démontrent l'importance de différentes sources d'hétérogénéité pour expliquer la consommation énergétique et les comportements observés, nous suggérons aux décideurs publics d'intégrer systématiquement une distinction entre les ménages aux faibles revenus des ménages aux revenus importants lorsqu'est considérée toute politique énergétique susceptible d'avoir des effets distributifs (exemple, taxe sur les contenus carbones des énergies résidentielles) ou « incitative » (subvention à la rénovation) visant à la réduction de la consommation énergétique. Cette distinction permettra de ne pas alourdir le fardeau économique des plus sensibles et d'assurer l'efficacité de l'allocation des subventions publiques. Pour viser les ménages les plus aisés, des campagnes d'information ou l'utilisation plus importante d'outils technologiques permettant de suivre la consommation d'énergie pourraient permettre d'économiser jusqu'à 20% de leur consommation d'énergie.

Chapitre 3 : Le rôle des préférences individuelles pour expliquer l'écart de performance énergétique[32].

Dans ce troisième chapitre, l'objectif est d'expliquer, à l'échelle du logement, les écarts entre la quantité d'énergie réellement consommée et la quantité d'énergie théorique prédite par des modèles ingénieurs. En plus de quantifier et de caractériser cet écart, l'intérêt majeur de notre étude réside dans le fait que nous estimons les contributions de facteurs comportementaux et économiques. À la clé de notre analyse se trouvent la meilleure compréhension des comportements énergétiques extrêmes (sur- et sous-consommation d'énergie).

À partir de l'enquête Phebus, nous avons calculé pour chaque couple ménage/logement l'indicateur d'intensité d'utilisation de l'énergie. Cet indicateur correspond au ratio de la consommation énergétique finale réelle sur la consommation d'énergie finale théorique. Cette dernière donnée est disponible comme output des Diagnostics de Performance Énergétique réalisés pour l'ensemble des 2000 ménages de l'enquête. Dans le cas où le ratio est significativement supérieur à 1, il s'agit d'une situation de « surconsommation » énergétique (relativement à la mesure théorique que l'on utilise) ; dans le cas contraire, il s'agit d'une situation de « sous-consommation » énergétique.

Les intensités d'utilisation de l'énergie ont été calculées sur deux périmètres qui se distinguent selon les usages énergétiques compris dans le numérateur du ratio. Tout d'abord, nous avons considéré dans le périmètre du numérateur la consommation totale d'énergie tous usages confondus. Ainsi, dans ce cas, les intensités d'utilisation sont a priori surestimées : en effet, les usages énergétiques du numérateur sont plus larges que ceux considérés au dénominateur (la consommation théorique produite par le DPE ne concerne que les usages chauffage et eau chaude sanitaire). Ensuite, dans une deuxième analyse, pour tester la robustesse de nos résultats, nous avons gardé dans le numérateur exclusivement les usages présents aussi au dénominateur. Pour cela, nous avons restreint l'analyse aux logements chauffés au gaz et utilisant le gaz pour l'eau chaude sanitaire (environ 500 logements).

Après une analyse descriptive poussée qui met en évidence un lien visible entre comportements énergétiques, variables économiques, préférences individuelles et performance énergétique du

[32] Ce chapitre a été publié sous la forme de working paper et de policy paper sur le site de la FAERE, co écrit avec Dorothée Charlier, sous le titre : *The role of individual preferences to explain the energy performance gap*. ;http://faere.fr/pub/WorkingPapers/Bakaloglou_Charlier_FAERE_WP2018.15.pdf;; http://faere.fr/pub/PolicyPapers/Bakaloglou_Charlier_FAERE_PP2018.08.pdf. Il a été soumis à l'Energy Journal en décembre 2018.

logement, nous avons réalisé une régression quantile et estimé les effets par quantile pour quantifier la contribution de nos facteurs explicatifs pour différents niveaux de valeur de notre variable explicative (ici, l'indicateur d'intensité d'utilisation de l'énergie).

Les résultats des différents modèles concluent que près de 12% de l'écart à la performance énergétique s'explique par des préférences individuelles pour le confort au détriment des économies d'énergie (échantillon gaz). Les variables socio-économiques comme le revenu, le prix de l'énergie auquel le ménage fait face, les habitudes énergétiques ont aussi un réel poids explicatif. Ainsi, les situations de sous-consommation par rapport aux prédictions théoriques sont avant tout liées à des contraintes financières fortes alors que les situations de surconsommation s'expliquent par des préférences individuelles fortes pour le confort. Par ailleurs, le facteur climatique joue aussi un rôle important pour justifier les écarts à la norme de la consommation énergétique.

Finalement, notre étude suggère l'existence d'un effet rebond visible sur des données en coupe. D'après les résultats précédents, il s'agirait en partie d'un effet rebond « légitime » de rattrapage de confort pour les ménages logeant initialement dans les bâtiments dotés d'une très faible efficacité énergétique. Encore une fois, des politiques publiques énergétiques n'aggravant pas ces inégalités doivent être élaborées en priorité. De plus, une reconsidération du périmètre de mesure de la précarité énergétique est conseillée à la suite des conclusions de notre analyse. Pour les ménages les plus aisés, des politiques à visée comportementale pourraient être efficace pour réduire la consommation énergétique.

Chapitre 4 : L'effet rebond direct pour la consommation de gaz résidentielle : le cas français[33].

Cet article s'intéresse à l'estimation de l'effet rebond direct pour le chauffage résidentiel français. L'estimation de l'effet rebond pour le secteur est essentiel pour mieux anticiper les effets des politiques d'efficacité énergétique et les trajectoires énergétiques. Les résultats montrent que l'effet rebond est de 60% dans le court terme et 64% dans le long terme.

D'un point de vue économique, l'effet rebond direct correspond à l'accroissement de la demande pour un service énergétique suite à l'augmentation de l'efficacité énergétique et donc

33 Ce chapitre a été publié sous la forme d'un articel par la revue Energy Policy début 2018 sous le titre *Direct rebound effect of residential gas demand: Empirical evidence from France*. Il a été co-écrit avec Fateh Belaïd et David Roubaud. Il est accessible sur le lien suivant : https://www.sciencedirect.com/science/article/pii/S0301421517308662

à la diminution du coût de ce service. Concernant l'usage du chauffage, l'amélioration de l'efficacité énergétique du système de chauffage et/ou l'amélioration de l'isolation de l'enveloppe réduisent le besoin d'énergie pour l'atteinte d'un même niveau de service énergétique : par exemple, chauffer son intérieur à 20°C en hiver demande moins d'énergie de chauffage une fois que le logement est isolé car il conserve mieux la chaleur. Cette baisse de besoin énergétique physique incite le ménage à augmenter la demande pour le service énergétique : dans le cas de l'usage de chauffage, suite à la baisse du coût du service, le ménage peut décider d'augmenter son confort thermique (chauffer son intérieur à 21°). Ainsi, l'amélioration de l'efficacité énergétique pour la production d'un service conduit à l'augmentation de la demande pour ce service dans une certaine mesure. Les économies d'énergie théoriquement attendues peuvent alors être moins importantes que prévu. L'effet rebond a été démontré dans de nombreux domaines et notamment sur les questions d'efficacité énergétique dans le résidentiel (Gillingham et al., 2016).

L'enjeu de cet article est d'estimer quelle part des économies d'énergie engendrées par la mise en œuvre d'une solution d'efficacité énergétique peut être perdue à cause de l'effet rebond direct. Le périmètre d'étude est le chauffage résidentiel français.

Ce travail utilise des séries temporelles sur la consommation de gaz résidentiel, le prix du gaz, le PIB et la population française et les degré jours (facteur climatique) de 1983 à 2014.
La méthodologie repose sur l'estimation de l'élasticité prix de la demande énergétique. Pour certains micro économistes, la justesse de cette approche est limitée à certains cas (Chan et Gillingham, 2015), notamment ceux où l'effet rebond est estimé pour un service énergétique correspondant à une seule énergie. La littérature a aussi montré qu'il existe une asymétrie de la réponse de la demande énergétique par rapport à la hausse et à la baisse du prix, qu'il est préférable de prendre en compte dans les estimations. En effet, une augmentation du prix entraine deux phénomènes : une réduction de la consommation énergétique et une opportunité d'investir en équipement plus efficace. Alors que, lorsque le prix baisse, seule la part flexible de la consommation énergétique peut s'adapter au changement du prix, i.e la part comportementale (effet rebond), car les équipements sont installés de façon irréversible.
Suite à ce constat méthodologique, nous estimons l'effet rebond par l'élasticité prix de la consommation d'énergie par rapport aux baisses cumulées de prix dans la présente recherche. Les estimations sont réalisées par l'utilisation d'une régression des moindres carrés et un modèle ARDL(autoregressive distributed lag cointegration).

Nos résultats rejettent l'hypothèse d'un effet rebond total qui annulerait toutes les économies d'énergie attendues par la mise en œuvre des solutions d'efficacité énergétiques relatives à l'usage chauffage. Les estimations mettent en évidence un effet rebond de 60% sur le court terme et 64% sur le long terme. En termes de politiques publiques, cela signifie que l'amélioration de la performance énergétique du parc ne sera pas vaine ; les réductions de consommation d'énergie existent malgré l'augmentation de la demande du service énergétique « chauffage » découlant de la mise en œuvre des solutions d'efficacité énergétiques.

Outre les économies d'énergie, la rénovation énergétique permet donc l'amélioration conséquente du bien-être individuel. L'effet rebond est à prendre avec précaution puisqu'il peut représenter deux phénomènes : un rattrapage de confort « légitime » ou un comportement de « surconsommation » énergétique.

Synthèse

Pour répondre à notre questionnement initial sur la nature des obstacles à la réduction des consommations énergétiques dans le secteur résidentiel français, quatre pistes de recherche pertinentes s'inscrivant dans la lignée des barrières de marché de la littérature relative à l'energy efficiency gap ont pu être identifiées: (1) la compréhension des barrières à l'investissement en efficacité énergétique avec l'étude du rôle de l'incertitude sur les bénéfices des travaux de rénovation, (2) l'identification des déterminants individuels de la consommation énergétique et (3) l'identification des déterminants individuels des comportements de maîtrise ou non des consommations énergétiques (sobriété) et (4) la possibilité d'un effet rebond par rapport à l'amélioration de l'efficacité énergétique pour l'usage chauffage. Nous en avons retenu un besoin de recherche empirique, mais aussi un challenge méthodologique relatif à l'amélioration de la connaissance sur ces différents sujets, notamment en vue d'apporter un éclairage opérationnel aux décideurs publics. Les quatre chapitres présentés ci-avant et détaillés dans le corps de cette thèse reprennent ces différents thématiques et les déclinent au cas français. Grâce à la disponibilité et l'analyse de données originales, les chapitres de cette thèse proposent de traiter ces thématiques avec une perspective empirique et « ménage ». Ainsi, les chapitres visent à mieux comprendre certaines barrières de marché comme le rôle de l'hétérogénéité individuelle (socio-économiques, préférences, perceptions, etc.) et de l'incertitude pour expliquer les décisions relatives à la consommation énergétique observables dans le parc résidentiel français, en vue d'identifier certains des obstacles à la réduction de la consommation énergétique.

Ces quatre chapitres permettent de mettre en évidence des schémas de la décision énergétique que ce soit par rapport à la décision de consommation énergétique et/ou la décision d'investissement en efficacité énergétique. Comme résultat principal, nous trouvons que les décisions énergétiques individuelles sont fortement liées aux préférences individuelles (pour le confort, le risque), ainsi qu'aux conditions économiques des ménages et aux caractéristiques de l'environnement décisionnel (incertitude) et de sa perception. En proposant des outils innovants, en accompagnant le marché ou en ciblant au mieux les politiques publiques de réduction des consommations énergétiques, lever certains des obstacles à la baisse des consommations énergétiques semble alors possible.

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Chapitre 1

Energy efficiency investment in the residential sector: The role of risk and uncertainties in shaping individual preferences for energy renovation decision.[34]

Abstract

This chapter examines a crucial question, which has raised in the last years both in policy and the economic literature; that is, the role of uncertainty as barrier to energy retrofit decision. To answer the issue, we develop a discrete choice experiment (DCE) addressed to 3000 French owner-occupiers to elicit individual preferences for energy retrofit measures. The methodological innovation is in the design of the DCE, in which two insurance schemes covering for potential sources of uncertainty (energy price and retrofit quality) are included as attributes of the energy retrofit alternatives. The DCE is then analyzed using a mixed logit and a latent class models to investigate the nature of systematic heterogeneity in household preferences for the attributes of energy retrofit solutions. The central message of this paper is risk and uncertainties related to energy prices and energy retrofit quality are negatively perceived during the energy-renovation decision-making process. This impact varies accordingly to household characteristics such as risk aversion and perception of the economic context.

Keywords: Stated preference method; Discrete choice experiment; Energy efficiency gap; Decision under uncertainty; Energy retrofit decision; latent class model; Mixed logit model.

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1.Introduction

Energy consumption in the housing sector accounts for about 30% of worldwide energy consumption. The urgent issues of fighting climate change, enhancing energy transition and improving energy security has put the residential sector of most western countries to the center of attention because of its important energy-savings potential, achievable trough the implementation of energy efficiency investment. Thus, for several decades, improving the energy efficiency of the residential sector has been put in the agenda of public policies.

However, energy efficiency investments in the residential sector seem to lag behind public policy objectives set in several countries (including France). In the international academic literature, the issue of understanding why households do not invest more in energy efficiency, despite the cost-effectiveness and the availability of energy efficiency solutions, has received a growing interest. As an explanation, some scholars argued that energy efficiency investments would not be as attractive as it has been theoretically predicted because of the existence of barriers that prevent their large-scale diffusion. In the literature, this framework of thinking is often refers to the *energy efficiency gap* or *energy paradox* (Jaffe and Stavins, 1994; Gerarden et al., 2015). More broadly, the literature on the barriers to energy efficiency investment has raised the debates for many years (Sutherland, 1991).

Among this latter literature, several theoretical and few empirical works pointed out the fact that risk and uncertainty about energy renovation benefits could have a crucial role to explain under-investment in efficient energy retrofit (Newell and al., 2015; Alberini, 2013; Sutherland, 1991).

Willing to contribute to this literature, the main questions we try to answer in the present research are the followings: (1) do risk and uncertainty about energy retrofit quality and future energy cost matter in energy efficiency decision of French homeowners ? (2) If yes, does the reduction of uncertainty have the same effect on utility for the two sources of risk ? (3) Finally, does risk aversion play a role in explaining heterogeneity in preferences for energy retrofit?

For this purpose, we elaborate a rich dataset gathering 3000 French private homeowners. In the survey, we use the flexibility of the methodology of the discrete choice experiment (DCE) to elicit how much households value reduced uncertainty on expected savings, influencing the decision to invest. The homeowner declares her or his interest for an investment opportunity that permanently improves the thermal insulation of their dwelling, according to the presence or not of two insurance schemes among other attributes: an insurance for quality of energy retrofit and a fixed energy price contract. We then use a mixed logit and a latent class models

to investigate the nature of systematic heterogeneity in household preferences for the attributes of energy retrofit solutions and its link with some individual characteristics.

This chapter is an original empirical contribution to the dense literature of the barriers to energy efficiency investment, related to the risk and uncertainty barrier. To our knowledge, this is the first work investigating the role of perceived risk and uncertainty in explaining decision making related to energy efficient investment for two sources of uncertainty and from household's perspective.

The methodological innovation and the contribution of this research are the followings. First, we use the methodology of the discrete choice experiment to test the importance of the risk and uncertainty barrier. Second, we implement econometric choice models allowing accounting for heterogeneity in preferences for energy retrofits. Third, we measure individual characteristics such as risk aversion and perception of the evolution of future energy prices and we used them to explain as possible this heterogeneity.

The central result of this paper is that risk and uncertainty about energy prices and energy retrofit quality do impact negatively the energy-retrofit decision-making process. Indeed, we provide evidence that greater certainty on future trend of energy price and quality of retrofit work is valued positively (i.e has a positive impact on utility) by French homeowners in the decision making.

Our result indicates some potential avenues for action to increase energy efficiency investment. Consistently with the theory, the impact on utility of reduced uncertainty is higher for risk averse individuals. The willingness to pay for an insurance regarding the quality of energy retrofits and for a fixed energy price contract are positive and heterogeneous across respondents. The insurance for quality (as presented in our DCE) is slightly preferred over the fixed energy price contract for a large share of the homeowners population. Finally, we use our results to simulate the impact of specific initiatives and show that they could help increasing substantially the energy retrofit rate of French homeowners (the share of households that invest). For instance, on average, a 5000 euros decrease of the investment amount has the same effect as the introduction of an insurance for retrofit quality over 10 years (as presented in the DCE) on the energy retrofit rate of French homeowners, i.e + 10-15% compared to the reference scenario. This result opens the discussion on the possible strategies to be considered by policy makers to combine the achievement of a certain energy retrofit rate with the cost-efficiency of public expenditures.

The remainder of the chapter is organized as follows: Section 2 describes the general context; Section 3 provides the review of the literature that helped elaborating both our research question and approach, and the contributions of the chapter. Section 4 details the dataset, the design of our discrete choice experiment and the main individual variables of interest. Section 5 presents the descriptive statistics. Section 6 provides the theoretical framework and econometric specification. Section 7 presents the main results and a simulation to enlighten discussion and Section 8 draws conclusions.

2. General Context

Following the greatest awareness of the climate change issue and the growing involvement of countries in limiting our environmental impact, the reduction of non-renewable energy consumption and greenhouse gases has been set on the agenda of most of the sectors. Among them, the building sector of Western countries, and more specifically, the residential sector, has been designated by the Intergovernmental Panel on Climate Change (IPCC) as having the biggest untapped energy-savings potential[35]. However, the energy transition of the residential sector is facing a major challenge. While binding commitments relative to the reduction of energy consumption and the increase of energy efficiency have been taken at national and international scale[36], their achievement depends on the good will and the capacity to act of millions of the housing stock's inhabitants, whether it concerns energy savings behaviors or energy efficiency investments. In recent years, because the energy savings in the residential sector have not reached the expected level and are behind on meeting the closest-in-time energy goals, designing efficient policies able to foster energy efficiency investments has become an urgent stake in European countries[37].

In France, the related stakes are particularly important. It is worth noting that the building sector represents about 45% of the global energy consumption, with 30% of the energy consumed by the residential sector[38]. Globally, the French residential dwelling stock has a poor energy performance, with more than 60% of the dwellings that have an Energy Performance Certificate

[35] International Panel for Climate Change: https://www.ipcc.ch/pdf/presentations/poznan-COP-14/diane-urge-vorsatz.pdf
[36] See Energy Efficiency Directive, revised in 2016. This legislation has set binding measures to help the EU member states to achieve the 30% energy efficiency target by 2030
[37] See EU news for more information: http://sdg.iisd.org/news/eu-invests-in-energy-efficiency-and-environment-reports-increase-energy-consumption/
[38] See the report published by the French Ministry of Environment for more details: http://www.carbone4.com/wp-content/uploads/2016/08/Revue_-_Renovation_thermique.pdf

below energy class D[39]. Moreover, as described in detail in section II of the General Introduction of the dissertation, more than 5 million people would be concerned by fuel poverty. Energy efficiency stakes are closely related to social and welfare issues (such as fuel poverty related-issues)[40].

The 2015 Energy Transition for Green Growth law in France set results-oriented and targeted objectives in order to increase quickly energy efficiency (for instance, in terms of number of energy retrofits implemented per year, or the amount of energy savings achieved, etc.) [41]. In order to foster the energy retrofit rate of private homes, the French government has deployed a set of financial incentives financed by public and private capital and introduced energy taxation (carbon taxation) with regular increases[42]. In 2014, a national survey estimated the number of energy retrofits of the residential housing stock to be in the order of 290 000 dwellings. Moreover, for the years 2015-2016, energy renovations have shown little dynamism. Should the trend continue in the next few years, it is likely that the level of energy performance of the housing sector to which public policies committed is not going to be achieved.

3. Literature review

As detailed in the General Introduction (section I), the motivation for this research is grounded in the literature on the barriers to energy efficiency investment and the *energy efficiency gap* or *energy paradox* (Jaffe and Stavins, 1994; Sutherland, 1991), which has raised the debate for many years. Researchers usually list several barriers to energy efficiency. A barrier to energy efficiency investment can be defined as a "*mechanism that inhibit investment in technologies that are both energy efficient and apparently cost-effective for the potential investor*" (Sorrell and O'Malley, 2004). Based on a rich literature, market failures (e.g., energy prices do not account for environmental externality, asymmetric information, split incentives between tenants and landlords, etc.), market barriers (contextual uncertainty, heterogeneity) and behavioral failures factors (such as individual preferences and behavioral bias) are hypothesized

[39] Energy Performance Certificates provide a ranking (from A, the best, to G the worst) accordingly to the energy performance of the dwelling.

[40] See the definition of fuel poverty in France by following the link: https://www.connaissancedesenergies.org/que-recouvre-la-notion-de-precarite-energetique-en-france-120425

[41] Therefore, all private residential buildings consuming more than 330 kWh pe/m².year should be thermally renovated once before 2025 and all the dwelling stock should be retrofitted with respect to the BBC standards or related rules in the horizon 2050. Moreover, the energy-saving renovation of 500 000 private housings a year from year 2017 has been included in the roadmap.

[42] For now (dec.2018), energy tax increases have been phased out by the government following a powerful protest movement of French medium and low-income households regarding fuel costs.

to display a major role in explaining the under-investment in energy efficiency in the residential sector (Gerarden et al., 2015; Gillingham and Palmer, 2014b; Sorrell and O'Malley, 2004; Sutherland, 1991). Among these barriers, the past theoretical literature has identified the role of risk and uncertainty as potentially crucial, but empirical evidence from household's perspective remains scarce.

3.1 Uncertainty and risk in energy efficient investment

Uncertainty and risk associated with energy gains of energy efficient alternatives can lead to an under -investment in energy technologies (in comparison to investment in a deterministic environment) if the households effectively perceive them as a concern. The sources of risk and uncertainty associated with energy efficiency investments in the residential sector are several:

(i) *Technical uncertainty*. This source of uncertainty finds its origin in different informational issues such as incomplete and asymmetric information.

First, technical risk is linked to the "innovation" status of energy efficiency technologies, which implies, for instance, a limited accessibility to robust feedbacks and the inaccuracy of measures of performance (and energy savings). Thus, expecting savings resulting from energy efficiency investment cannot be fully certified. On this topic, some empirical works provided evidence that real energy savings could be heterogeneous and far from the expected savings in commercial and residential buildings (McCoy and Kotsch 2018; Laurent et al., 2013; Sutherland, 1991).

Secondly, adverse selection and moral hazard that occur in principal-agent situation (see Laffont and Martimort, 2009) can lead to defects regarding retrofit quality, which results in an uncertain outcome relative to retrofit quality and energy savings, in particular potentially lower and inefficient than expected.. For instance, Giraudet, Houde and Mayer (2018) provided evidence of moral hazard in home energy retrofits in Florida.

(ii) Uncertainty about *future energy rate.* Future energy rate cannot be fully anticipated by households; thus, energy savings benefits that depends on it can be perceived as uncertain or risky, and households can decide to invest less often than expected in energy efficiency technologies. The apparent volatility of energy price, myopic perception, ignorance and misperceived energy costs can explain the existence of this source of uncertainty (Alberini, 2013; Jessoe and Rapson, 2012; Sutherland, 1991).

(iii) Other types of uncertainty – From an asset management perspective, the Green value[43] of energy efficient dwellings may not be properly valued by the market (Kahn and Kok, 2014), which could be considered as an additional risk if individuals plan to sell their homes. The rebound effect[44] (Gillingham et al., 2016) could also be considered as an additional risk that can reduce energy savings benefits; however, as it results from a decision made by the individual itself (tradeoff between energy savings and comfort improvement), it is not considered here.

Expected energy savings which constitute one of the main benefits of energy efficiency investment depend both on the level of efficiency of the equipment and the cost of energy (mainly the cost of the heating fuel[45]). According to the abovementioned sources of risk and uncertainty, it seems that energy efficiency investments can effectively be perceived as risky or uncertain. The theoretical literature tells us that if it is the case, this could limit investment in energy efficient technologies. Different strands of the academic literature, from general decision-making theory to empirical evidence (even if the latter is scarce), are relevant to support this assumption.

3.2 Decision making under risk and uncertainty

Let us first define the crucial concepts of risk and uncertainty. Knight (1921) defined the risk as a measurable uncertainty. The probability of occurrence of a risky event and its potential associated impacts are, thus, quantifiable (i.e. known). In the contrary, a "true uncertainty," is "not susceptible to measurement", meaning that we can neither assess its occurrence nor its consequences (Knight, 2012). In the common language, the fact is that the terms *risk* and *uncertainty* are often used without distinction.

Economic behaviour under risk and uncertainty: the traditional approach

The traditional approach to modeling behavior under risk is through the use of the expected utility theory. Von Neumann and Morgenstern (1944) first suggested it and described the relationship between an individual's scale of preferences for a set of lotteries and their associated consequences. The relationship among preferences is associated with a utility function (defined for a range of lotteries), whose properties are based on three axioms (the

[43] i.e. the value of good environmental characteristics of a good; See, for instance, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1839429

[44] The rebound effect characterizes the fact that energy savings resulting from energy efficiency investment can be reduced because individuals increase their level of thermal comfort (or more generally, the demand for the energy service)

[45] Indeed, heating energy represents on average more than 60% of the energy bill. Moreover, energy retrofit measures mainly concern energy savings related to the heating use.

ordering, continuity and independence of individual choice). The shape of the utility function defines preferences towards risk. Risk-averse decision makers will display a decreasing marginal utility of wealth; they will then tend to choose options that have very little variation about expected monetary returns, which could not be the case for energy efficiency investments. In that context, the certainty equivalent is defined as follows: the guaranteed amount of cash that would yield the very same expected utility as a given risky choice with absolute certainty, this represents the opportunity cost of risk. It depends on risk tolerance. The "risk premium" is then defined as the maximum amount that the individual is willing to pay in order to receive the same expected value but with no risk. As a result, the greater the risk is, the greater the risk premium will be; the greater the risk aversion is, the greater the risk premium will be.
The traditional approach of the expected utility theory is applicable to many real situations; however, some limits appeared and led to the development of new theories. The *Allais paradox* showed that an outcome is overweighed when it is sure, which led to the development of the prospect theory (Kahneman and Tversky, 1979). Another criticism is the one from Ellsberg (1961), who says that the trust of the decision maker about his own beliefs is also playing a role in investment under uncertainty.

Investment decision under risk and uncertainty.

Total energy savings are not immediate outcomes of energy retrofit decision. Energy efficient technologies are investments, defined by the act of spending an immediate cost (initial investment) while being in the expectation of future benefits (energy savings, comfort) over the lifetime of the technology. Thus, literature about investment under risk and uncertainty is also adequate to our topic. The theory on investment introduces the calculation of the Net Present Value (NPV) of a project as criteria to decide whether to invest or not at a given time; it corresponds to the summation of the present value of a series of present and future cash flows (through the discount rate). To be attractive, the NPV of an investment should be greater than zero. Uncertainty and risk around outcomes of energy efficient investments can be accounted in NPVs and often lead to the reduction of current investment profitability.

The Net Present Value (NPV) over a period τ is calculated as follows (0), with I_0 the investment cost of the energy efficiency measure considered, CF the net cash flows of year i, corresponding mainly to the energy saving benefits for the year i expressed in euros (previous energy consumption minus new expected energy consumption), and d the discount rate.

$$NPV(\tau) = -I_0 + \sum_{i=1}^{\tau} \left(\frac{CF,i}{(1+d)^i} \right) \qquad (0)$$

However, in most of cases, the cash flows cannot be estimated very precisely since they involve cash flows of future periods that can be uncertain. Thus, considering NPV under uncertainty is justifiable; researchers suggest different ways of doing it.

Keown et al. (1985) argued that if a project bears more risk or uncertainty than an ordinary project, a higher rate of return should apply. In line with this, uncertainty about future energy prices and technical risk might lead individuals to apply a higher discount rate to energy efficiency measures (higher than the market rate of interest). Including a higher discount rate in NPV gives less weight to the future cash flows (benefits) in comparison to present, and then reduces the NPVs of energy efficient investments. According to Thompson (1997), however, this standard approach of the higher discount rate for energy efficiency investment should be revised as follows; the stream of future benefits should be divided in two streams of future costs (status quo vs project) and a lower discount rate should apply to costs in the project as energy efficient investments have the effect of lowering economic risk relative to the status quo. According to Gollier (2007, 2013), increasing the discount rate is not the best way to account for risk in NPV because it penalizes less risky projects or those were uncertainties occur in the very far future. Gollier suggested accounting for risk by replacing expected cash flows by certainty equivalent. In any cases, for risk averse people, this leads to the reduction of investment profitability.

Finally, when irreversibility, uncertainty and timing (possibility to delay the investment) are considered, the NPV framework must be adapted. According to (Henry, 1974) and Dixit and Pindyck (1994), sunk costs of an investment project create an option value if the investment decision can be postponed in order to wait for new information. This option value is the value of information gained by delaying a decision to engage some irreversible action. As energy efficiency investments are irreversible (they cannot be removed), the option value may exist and should be added to project cash flows; it could contribute to the reduction of the NPV and the delay of the decision of investing. Based on the results of empirical studies, and thanks to a model based on a stochastic representation of the energy price, Hassett and Melcalf (1993) argued that the irreversibility of energy measures may make individuals want to postpone the adoption in order to wait for more information about energy price. However, it is worth mentioning that, for some scholars, the value of postponing investment for energy measures is not that clear because this could lead to the loss of benefits that are less uncertain (Howarth and Sanstad, 1995). For instance, energy prices are predicted with more confidence over the close-term than in the more distant future.

Risky asset & Portfolio theory: the case of homeownership

The third strand of the literature is the one related to portfolio theory. For homeowners, housing is a consumption good but also a financial asset: owning a house is often a major capital asset in individual portfolio. Depending on portfolio composition and global wealth, real estate property could influence the choice of investing in future risky assets (Flavin and Yamashita, 1998; Kullmann and Siegel, 2005; Sutherland, 1991).

The CAPM (Capital Asset Pricing Model) first introduced by Treynor (1961), develops the equilibrium relationship between risk and return of individual assets and portfolio. One of the results of this model is that random risk of an individual asset does not affect overall portfolio risk if the portfolio is efficient, i.e. diversified. Then, for Sutherland (1991), energy efficiency investments should expect a high discount rate because they are illiquid, and their risk cannot be diversified away (they tie up a large share of the investment portfolio). However, this result is discussed by Johnson (1994), who argues that, on the contrary, a negative systematic risk premium should apply for energy efficiency investments, since rising energy prices associated with future environmental policies are likely to affect the global economy and the value of energy efficiency investments in opposite ways.

Otherwise, through the analysis of the ratio of house value to wealth based on US data, Flavin and Yamashita (1998) provide evidence that life cycle and portfolio composition (in terms of risky or non-risky assets, i.e share of stocks and bonds) were linked. Young people, with very high housing constraint (large holding of real estate relative to their net worth) are forced to be into a situation of high portfolio risk, which lead them to use their worth to pay down their mortgage or invest in bonds (non risky asset). For older individual with low housing constraint, the effect is opposite and they are more likely to invest in stocks. As a result, if we hypothesize that energy efficiency investments can be compared to such financial assets, and if we consider the fact that they increase housing constraint and reduce portfolio diversification, they are not likely to be considered as consistent with an efficient portfolio strategy (even less for low-income households).

In conclusion, it seems that strong theoretical arguments exist to support the idea that risk and uncertainty could have a crucial role to explain inefficient energy renovation investment from a household perspective.

3.3 Empirical evidences in the residential sector

Empirical evidences about the role of risk and uncertainty in explaining the energy efficiency investment are scarce.

Thanks to a discrete choice experiment conducted among 473 Swiss homeowners, Alberini et al. (2013) provided empirical evidence that individuals that declared being completely uncertain about future energy prices were less likely to invest in energy retrofits. The authors show that household heterogeneity in belief regarding the future trend of energy price does play a role to explain differences in willingness to implement energy efficiency investments. However, the reach of their study regarding the role of respondent characteristics in explaining heterogeneity is limited by the size of their sample (473 homeowners). Moreover, they do not consider the role of other sources of uncertainty in their analysis.

Other works focused on the role of time and risk preferences in explaining energy efficiency investment.

Thanks to a survey addressed to 1200 US homeowners, Newell and al. (2015) provided evidence on the existence of strong link between discount rates and demand for energy-efficient products. Using both hypothetical choice situations, in which individual have to choose between water heaters with different prices and energy efficiency, and direct questions, the authors suggested the existence of a robust negative relationship between measured discount rates and willingness to pay for energy efficiency. This study however does not allow distinguishing the sources of risk and uncertainty that matter.

Scholars also studied the role of heterogeneity in risk attitude to explain energy efficiency investment; they tend to find a quasi-systematic negative relationship between risk aversion and energy efficiency investments in the residential sector (Fischbacher et al., 2015; Qiu et al., 2014; Volland, 2017). This result presumes a certain degree of perceived risk or uncertainty for these investments, but, again, these papers do not identify the sources. Moreover, the measure of risk aversion can differ among studies (contextualized or non-contextualized risk aversion, self-declared vs choice list). Finally, one of the limitation is that the measure of risk aversion and the decision of implementing energy efficiency investment that are put in relation in these studies are not assessed at the same period. Indeed, the measure of risk aversion was assessed at the time of the survey and the energy retrofit decision[46] was made potentially many years before.

[46] Energy efficiency decisions refer to “real” actions that were implemented in the past.

3.4 Contribution of our research to the literature

Thus, despite the existence of a rich theoretical literature supporting the idea that technical and economic risk and uncertainty could play a crucial role in explaining under-investment in energy efficient, we see that empirical evidence remains scarce. According to the literature, this is, indeed, a complex issue. In particular, the effects of different individual factors, such as individual risk aversion, subjective perception of the economic environment and the relationship with the portfolio strategy (for homeowners), etc. must be disentangled or at least, consistently examined. Moreover, different sources of risk and uncertainty should be accounted for. Finally, from a methodological perspective, time-consistency between the energy efficiency decision and the measure of different individual characteristics should be considered in empirical studies.

Thus, original empirical research is needed to investigate the sources of uncertainty that matter and their importance in the decision-making process of energy efficiency investment, along with the relationship with household characteristics. This research aims at contributing to the debate. More precisely, we want to identify the role of perceived risk and uncertainty in explaining energy efficiency investment and to test how much its importance varies accordingly to individual characteristics such as individual risk aversion and perception of the economic context[47]. To do so, we elaborate a rich survey using the methodological approach of the Discrete Choice experiment, guided by the work of Alberini (2013). We use this flexible methodology in an innovative way to elicit how much households value reduced uncertainty about energy price and retrofit quality that affect perceived savings benefits from energy efficiency investment decision. Moreover, we also try to link these tastes to individual preferences towards risk, individual characteristics and perceptions.

As far as we know, this is the first empirical work addressing this particular issue.

4. The Discrete Choice Experiment

Our dataset stems from a survey funded by the Centre Scientifique et Technique du Bâtiment (CSTB) and carried out by the agency Sphinx[48] from December 2017 to January 2018. The

[47] The relationship between energy efficiency investment and portfolio strategy was also identified as an important question. However, it requires very rigorous data on individual worth (income, financial assets, global capital) that are very difficult to get in non-official surveys.

[48] See more details on the agency by following the link: http://www.lesphinx-developpement.fr/contact-2-2/contactez-nous/

survey was conducted online and addressed to 3000 French homeowners (main residence). The dwellings characteristics of homeowners our sample are quasi-representative[49] of the French owners housing stock.

As mentioned before, the survey includes a discrete choice experiment (DCE) to assess the role of uncertainty associated to future energy cost and quality of retrofit work in explaining the energy retrofit decision. The DCE was introduced at the beginning of the survey just after few framing questions. In order to capture household and dwelling heterogeneity, the survey also includes several questions about the socio-economic characteristics of the households (age, economic information, type of urban area) and the housing characteristics (surface, construction data, energy performance, dwelling type, stated heating energy bill, etc.). Moreover, the survey asks questions related to individual environmental attitude regarding the purchase of new equipment, and assesses individual risk aversion in the energy context[50]. Finally, it also contains questions about households' perception of energy-saving renovations and future trend of energy price, asked as direct questions in order to contrast and link them with the energy efficiency preferences elicited trough the DCE. The questionnaire is available in appendix C.

In the next paragraphs, we detail first the challenges behind our empirical question and the choice of the methodological approach. Thus, we first introduce the goals and the description of the Discrete Choice Experiment (presentation of the attributes, its design and implementation). Then, we explain in detail the construction of other important variables, which allow us to characterize the heterogeneity in preferences for energy retrofit elicited trough the DCE.

4.1 The discrete choice experiment

4.1.1 Methodological considerations and objectives

The present work aims at understanding the role of two sources of risk and uncertainty as barrier to energy efficiency investment in the residential sector. We are particularly interested in estimating the importance of perceived risk and uncertainty in the decision making of energy renovation, while accounting for the role of individual heterogeneity (such as risk aversion and

[49] Representativeness criteria are: building construction date and type of urban area, source: INSEE https://www.insee.fr/fr/statistiques/1373386?sommaire=1373438

[50] The survey also assesses the time preferences of respondent in an energy-contextualized framework (see questionnaire in appendix C). However, this information has not been exploited yet.

individual perception) as possible. This represents an empirical challenge and requires adequate approaches.

To answer this issue, classical revealed preferences surveys have several shortcomings. First, they do not allow to rigorously account for the relationship between individual perceptions, preferences and beliefs (about energy price, defects, risk aversion) and action (energy efficiency investment). For instance, it seemed difficult to ask individuals to remember what was their perception of the context at the time they made the decision to invest (which can be many years ago). Secondly, it would require a larger sample to control for all sources of heterogeneity since several other characteristics can affect the decision (such as the type of retrofit, the characteristics of housing, the motivations, etc.). Lastly, they do not allow to value properly the potential benefits of the reduction of the uncertainty (in terms of utility, energy retrofit rate). Thus, we needed other methods.

The seminal work of Alberini and al. (2013) is the main academic input that participated to elaborate the approach implemented in this article. In this research paper, the authors use the outcomes of a Discrete Choice Experiment (DCE) to investigate the role of individual belief about the trend of the future energy cost in explaining the preference for energy renovation. These preferences are elicited trough hypothetical choice situations. The paper provides evidence that uncertainty about future energy price explains the preference for the status quo (doing nothing) over energy efficiency investment for Swiss homeowners. To our knowledge, this work is the first to provide an empirical evidence of the role of (perceived) price uncertainty as barrier to energy retrofit. However, one limit is that this work only focuses on the role of energy price uncertainty and so neglects the role of other perceived risk or uncertainty (as technical risk).

The DCE is a stated preferences methodology build to elicit preferences for goods or project by putting individuals in hypothetical choice situations (Johnston et al., 2017). Individuals compare the different alternatives of the choice situation based on their attributes (i.e characteristics of the alternatives) and chose, by making trade-offs between the level of attributes, the alternative that provides them the greatest utility (Lancaster, 1966). It is then possible to estimate the relative weight of the different attributes in explaining the utility derived from the choice. DCEs are often used for evaluation of non-market products because they allow a certain flexibility in the design of the choice situations (test of implicit attributes, design and test of a new product) while controlling the context (at some point) (Alpízar et al., 2001). This flexibility is a precious and useful advantage to test empirically the hypothesis of the role of

different sources of uncertainty in explaining energy efficiency investment (see next paragraph for more details on how this was included in the DCE framework). On the topic of energy efficiency investment, some scholars used the DCE framework to reveal the importance of benefits such as energy savings, thermal comfort and improvement of indoor air quality in the decision-making process of energy efficiency investment (Galassi and Madlener, 2017a; Kwak et al., 2010a). Moreover, Galassi and Madlener (2017) provided evidence that environmental concern was a significant individual-specific variable to explain heterogeneity in preferences regarding energy efficiency investment attributes. In the French context, Stolyarova used the choice experiment methodology to estimate the willingness to pay for different energy efficient technologies (Stolyarova, 2016).

Thus, the use of Discrete Choice Experiments has grown significantly in the field of environmental economics since a decade, including studies to elicit preferences for energy retrofit solutions. However, when using these methods, one still must be careful about extrapolation and their abilities to elicit true preferences (Alpízar et al., 2001). To limit bias as possible, some guidelines regarding the design and the implementation of the DCE (number of choice tasks, order of presentation, etc.) have to be followed (Johnston et al., 2017).

4.1.2 Description of the DCE

In the DCE conducted in our survey, individuals are put in several hypothetical choice situations and decide whether they will invest or not in energy efficiency based on the characteristics of the energy retrofit offer. The energy solution considered in the DCE is the external wall insulation[51]. To elaborate our discrete choice experiment, we used five attributes to characterize the energy retrofit alternatives. Attributes and levels are detailed in Table 1.

Three of the attributes are a "common practice" in discrete choice experiment related to energy efficiency investment (Alberini et al., 2013; Galassi and Madlener, 2017a; Kwak et al., 2010b; Stolyarova, 2016). They include the investment costs (amounts were defined according to observed market costs reduced by public subsidies), the energy savings potential and the possibility to increase or the improvement of thermal comfort (increased or similar thermal comfort in comparison to the current situation.

[51] This type of energy retrofit presents several advantages regarding its implementation, which facilitates the appropriation of the hypothetical situations by individuals: individuals can stay at home during the retrofits, it does not reduce the living area (as opposed to insulation from the interior), it does not depend on current heating system, etc.

The two last attributes are innovative and designed to test if uncertain parameters associated to the investment context are effectively sources of concern affecting individuals' energy retrofit decision. Among them, according to the literature review, the uncertain trend of future energy price (that determines energy service cost) or uncertain level of quality achieved by the building works could be internalized by households and negatively affect the decision-making. To test this hypothesis, we consider two insurance schemes as attributes of the energy retrofit offer: (1) an insurance on the quality of the energy retrofits, (2) a contract offering a fixed future energy price. The hypothesis behind is that, if these two sources of uncertainty matter for the investment decision, then, the presence of the two insurance schemes will be valued positively in the energy retrofit alternatives.

We define the two insurance schemes as follows.

The first one is an insurance for energy performance/quality of retrofit work, valid 10 years[52]; it ensures that the energy retrofit works have effectively achieved a certain level of thermal quality, the quality of the retrofits is checked ex-post by an external expert. This insurance reduces the technical risk identified earlier by insuring against potential defects.

The second insurance scheme is entitled "fixed energy price contract"; it ensures that individuals will pay a fixed price (the current price) for a unit of their heating energy over the next 5 years following investment[53]. For more realism, the contract is declared to be founded by public funds. Today, some energy providers already offer customers to subscribe fixed price contracts (over 2-3 years), so that such fixed energy price contract can be considered credible.

[52] The duration of the quality-guarantee is consistent with the existing 10-year guarantee that insures the compensation for damages after building or retrofit work in the French building sector.

[53] The duration of this contract is inferior to the one of the quality guarantee because of credibility considerations. The fixed price is the current price of their heating energy.

Table 1: Attributes and levels in the DCE

Attributes	**Levels**
Investment costs (net of public incentives)	7000€ 10 000€ 13 000€ 16 000€
Energy saving potential of the Insulation offer	-25% -40%
Insurance for performance/quality of energy retrofits	Included Non-Included
5 Years Fixed energy price contract	Included Non-Included
Thermal comfort after retrofits	Same heating temperature as before Higher heating temperature than before

By including these insurance schemes, we are interested in (i) identifying if uncertainties about energy price and thermal quality are sources of concern for the decision-making on energy efficiency investment; (ii) ranking the preferences for the different attributes, (iii) testing if these preferences are heterogeneous across individuals.

4.1.3 DCE design and implementation

Each energy efficiency offer consists of five attributes with 2 or 4 levels (see Table 1). We use a d-efficient[54] design generated with the NGENE software[55] to obtain 8 choice situations in which individuals have to choose among two energy retrofits alternative and the status quo option (see the example of a choice card in Figure 1). Priors, i.e expected signs for the effects of attributes, were required to define the optimal combination of attributes in the choice situations. We used findings from previous literature to establish our assumptions about attributes impacts: a negative sign for the investment costs, a positive sign for the energy savings potential, a positive sign for an increase of thermal comfort (Alberini et al., 2013; Galassi and Madlener, 2017a; Kwak et al., 2010b). For the insurance for retrofit quality and the fixed energy price contract, we make the hypothesis that the signs will be positive based on theoretical literature and the work of Alberini (2013). Our final design is efficient and with

[54] In a choice model as presented in the *modelling approach* section, the precision of the estimates is reflected by the variance-covariance matrix of the estimated coefficients β. Efficient designs are based on the idea to minimize the size of the variance-covariance matrix given a prior for β.

[55] We are grateful to Benjamin Ouvrard (INRA, Nancy) for his help for the design of the DCE with NGENE.

balanced attribute-levels. The selection of a D-efficient design uses the D-error measure as efficiency indicator; efficiency is obtained based on the standard deviation of the estimated parameters[56].

The eight choice situations were presented in a random order to avoid declining concentration and limit the learning effect bias. At the end of the experiment, one of the choice card (the same for everybody) was resubmitted in order to appreciate the consistency of each individual across the different choice situations. A "consistent" individual is expected to make the same choices for the two similar choice sets.

Figure 1. Example of choice card

Attributes	**A** **Wall insulation**	**B** **Wall insulation**	
Net investment cost	10 000 €	13 000 €	
Energy-savings potential	-25%	-40%	
Insurance for quality of retrofits/energy performance	✗	✓	**No retrofit works**
Fixed energy price contract	✗	✓	
Indoor temperature	No change	Increased	
Choice	□	□	□

[56] D-optimal designs are used when resources are limited (for instance, the number of choice sets presented to respondents). Indeed, not all combinations of attributes can be presented to the respondent. A D-optimal design minimizes the generalized variance of the parameter estimates for a model that is specified in advance. The multinomial logit is generally used as it is the less sophisticated. D-optimal designs maximize the D-efficiency, which is a criterion based on the standard deviation of the estimated parameters. The D-efficiency values depend on the number of choice situations and alternatives in the design, the number of independent variables in the model, and the maximum standard error for prediction over the design points. The design with the highest D-efficiency is preferred. See the following web link for more information: https://www.itl.nist.gov/div898/handbook/pri/section5/pri521.htm (accessible in February 2019).

4.*2 Presentation of the main individual variables of interest measured in the survey*

4.2.1 Measure of individual Risk aversion

In the survey, we also included a measure of individual taste for risk. Since measures of risk aversion across contexts are correlated but not equal (Dohmen et al., 2011), we decided to measure risk aversion of French homeowners within an energy-contextualized framework. Thus, we used the consensual choice list adapted from (Holt and Laury, 2002a) and inspired from (Qiu et al., 2014) to assess individual risk aversion in an energy efficiency renovation framework.

Each individual was put in the context of a one-year rental situation. In this context, it had to choose between two apartments that are identical except regarding the heating systems in place. Apartment A has the heating equipment A and apartment B has the heating equipment B; both systems lead to energy savings in comparison to a "classic equipment". After this introduction, each individual faced 9 ordered hypothetical choice situations where it decides between the two systems A and B. Heating systems outcomes are defined by a probability of occurrence and a yearly monetary gain (monetary energy savings). The heating equipment B involves a more risky outcome than the heating equipment A. The switch from equipment A to equipment B determines the end of the experiment and the level of risk aversion of the respondent. The later (in terms of number of the choice situation) it chooses alternative B, the more risk averse the individual is. Table 2 represents the choice list presented to each respondent for the elicitation of risk aversion.

Table 2: Choice list used to elicit contextual risk aversion of the individuals.

Number of the situation	Heating Equipment A	OR	Heating Equipment B
Situation 1	20% chance that you save 400€ and 80% chance that you save 320€	OR	20% chance that you save 770€ and 80% chance that you save 20€
Situation 2	30% chance that you save 400€ and 70% chance that you save 320€	OR	30% chance that you save 770€ and 70% chance that you save 20€
Situation 3	40% chance that you save 400€ and 60% chance that you save 320€	OR	40% chance that you save 770€ and 60% chance that you save 20€
Situation 4	50% chance that you save 400€ and 50% chance that you save 320€	OR	50% chance that you save 770€ and 50% chance that you save 20€
Situation 5	60% chance that you save 400€ and 40% chance that you save 320€	OR	60% chance that you save 770€ and 40% chance that you save 20€
Situation 6	70% chance that you save 400€ and 30% chance that you save 320€	OR	70% chance that you save 770€ and 30% chance that you save 20€
Situation 7	80% chance that you save 400€ and 20% chance that you save 320€	OR	80% chance that you save 770€ and 20% chance that you save 20€
Situation 8	90% chance that you save 400€ and 10% chance that you save 320€	OR	90% chance that you save 770€ and 10% chance that you save 20€
Situation 9	100% chance that you save 400€ and 0% chance that you save 320€	OR	100% chance that you save 770€ and 0% chance that you save 20€

Note for the reader: In every choice situation (1 to 9), individuals have to make a choice between two energy efficient heating systems, leading to different outcomes (measured in yearly monetary savings). Option A is the safe choice.

4.2.2 Individual perception of the future evolution of energy price

Based on the work of Alberini (2013), we also asked respondents their opinion about the future evolution of their heating energy price. The question was asked as follows: *How do you see the evolution of the price of your heating fuel for the next five years?* The possible answers were the followings: "*no opinion*", "*constant energy price*" (in comparison to the price of their heating fuel at the time of the survey), "*increase*" or "*decrease*" (with the possibility to specify the magnitude of the increase/decrease).

5.Descriptive statistics

We present here the descriptive statistics for all individuals. The total sample is composed of 3000 French homeowners. We describe the main characteristics of our sample in Table 3 and 4.

First, 27% of the individuals are found to be non-consistent in their choices across the 9 choice situations presented in the Discrete Choice experiment[57]. The share of non-consistent individuals is very close to what was found in (Galassi & Madlener, 2017). This can reveal respondent's inattention to the survey or reflects a learning effect or other behavioral features. For information, descriptive statistics for only "consistent" individuals are also presented in appendix B. The sub-sample composed of only the consistent respondents is used for robustness check in our modelling section.

Table 3: Representativeness of our sample.

Share of owner-occupied dwellings	French dwelling stock (Insee[58]) (%)	Sample (%)
Building period		
Before 1949	31.3	26.0
Between 1949 and 1974	23.6	25.0
Between 1975 and 1999	29.8	31.0
After 1999	15.3	19.0
Location (type of urban area)		
Rural commune	29.2	26.4
Urban area < 20 000 habitants	19.5	18.4
Urban area between 20 and 100 000 hab.	12.9	13.7
Urban area > 100 000 habitants	25.8	27.9
Paris conurbation	12.5	13.1

Our sample is quasi representative of the French homeowner dwelling stock. We denote a slight underrepresentation of very old buildings (built before 1949). 26% of the dwellings of the sample are located in rural area. 78% are houses. Gas and electricity are the two major heating energy sources (which is consistent with national statistics). The average heating energy bill is

[57] The individual drivers of inconsistency were tested using a logistic regression. No driver was found to influence importantly the fact to be non-consistent (age and occupation were found to have a significant but model demonstrates a very low explanatory power).

[58] See more information on the statistics regarding the homeowners dwelling stock (link available in February 2019): https://www.insee.fr/fr/statistiques/3269496

1187 euros; this is lower than the national average[59] . The difference can be explained by inaccurate declared responses and the presence of many "outliers" (we can see that the standard variation is very high). Electricity and natural gas are the two main heating energy sources. Finally, 43% of the homeowners of our sample are familiar with energy retrofit renovation as they have already implemented an energy retrofit on the building envelope of their dwelling in the past.

Regarding the individual characteristics, women are a little bit under represented. The average age of the respondents is 50 years old. Almost the half of the respondents pay attention to environmental label when buying appliances and used it as a major choice criterion. 16% of the respondents owns an other real estate and are landlords. Finally, 53% of them have a loan in progress for their main residence. Descriptive statistics regarding net monthly income are not presented here as we noted the presence of numerous high and zero values which suggests the refusal of respondents to answer this sensitive income question and points at potential bias in the mean income over the population.
Regarding the perceived quality of energy retrofits, we asked respondents to give a mark from 0 to 10 to evaluate the risk of defects in retrofit works in general. The average mark for the assessment of defects is higher than the mean (6.5/10), meaning that, for respondents, defects are likely to be a concern. Moreover, 24% of the respondents are "fully" satisfied with the thermal comfort of their dwellings.

We also directly asked the respondents whether they perceive the energy efficiency investment as risky or not in the last part of our survey. 72% of the global sample effectively perceived energy efficiency investment as risky. Then, we asked them to identify the sources of risk that matter. They had the possibility to select several of them from a list. Figure 2 identifies the results: profitability and risk of defects (low quality) are the two main sources that matter.

[59]The average heating energy bill was 1611euros 2017, see more information on the following web link: https://www.lenergietoutcompris.fr/actualites-et-informations/prix-des-energies/facture-de-chauffage-les-francais-debourseraient-1611-eu-par-an-48094

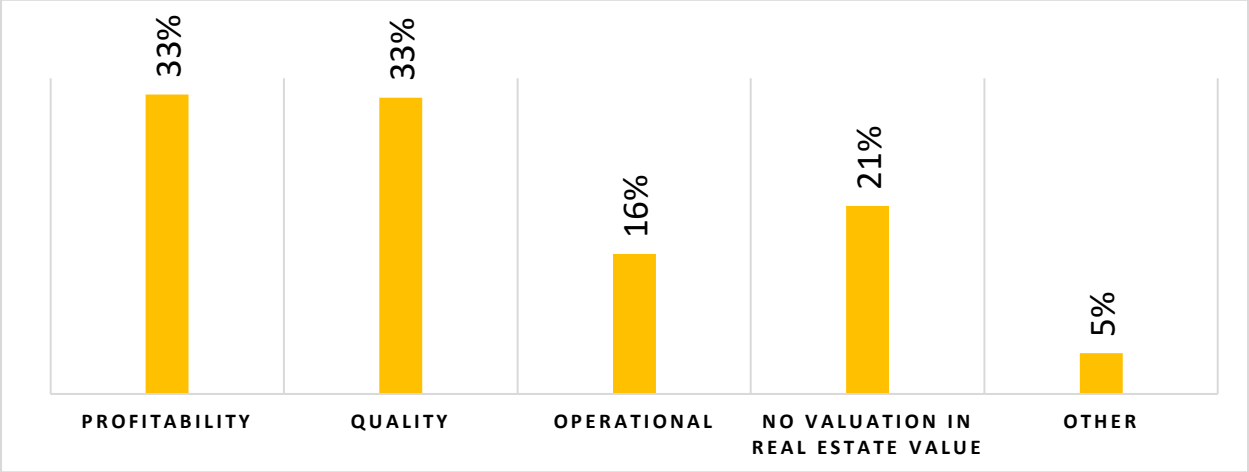
Table 4: Descriptive statistics (3000 observations). Source: author's survey

	Mean	Std deviation
Characteristics of individuals		
Female	0.46	0.5
Age of the respondent (in years)	50	13.9
Households who has a loan in progress[60](main residence purchase)	0.53	0.49
Landlords (renting out a property)	0.16	0.36
Risk averse Individuals*	0.66	0.47
Savings between 0 and 5000 euros	0.25	0.43
Perception of the energy context		
Perception of quality of retrofits works (1: non-conformity never happens. 10: non-conformity is always an issue	6.5	1.9
Individuals having no opinion about the trend of the future energy price	0.62	0.48
Environmental label is a significant criterion when buying appliances	0.48	0.49
Is fully satisfied with the current level of thermal comfort (%)	0.24	0.43
Dwelling characteristics		
Owners living in a house	0.78	0.41
Surface of the dwelling (m2)	128	370
Energy bill (euros)	1187	1326
Heating fuel source (%)		
Electricity	0.32	0.47
Gas	0.37	0.48
Wood	0.12	0.33
Fuel	0.10	0.31
Retrofit		
Household having implemented at least one energy measure (envelope)	0.43	0.5

* We built a dummy variable equals to 1 when individual was *slightly risk averse*, *very risk averse*, *highly risk averse* and *stay in bed* according to Holt and Laury classification and equals to zero otherwise.

[60] We obtain a low response rate for other questions related to the financial portfolio of respondents. These data were not included in the analysis.

Figure 2: Type of risks that matter in energy efficiency investments (stated risks). Source: author's survey

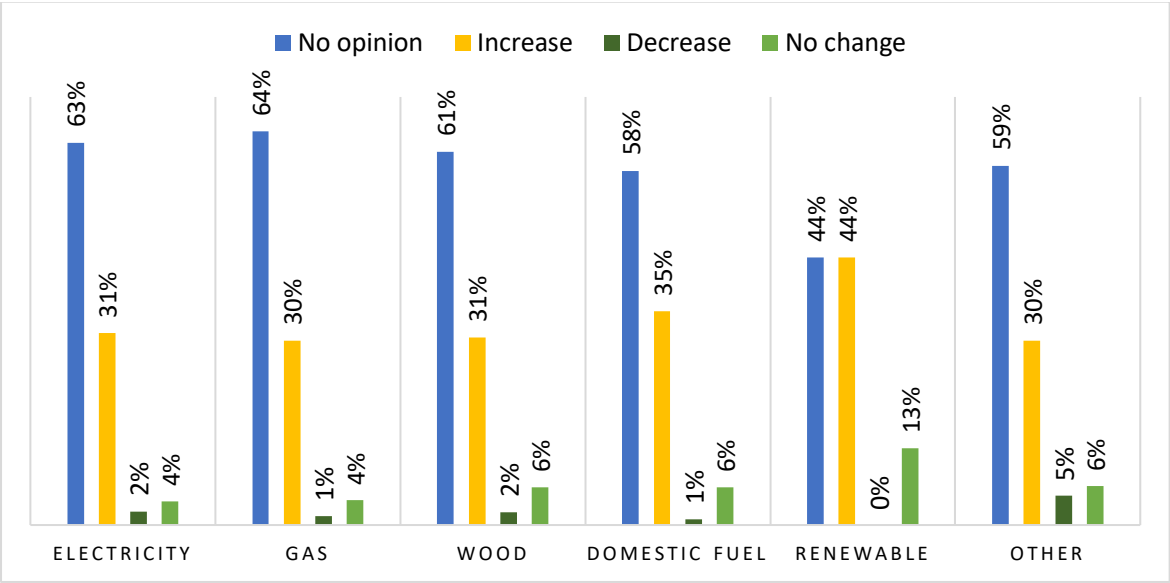


Note for the reader: the risk related to the profitability of energy efficiency investments is designated by 33% of the households who declared these investments as "risky".

Perception of the evolution of future energy price over the next five years.

We can note that more than 60% of our observations has no opinion about the evolution of energy price over the next five years (see Table 4 and figure 3), whereas 30% believe in an increase on average. In Alberini (2013), only 12% of the respondents declared to have no opinion about the evolution of the heating fuel price (over 20 years) in the Swiss context. In the future, it could be interesting to investigate if these perceptions are linked or not to past trends of energy rates or if they are disconnected.

Figure 3: Individual perception of the future evolution of the price of heating energy according energy sources. Source: author's survey



Measure of risk aversion

Regarding the contextualized measure of individual risk aversion, descriptive statistics show that a large share of the respondents is averse to risk with different but high degrees of risk aversion. The majority of the respondents switches from alternative A to alternative B in the very last situation; thus, their degree of risk aversion in the energy efficiency context is very high. Table 10 presents the link between the number of the switching situation and the degree of risk aversion according to Holt and Laury (2002b) classification. Figure 4 shows the share of respondents switching from A to B at each choice situation.

To facilitate the analysis, we also built a dummy variable equals to 1 when individual was *slightly risk averse*, *risk averse*, *very risk averse*, *highly risk averse* and *stay in bed* according to Holt and Laury classification (see table 5) and equals to zero otherwise. According to this specification, 66% of the individuals are risk averse within the energy efficiency context.

Figure 4: Share (density, on vertical axis) of respondents switching from A to B for each number of situation (abscises axis: number of the choice situation).

Source: author's survey.

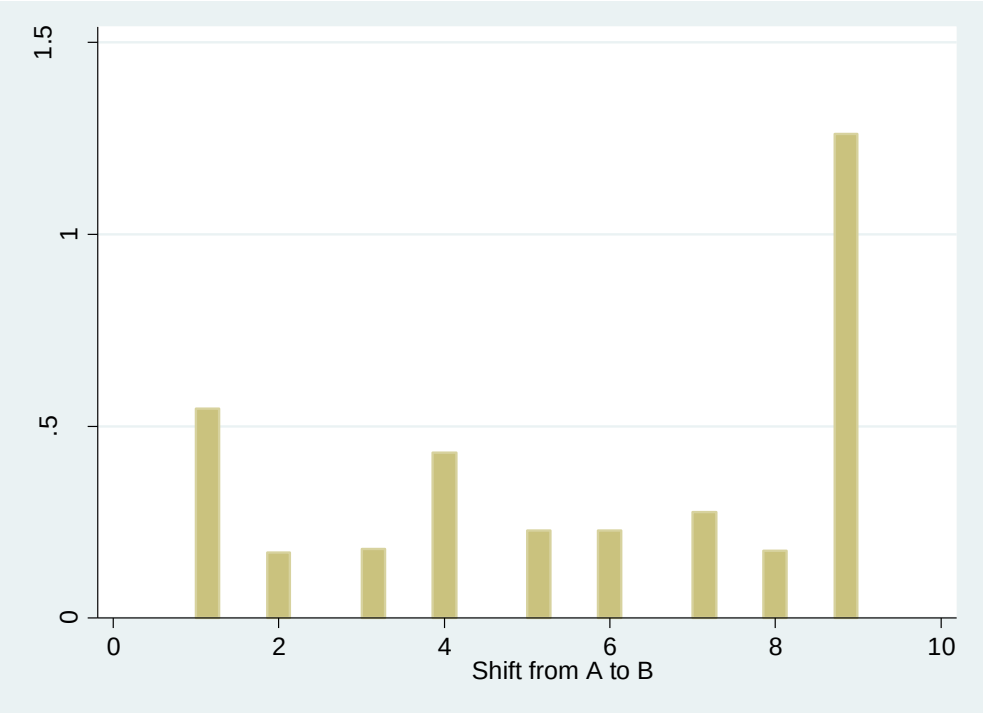


Table 5: Risk aversion classification based on lottery choices (adapted from Holt and Laury (2002))

Number of the situation in which individuals choose the option B	Range of relative risk aversion for $U(x) = x^{1-r}/(1-r)$	Risk preference classification
1	r <-0.95	Highly risk loving
2	-0.95<r<-0.49	Very risk loving
3	-0.49<r<-0.15	Risk loving
4	-0.15<r<0.15	Risk neutral
5	0.15<r<0.41	Slightly risk averse
6	0.41<r<0.68	Risk averse
7	0.68<r<0.97	Very risk averse
8	0.97<r<1.37	Highly risk averse
9	1.37<r	Stay in bed

6.Modeling framework and econometric specification

In our discrete choice experiment framework, each homeowner faces 8[61] distinct choice situations in which it chooses among three alternatives (two energy efficiency offers and one status quo option) described by five attributes.

The modeling framework of the discrete choice experiment is based on two main theoretical frameworks. First, the characteristics demand theory (Lancaster, 1966), which defines the value of a good as the sum of values of each of its characteristics (here the attributes of the energy efficiency offer). Second, the random utility theory (McFadden, 1973) that says that utility derived from a choice is composed of a deterministic part and a random part. Respondent then chooses the alternative with the highest utility, given the realization of the random part.

Let us consider a population composed of N decision-makers. These decision makers face J potential choices that are exclusive. For an individual n ($n \in \{1, \dots, \mathrm{N}\}$), the utility U_{nj} of choosing the alternative j ($j \in \{1, \dots, \mathrm{J}\}$) can be expressed as a linear combination of a deterministic part, V_{nj} and a stochastic term ε_{nj}, capturing the unobserved random term of respondent n's choice (Holmes and Adamowicz, 2003; Louviere et al., 2000). The observable part V_{nj} is obtained from the K observable attributes of the alternative j, designated by $X_j = (x_{j1}, \dots, x_{jk}, \dots, x_{jK})$ and a set A of individual observable characteristics, denoted here as $Z_n = (z_{n1}, \dots, z_{na}, \dots, z_{nA})$. Thus, we have:

[61] In fact, there are 9 choice situations but two of them are similar.

$$U_{nj} = V_{nj} + \varepsilon_{ij} \quad (1)$$

with

$$V_{nj} = V(X_j, Z_n)$$

Rational respondents will choose the alternative j from a finite set of alternatives S, if the utility U_{nj} is superior to the utility $U_{nj'}$, obtained from any other alternatives j' in S. Thus, we get:

$$U_{nj} > U_{nj'} \Rightarrow V_{nj} + \varepsilon_{nj} > V_{nj'} + \varepsilon_{nj'} \qquad \forall\, j \neq j', j, j' \in S \quad (2)$$

Thus, the probability of choosing the alternative j by individual n is equivalent to the probability that the utility of alternative j overcomes the utility of any other alternatives j' (Hanley et al., 1998). Then, P_{nj}, the probability that the respondent n chooses the alternative j over any other alternative j', is:

$$P_{nj} = P\{U_{nj} > U_{nj'} \quad \forall\, j \neq j',\ j, j' \in S\}$$

$$\Leftrightarrow\ P_{nj} = P\{V_{nj} + \varepsilon_{nj} > V_{nj'} + \varepsilon_{nj'} \quad \forall\, j \neq j',\ j, j' \in S\}$$

$$\Leftrightarrow\ P_{nj} = P\{\varepsilon_{nj'} - \varepsilon_{nj} < V_{nj} - V_{nj'} \quad \forall\, j \neq j',\ j, j' \in S\}$$

Depending on the different specifications of the density function of the error term (i.e. different hypothesis about the distribution of the unobserved portion of utility ε_{nj}), we obtain different discrete choice models (Train, 2009).

Econometric specifications

To estimate an econometric model, the deterministic part of the utility function V_{nj} (in (1)) needs to be specified. The linear specification is often chosen in the literature.

The column vector of parameters $\beta_n = (\beta_{n1}, \dots, \beta_{nK})'$ is introduced; these parameters are the coefficients quantifying the influence of the K attributes on utility. They may be respondent specific. We also introduce the matrix Λ of size (K, A), composed of coefficients α_{ja} capturing the cross-effect of individual characteristic a on attribute k (Paris, 2018).

Finally, an Alternative Specific Constant (ASC) is considered, as a dummy variable taking the value 1 if the status quo is chosen over the two other alternatives, and 0 otherwise. We associate

to this dummy a coefficient ρ_n. A positive significant coefficient ρ_n would indicate a strong preference to stay in the current situation (Paris, 2018).

Then, the model (3) can be specified as follows: the probability of choosing a particular energy retrofit scenario j by individual n is a linear function of observed attributes of the discrete choice experiment X_j, of the individual characteristics Z_n and of the ASC. So we get:

$$U_{nj} = \rho_n ASC + X_j(\beta_n + \Lambda Z'_n) + \varepsilon_{nj} \qquad (3)$$

In (3), $Z'_n = (z_{1n}, \dots, z_{An})$ is the vector of the A individual characteristics of the n-th individual (in our analysis, we will use the measure of risk aversion as individual characteristic). X_j includes all x_{jk} corresponding to the different levels taken by the five attributes of our Discrete Choice Experiment that are: "investment costs", "energy savings potential", "insurance for quality", "fixed energy price contract", "indoor temperature". McFadden (1974) showed that, if the ε_{nj} are independently identically distributed (IID) and are assumed to follow the Gumbel distribution (type 1 extreme value) with the distribution function $F(\varepsilon_{nj}) = exp[-\exp(-\varepsilon_{nj})]$, then, the probability of choice of the alternative j is

$$P_{nj} = \frac{\exp(V_{nj})}{\sum_{j'} \exp(V_{nj'})} \qquad (4)$$

(4) defines the Conditional Logit model (CL model), which is the most frequent model used for analyzing discrete choice data and especially, for analyzing outcomes of Discrete Choice Experiments. Because of the ease of integration, the logit model is prevalent to estimate discrete choice models. In (4), P_{nj} only depends on observable elements. The β' vector includes the β_{jk} parameters and the vector X_j contains the attribute content of alternative j.

The CL model has two main limitations.

First, it assumes that preferences are homogeneous across respondents (i.e. $\beta_n = \beta$). In this model, the only way to account for the effect of heterogeneity of respondents is to cross attributes with socio-demographic variables (if considered alone, parameters associated to individual characteristics can not be identified as they do not vary across choice situations). However, a large portion of heterogeneity can remain unexplained because of the existence of intrinsic dissimilarities in preferences across respondents and failures of surveys to capture all relevant respondents' characteristics that could help explaining differences.

Moreover, the crucial assumption of IID (uncorrelated unobserved components) must hold in CL model. The direct consequence of the IID hypothesis is the independence of irrelevant alternative (IIA), which implies that the relative probabilities of two options being chosen are not influenced by the addition or removal of any other alternatives. In the case where unobserved factors related to different alternatives are similar, this assumption is not appropriate anymore. If the IIA assumption does not hold, then, less restrictive models have to be considered. This is likely to be the case here as we propose a status quo option. Thus, we consider two other models.

In comparison to the CL model, the advantages of the *Random Parameter Logit model* or *Mixed Logit model (ML)* (Train, 2009) are twofold. First, the alternatives are not independent anymore (releasing the IIA property). Indeed, the mixed logit allows the presence of correlation between alternatives, allowing flexibility of substitution patterns. Second, unobserved heterogeneity is explicitly accounting for, as we have $\beta_n \neq \beta_m, \forall\, n \neq\ m, n, m \in 1, \dots, N$. In the ML model, conditional on the individual parameter and error terms, the logit probability L that individual n chooses the alternative j for a given β is defined as follows:

$$P_{nj}|\beta = L_{nj}(\beta) = \frac{e^{V_{nj}(\beta)}}{\sum_{j'} e^{V_{nj'}(\beta)}} \qquad (5)$$

The unconditional choice probability of choosing alternative j is the logit formula L in equation (5) integrated over all values of β weighted by the density of β, as follows:

$$P_{nj} = \int L_{nj}(\beta) f(\beta|\Omega) d\beta \qquad (6)$$

with $f(\beta)$ the density function for β, that describes the distribution of preferences over individuals in the sample, and $\boldsymbol{\Omega}$ is the fixed parameter of this distribution. In the ML model, we usually make the hypotheses that β takes on a multivariate normal distribution, with mean b and covariance μ and the random parameters are normally distributed. However, β can also take on other distributions: lognormal, triangular, etc.

As the multidimensional integral in (6) does not have a closed form, it is approximated through simulations by using the Maximum Simulated Likelihood method. For a given value of $\boldsymbol{\Omega}$, a value of β is drawn from its distribution. The logit formula in (5) is calculated based on this draw. Then, the process is repeated for R draws, and the mean of the resulting $L_{nj}(\beta)$ is considered as the approximate choice probability. Thus, the simulated probability that a respondent n chooses the alternative j is defined as follows (Paris, 2018):

$$S\,P_{nj} = \frac{1}{R}\sum_{r=1}^{R} L_{nj}(\beta_r) \qquad (7)$$

The ML model allows an important range to specify unobserved heterogeneity. According to some scholars, this flexibility offsets the specificity of the hypotheses on the distribution (Greene and Hensher, 2003).

However, in some cases, the specified distributions of marginal utilities due to unobserved heterogeneity do not represent the true underlying preference in an accurate way. For example, there could be a multi-mode distribution of marginal utility or respondents could systematically ignore some attributes (attributes non-attendance). In these cases, the assumption of continuously distributed marginal utility will fail because of discontinuity of preference. This mismatch can have strong impacts on the estimates of willingness-to-pay (Shr and Ready, 2016).

Thus, the *Latent Class Model* (LCM) (or discrete mixture logit model) (Garrod et al., 2012; Roussel et al., 2012; Paris, 2018) is a second option to account for heterogeneity in preferences. This model does not require making hypothesis on the distribution of parameter β. In LCM, individuals are sorted into a number of classes C based on their preferences for the attributes of the alternatives. Preferences are homogeneous within a class ($i.e. \beta_n = \beta_c$ within a class, $c \in \{1, \dots, C\}$) and are heterogeneous between the classes (the βs are assumed here to follow a discrete distribution). Classification is unsupervised. Individual characteristics indirectly drive the choice individuals make via the class membership.

In the LC model, the probability that individual n prefers a specific alternative j over alternatives j' is no more defined for a given β as in (5) but is now conditional on class c. The probability of an alternative j to be chosen by individuals n, member of a class c, $c \in C$, is:

$$P_{nj}|\beta_c = \frac{e^{V_{nj}(\beta_c)}}{\sum_{j'} e^{V_{nj'}(\beta_c)}} \qquad \forall c \in \{1, \dots, C\} \ (8)$$

where β_c is the vector of preferences parameters specific to segment c, it represents the average importance of each attribute for individuals in c. If we denote π_{nc} the probability of membership of individual n to class c, the unconditional probability of individual n choosing option j can be expressed as:

$$P_{nj} = \sum_{c=1}^{C}(\pi_{nc}\ P_{nj}|\beta_c) = \sum_{c=1}^{C}\left(\pi_{nc}\frac{e^{\beta'_c x_j}}{\sum_{j'} e^{\beta'_c x_{j'}}}\right) \quad (9)$$

Assuming that the error components in the individual membership likelihood function are IID across respondents and classes, following a Gumbel distribution, π_{nc} is defined as follows:

$$\pi_{nc} = \frac{e^{Z'_n \theta_c}}{\sum_{h=1}^{C} e^{Z'_n \theta_h}} \quad (10)$$

Z_n is the vector of individual specific characteristics used to estimate class membership (Greene and Hensher, 2003). θ is the column vector of parameters associated to Z_n. Thus, the probability of belonging to a class c with specific preferences is probabilistic, and depends on observed characteristics of the individuals (Paris, 2018). Latent class models are estimated by using the Expectation- Maximization (EM) algorithm (Dempster et al., 1977).

The number of classes is not a parameter of the model and must be defined by the researcher. According to Louviere et al. (2000) information criteria such as Akaike Information Criterion (AIC) and its variants can be used to determine the number of segments. The number of classes is classically determined according two information criteria: the Akaike's entropy-based Information Criterion (AIC) and the Bayesien Information Criterion (BIC). More precisely, we used the CAIC (corrected AIC), which is an adapted version of the AIC (Bozdogan, 1987) but makes AIC asymptotically consistent and penalizes over parameterization more stringently. The two criteria are defined as follows:

$CAIC = -2 * LLF + p[\ln(N) + 1]$.

$BIC = -2 * LLF + p * ln(N)$.

LLF is the value of the log-likelihood function at convergence, p is number of free parameters in the model, N is the total sample size. To select the optimal statistical number of latent classes, these criteria must be minimized.

Willingness to pay

To distinguish between monetary and non-monetary attributes, (3) can be rewritten as follows:

$$U_{nj} = \rho_n ASC + \gamma_n M_j + X_j(\beta_n + \Lambda Z'_n) + \varepsilon_{nj} \quad (4)$$

With M_j corresponding to the monetary attribute "investment costs" and X_j including all other k attributes as presented in (3).

Willingness to pay (WTP) estimates measure welfare in a monetary unit. Usually, they are calculated by estimating the Marginal Rate of Substitution between the attribute for which we

want to estimate the WTP and the income. In choice experiments, the marginal utility of income corresponds to the coefficient of the cost attribute (here the coefficient associated to the investment costs). If we assume that the utility function is linear in the parameters and attributes (as it the case here), the WTP for attribute k is written as follows:

$$WTP_k = \frac{\beta_k}{\gamma} \quad (6)$$

with β_k is the parameter for attribute k and γ is the parameter for cost. The Krinsky and Robb parametric bootstrapping method is used to obtain confidence intervals around the mean of the WTP estimates (Krinsky and Robb, 1986).

Implicit discount rate

Let us recall the expression of the Net Present Value used to assess the profitability of energy efficiency investment. The NPV is calculated as defined in (0):

$$NPV(\tau) = -I_0 + \sum_{i=1}^{\tau} \left(\frac{CF, i}{(1+d)^i} \right)$$

The profitability of a project (NPV>0) depends strongly on the discount rate. Households are not used to practice the NPV, but do expect implicitly a certain return from the investment. The implicit discount rate corresponding to their investment choice is noted d^{imp}. In the literature review of section 3, let us recall that some scholars suggest that the discount rate would reflect the risky nature of an investment. The discount rate would be higher for a project with risky or uncertain outcomes (Hassett and Metcalf, 1993).

Hausman (1979) and Train (Train, 1985)proposed to estimate this implicit discount rate from discrete choice models. Consider that the utility associated to the choice of alternative j is now defined as (7) below, depending on the ASC, the investment costs M_j with coefficient γ, the energy savings expressed in monetary units B_{nj} with coefficient δ, and all other remaining attributes X_j and individual characteristics Z'_n defined as in (3). We have then:

$$U_{nj} = \rho_n ASC + \gamma_n M_j + \delta B_{nj} + X_j(\beta_n + \Lambda Z'_n) + \varepsilon_{nj} \quad (7)$$

The ratio of the coefficients of capital costs (investment costs) and operating costs (negative savings) is used to calculate the discount rate (Train, 1985). Making the strong hypothesis that the lifetime of the energy efficiency equipment is infinitely long, the implicit discount rate is calculated as follows:

$$d^{imp} = -\frac{\gamma}{\delta}$$

7.Results

In this research, both the mixed logit and the latent class models are used to identify the weight of our different attributes in explaining the utility provided by the different alternatives of energy retrofit. The mixed logit model allows us to test the hypothesis of heterogeneity in preferences regarding the different attributes of our choice experiment. This approach also allows us to test the effect of individual-specific variables on these preferences (risk aversion and perception of the economic context). Moreover, results from the mixed logit model allow us to run simulations to assess the effect on the energy retrofit rate of different insurance and contractual schemes. Instead, the latent class model allows us to identify specific preferences patterns among groups of respondents, relevant for understanding the drivers behind the household's valuation of these insurance and contract schemes.

To begin with, let us notice that "protest answers" do not seem a concern in our dataset. In fact, only 6% of the individuals selected the status quo alternative in every choice situation. Moreover, only 0, 6% of the individuals selected the alternative A in every choice situation and 0,8% of the individuals always selected the alternative B[62].

The results of the conditional logit model and the Hausmann test (to test the IIA hypothesis) are presented in appendix A. The test confirms that this hypothesis does not hold. Thus, the mixed logit model and the latent class model are presented in the next section.

7.1 Mixed logit model

We run the estimations based on the whole sample. Robustness checks are implemented using the sample of 2200 individuals that answered correctly the consistency test and are available in appendix B[63].

The model specification sets all coefficients as random parameters in the mixed logit model, allowing them to vary across respondents[64]. We run two models; results are presented in Table 6 below. In both models, the explanatory variable is the choice of the energy retrofit offer. In

[62] Protest answers are characterized by individuals choosing the same alternative (A, B or Status quo) within every choice situation of the discrete choice experiment, which could be a way to traduce the "rejection" of the DCE.

[63] All estimations are conducted with stata software using clogit, mixlogit, lclogit commands. See the following paper for more details: http://www.dt.tesoro.it/export/sites/sitodt/modules/documenti_en/analisi_progammazione/working_papers/WP_N._6-2012.pdf. In stata, LCM is fitted by the implementation of the expectation-maximization (EM) algorithm (Pacifico, 2012).

[64] The random parameters are usually assumed to follow a normal distribution, and the resulting model is fit through simulated maximum likelihood, as in (Hole, 2016)).

model 1, the explanatory variables are only the different attributes and the Alternative Specific Constant. In model 2, we use the different attributes as explanatory variables but the model also includes interactions between some individual specific variables (measure of risk aversion and perception of the economic context) and the attributes.

Table 6: Results from the mixed logit model.

Explained variable: choice of the retrofit offer	**Model 1**		**Model 2**	
	Coefficient	**Std.Err**	**Coefficient**	**Std.Err**
Investment	-0.00017***	(0.000005)	-0.00018***	(0.000005)
Insurance for quality	1.0***	(0.03)	0.93***	(0.04)
Risk averse	-	-	0.14***	(0.05)
Fixed energy price contract	0.81***	(0.02)	0.71***	(0.05)
Risk averse	-	-	0.18***	(0.05)
No opinion about future energy price	-	-	-0.0002	(0.05)
Increased indoor temperature	0.56***	(0.03)	0.58***	(0.03)
Energy savings	0.05***	(0.002)	0.05***	(0.0017)
ASC	-2.0***	(0.13)	-2.6***	(0.21)
Risk averse	-	-	0.33*	(0.20)
No opinion about future energy price	-	-	0.61***	(0.19)
Standard deviations				
Investment	0.0002***	(0.000005)	0.00016***	(0.000005)
Insurance for quality	0.70***	(0.04)	0.72***	(0.041)
Risk averse	-	-	0.11	(0.14)
Fixed energy price contract	0.49***	(0.04)	0.52***	(0.04)
Risk averse	-	-	0.012	(0.09)
No opinion about future energy price	-	-	0.04	(0.16)
Increased indoor temperature	0.93***	(0.04)	0.97***	(0.04)
Energy savings	0.03***	(0.003)	.035***	(0.002)
ASC	3.9***	(0.13)	3.86***	(0.13)
Risk averse			0.28	(0.23)
No opinion about future energy price			0.32	(0.23)
Loglikelihood	-17134		-17099	
Numbers of individuals	3000		3000	
Numbers of observations	72000		72000	

*, **, *** respectively refers to the 10%, 5% and 1% significance level, respectively

The signs of the coefficients associated with our DCE attributes are consistent with expectations.

First, according to the negative coefficient associated to the attribute of investment costs, the utility of energy efficiency investment is found to decrease with investment costs, which is consistent with the literature (Achtnicht and Madlener, 2014; Alberini, 2013; Galassi and Madlener, 2017b). Energy savings and comfort improvement provide a positive utility to

individuals; which is consistent with household's declarations on their motivation to invest in energy efficiency (see the results of the French survey OPEN 2015[65]). Thus, this means that French homeowners are responsive to the upfront costs and the benefits of energy efficiency investments. The positive effect on utility of the increased indoor temperature suggest a potential for the rebound effect, which reflects an increase in the demand for an energy service after the improvement of energy efficiency (Gillingham et al., 2016). The rebound effect related to heating use indeed occurs in the French residential sector. For more information and an estimate of this effect, see the chapters 3 and 4 of this thesis. According to our results, the rebound effect involves reduced energy savings but a legitimate increase of welfare for an important share of the French population.

Regarding the effect of the insurance schemes, they both provide a positive utility to respondents. The associated coefficients are positive and significant. This result confirms that greater certainty about quality of energy retrofits works and evolution of future energy price (fixed price here) is positively valued by French homeowners during the energy efficiency decision making process. As a result, this means that uncertainty could provide a disutility to respondents and then be considered as a barrier to energy efficient investment. Moreover, on average, as presented in the discrete choice experiment, the insurance covering for the quality of insulation over 10 years seems to provide a slightly greater utility than the contract insuring a fixed energy price over the next 5 years.

Model 2 confirms all these findings but provides further insights. We see that reduced uncertainty about energy savings provides a higher utility to risk-averse respondents than to non-risk-averse individuals. Indeed, there is a surplus of positive utility provided by both insurance schemes for risk averse individuals. Thus, we provide evidence that risk averse individuals demonstrate a greater risk premium than risk lovers regarding uncertainty in the energy retrofit context. This result is consistent with the literature (Neumann and Morgenstern, 1944). It worth mentioning that the fact that even low risk averse respondents value greater certainty about retrofit quality and price evolution could be seen as consistent with the option value theory and irreversibility effect as in (Dixit and Pindyck, 1994).

There is no effect of the interaction (cross variable) between the presence of the fixed energy price contract in the offer and the individuals that have no opinion about the evolution of energy price over 5 years. This result can be interpreted as follows. According to Figure 3, the largest share of respondents declares "no opinion" on the likely evolution of the price of their heating

[65] See the main results of the French survey on energy renovation in the residential sector, available here: https://www.ademe.fr/sites/default/files/assets/documents/open_2015_8679.pdf

energy, while the second largest share believe in an “increase” of the energy price for the next 5 years. The latter type of respondents could also give a positive value to the fixed energy price contract that allows them to avoid this expected price increase. As a result, the effect to have no opinion about the evolution of energy price could be non-distinguishable from the effect to believe in an increase of energy price, leading to a non-significant coefficient estimate for the interaction term “no opinion x fixed priced contract”.

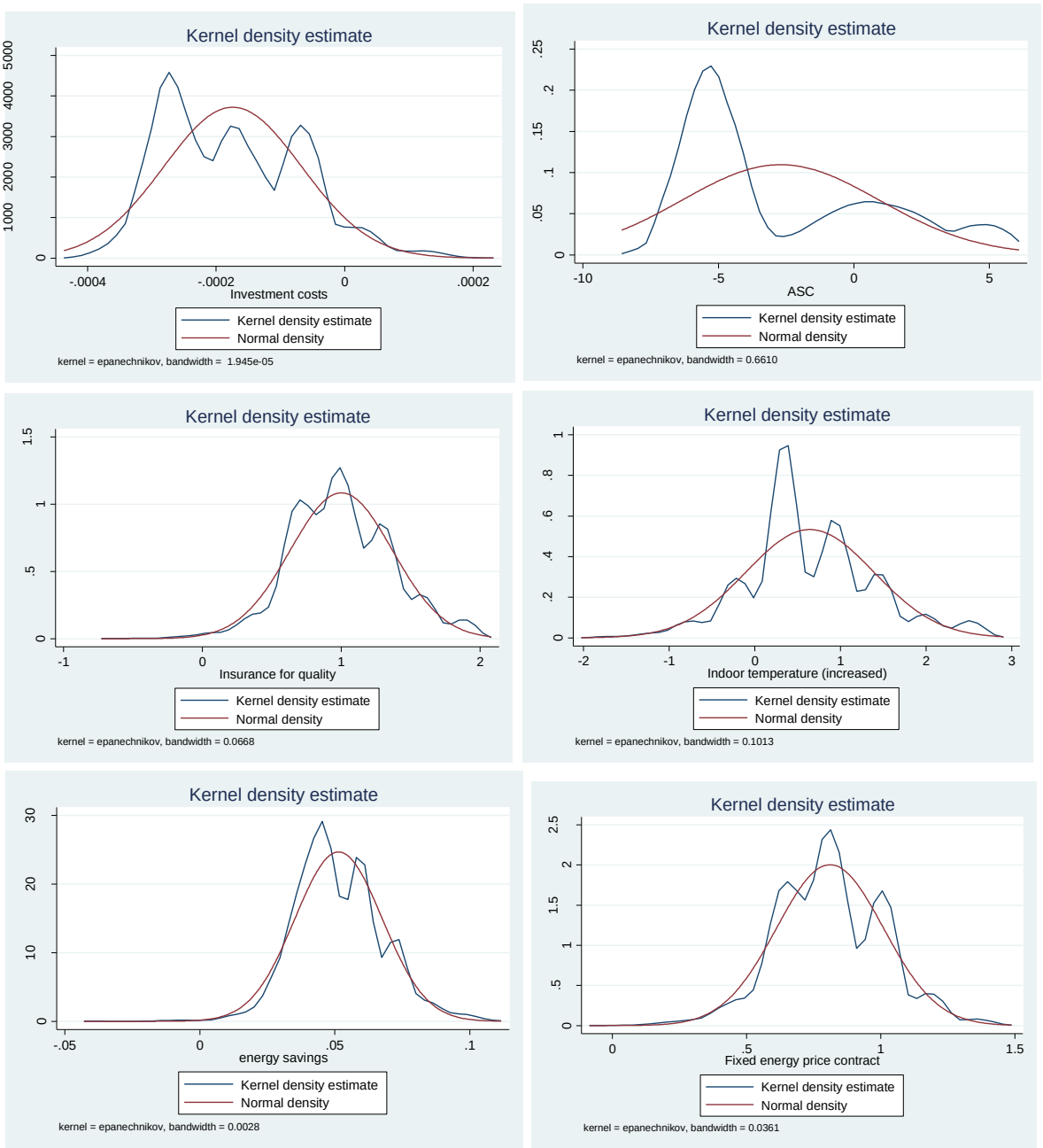
Finally, the last variable of interest is the Alternative Specific Constant (ASC). In model 1 and 2, the effect of the ASC is found to be negative. This means that, on average, respondents value negatively to stay in the status quo situation. According to the literature, this negative value could be biased by behavioral patterns. For instance, some papers provide evidence of the potential existence of a “yeasaying bias” in contingent valuations. Such a bias is present if the respondent chooses an alternative to please the surveyor. Instead, a positive coefficient could reflect respondent risk aversion or inertia to change (Bonnieux and Carpentier, 2007). Model 2 provides evidence on the second point: risk averse individuals and respondents that have no opinion about the evolution of future energy price (over 5 years) value the status quo more than the others, i.e they are more likely to prefer the status quo alternative. This result is consistent with Alberini (2013) who found that individuals having no opinion on the trend of future energy price over the next 20 years value positively the status quo. She concludes that greater the uncertainty about price is, the more likely is an individual to wait before committing to an irreversible energy efficiency investment. Our finding however provides complementary evidence on the relevance of attitude toward risk for this bias in energy efficiency investment decisions.

In Figure 5, we draw the kernel density plots of the simulated individual coefficients[66]. for each attribute (Epanechnikov, 1969; Terrell and Scott, 1992). It makes clearly appear groups of preferences in comparison to the normal density distribution. Thus, the presence of heterogeneity in individual preferences is confirmed for all attributes: all standard deviations of coefficients are highly significant (as can be seen in Table 6 where the standard deviation of coefficients is statistically significant). Regarding the variables "insurance for quality", “energy savings” and the "fixed energy price contract", despite a significant standard deviation, the distribution of the individual coefficients seems to be concentrated around a single value. The coefficients of the three other variables "Indoor temperature", “net investment costs” and the Alternative Specific Constant appear to be distributed around different local values. It is worth

[66] Individual coefficients for each attribute were calculated them thanks to the log likelihood maximization (mixlbeta command)

mentioning that the value of some individual coefficients for the "indoor temperature" attribute could be negative. A slight share of respondent does not value the increasing of indoor temperature.

Figure 5: Kernel density plots of coefficients, model 1



All of the local values are negative for the "net investment costs" attribute; we distinguish at least three groups of preferences. Regarding the ASC, local values can be positive, null and negative (the majority). This reveals that some of the respondents do value positively the status

quo in contrary to the average estimate. We will investigate further this heterogeneity in preferences applying the latent class model approach in the next section.

Based on model 1, we display the average willingness to pay of respondents for each attribute of the discrete choice experiment in Table 7. The results confirm previous information.

Table 7: Willingness to pay for attributes of the energy renovation alternative (in euros)

Insurance for quality	Risk averse * insurance for quality (surplus)	Fixed energy price contract	Risk averse* fixed price contract (surplus)	Energy savings (euros/%)	Indoor temperature
6505 [5903; 7107]	755 [101 ;1410]	4871 [4213 ; 5529]	1238 [582 ;1893]	327 [304 ; 351]	3869 [3680 ; 4259]

Note for the reader: Confidence intervals are calculated using the Krisnky and Robb procedure for each attribute level. [] confidence interval at 90% level. The parameter associated to the investment costs was set as non-random for the calculation of WTP measures

We note that, on average, respondents are willing to pay more for the insurance for quality (6627 euros) than for the fixed energy price contract (4838 euros) as presented in our choice experiment. Moreover, risk averse individuals are willing to pay a surplus in comparison to non risk averse individuals, which is consistent with theory described in the literature review. Finally, on average, respondents are willing to pay 332 euros per percentage of energy savings potential. This result is very close to what is found in (Stolyarova, 2016) concerning the French residential sector, where the central estimate is 308 euros/% of energy savings. Finally, respondent are willing to pay 3994 euros on average to increase the indoor temperature.

Implicit discount rate

Finally, we calculate the average implicit discount rate for thermal insulation based on the coefficients of our mixed logit model[67]. First, we calculated the energy savings expressed in euros for each alternative and each respondent. To this end, we used the question asking for the approximate heating energy bill of each household and we multiplied the given amount by the energy savings potential (%) considered in each alternative. We then run the mixed logit model by replacing the energy savings potential attribute by the individual monetary energy savings. Results are available in table 13 in appendix A.

[67] We set as "non random" the parameters associated to the invested amount and the energy savings expressed in euros.

We obtain an implicit discount rate of 13.6%, which is higher than classical discount rate used for cost benefit analysis[68]. Although this result should be used cautiously (since it is based on stated heating energy bills), it is consistent with the results found in the literature. Train (1985) estimates that the discount rate for heating system is between 5% and 35%. Cayla (2011) finds based on French data that the discount rate for heating system is about 11.6%. Finally, based on the results of a discrete choice experiment, Stolyarova (2016) shows that the average implicit discount rate is comprised between 5.7% and 10.2%.

7.2 The latent class model

Our comments to Figure 5 in the previous sub-section suggest that heterogeneity in preferences is common. To investigate further the heterogeneity in preferences in terms of relative weight of attributes, a latent class model is run. This approach indeed accounts for potential heterogeneity without constraining the distribution of parameters. For this latent class model, the alternative attributes are considered as unique determinants of the choice. We decided to run the model without variables explaining class membership to get absolute preferences (i.e. thus, the groups with homogeneous preferences are only determined based on individual heterogeneity in preferences for attributes).

The number of classes was determined using the information criteria CAIC and BIC (Pacifico and Yoo, 2012). Figure 6 represents graphically the information criteria for the 2 to 8 classes latent class Models. According to these information criteria, the six classes latent class model seems to be interesting in terms of goodness of fit (minization of CAIC and BIC criteria and of loglikelyhood function). However, because the number of classes identified is high, we decide to reduce the number of classes to 4. For information, the table of results for the 6 classes LC model is presented in appendix A. Results for the 4 classes LC model are presented below in Table 8. Table 9 presents the WTP for the attributes in each class. Table 10 provides some descritpive statistics to characterise individuals in each class identfied by the 4 classes LC model. To confirm the robustness of our estimates, we also run the latent class models over the consistent respondents population. Results are available table 12 in appendix A.

Figure 6: CAIC (scale on the left), BIC (scale on the left) and loglikelyhood (LLF, on the right) criteria according to the number of classes latent in the model (abscissa axis).

[68] In France, the discount rate usually used for a project is 4.5%. See the recommendation of the Quinet Commission.
https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/10_fs_discount_rate_in_project_analysis.pdf

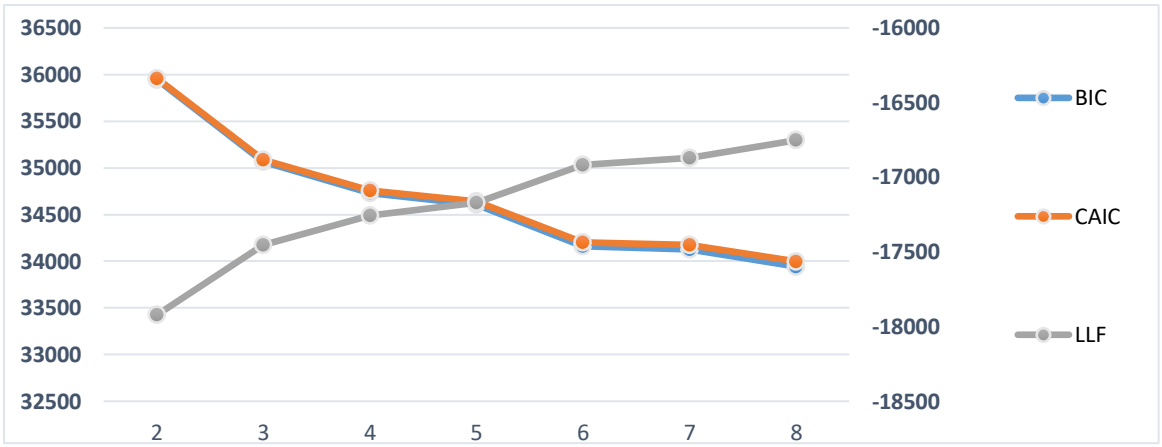


Table 8: 4-classes Latent class model for the whole sample

	Class 1	**Class 2**	**Class 3**	**Class 4**
Share of respondents	10%	27%	41%	21%
	Coefficient	Coefficient	Coefficient	Coefficient
Initial investment (euros)	-0.00027***	-0.00032***	-0.00003***	-0.00015***
	(0.00005)	(0.00002)	(0.000005)	(0.000008)
Energy savings (%)	0.066***	0.086***	0.025***	0.040***
	(0.015)	(0.01)	(0.002)	(0.003)
Insurance for quality	1.51***	0.80***	0.67***	1.03***
	(0.26)	(0.07)	(0.03)	(0.06)
Fixed price contract	0.76***	1.06***	0.48***	0.88***
	(0.26)	(0.09)	(0.03)	(0.054)
Increased indoor temperature	0.58***	0.14	0.41***	0.56***
	(0.20)	(0.09)	(0.03)	(0.05)
ASC	4.59***	-2.82***	-2.04***	1.53***
	(0.71)	(0.27)	(0.15)	(0.16)

*, **, *** respectively refers to the 10%, 5% and 1% significance level, respectively. Coefficients are on the first line, standard errors on the second line.- 72000 observations.

Table 9: WTP for attributes in the latent class model.

	Class 1	**Class 2**	**Class 3**	**Class 4**
Insurance for quality	5579 [3141 ; 8016]	2507 [1869 ;3145]	24571 [15405 ; 33737]	6944 [6011 ; 7877]
Fixed energy price contract	2802 [1107 ; 4497]	3320 [2908 ; 3732]	17759 [11147 ; 24370]	2802 [1107 ;4497]
Energy saving (euros/% of energy savings)	243 [114 ; 373]	270 [235 ;305]	914 [591 ; 1237]	270 [222 ; 318]
Increased indoor temperature	2128 [538 ; 3717]	442 [-112 ; 1007]	15027 [8664 ; 21390]	2128 [539 ; 3717]

[] confidence interval at 90% level

In comparison to the mixed logit model, the LC model provides additional information about the heterogeneity in preferences regarding attributes. However, it does not perform much better, (see the value of the LLF in figure 6, which is higher than the one found in the mixed logit models). Class 1 is composed of 10% of the population of homeowners, Class 2 of 27% of the population, Class 3 of 41% of the population. The rest of the respondents (21%) belong to class 4.

First, we see that heterogeneity in the preferences for the Alternative Specific Constant variable, that we observed in the kernel density plots, is confirmed as Class 1 and Class 4 gather respondents with a positive coefficient for the ASC. These preferences for the status quo over energy efficiency investment concern more than 30% of the population of respondents.

Moreover, the second interesting fact that was not observable with the mixed logit model is that, for 27% of the respondents, the fixed energy price contract provides a greater utility than the insurance for quality. Thus, for a relatively important share of the population, uncertainty about future economic conditions could be a (slightly) more important barrier to energy efficiency investment than technical risk and uncertainty. This is confirmed by WTP measures in table 10 (WTP for the fixed energy price contract is higher than the one for insurance for quality in Class 2). However, one must keep in mind that this result is dependent on the description of both insurance schemes we provided to respondents.

Moreover, compared to class 1 and class 2, the third and fourth classes have a stronger disutility to see an increase in the investment costs. This means that respondents in these classes are more reactive to a decrease/increase of the investment costs in terms of energy retrofit decision (cf coefficients in table 8: -0.0003 approximatively for classes 1 and 2 against 0.00003 for class 3 and 0.00015 for class 4).

Heterogeneity in preferences is also observable regarding the energy savings attributes. The positive impact of the increase of the energy savings potential on the utility varies across classes. Classes 1 and 2 have a stronger utility to see an increase of the energy savings potential. However, if we look at the WTP measures, respondents of these classes are not willing to pay that much (in comparison to other classes) to save energy.

We also note that heterogeneity in preferences regarding the indoor temperature attributes is also confirmed. Thus, for 27% of the respondents (Class 2), the improvement of the temperature do not provide a significant additional utility to the homeowners. For the individuals belonging to this class, this could mean that they may not increase their demand for heating use after the energy retrofit (no rebound effect).

We note the very high measures of willingness to pay for all attributes in class 3. These high values are related to a very low sensitivity to the decrease in investment cost.

Finally, respondents willing to pay twice as much for the insurance for quality than for the fixed energy price contract characterize class 4. This characterizes reflects a potential strong interest regarding the comfort benefit of energy renovation.

The next interesting step is to try to identify the main characteristics of the individuals in each class. This could be helpful to be able to assign a class to any households, which can helps understanding in more detail how public policy interventions or new market tolls will impact the behaviour of a population. In Table 10 below, we provided some descriptive statistics regarding several individual specific variables that can be useful to explain inter class heterogeneity.

Table 10: Descriptive statistics by class

	Class 1	**Class 2**	**Class 3**	**Class 4**
Savings between 0 and 5000 euros	0.23 (0.42)	0.22 (0.42)	0.29 (0.45)	0.26 (0.44)
No opinion about future energy price over the next 5 years (share)	0.71 (0.46)	0.61 (0.49)	0.60 (0.49)	0.64 (0.48)
Belief that energy price will increase over the next 5 years (share)	0.20 (0.40)	0.34 (0.47)	0.33 (0.47)	0.29 (0.46)
Men (share)	0.53 (0.50)	0.57 (0.49)	0.54 (0.50)	0.49 (0.50)
Environmental label is a significant criterion when buying appliances	0.40 (0.42)	0.49 (0.50)	0.51 (0.50)	0.46 (0.49)
Is fully satisfied with the thermal comfort of its dwelling (%)	0.29 (0.45)	0.23 (0.42)	0.24 (0.42)	0.25 (0.42)
Heating bill (euros/year)	959 (675)	1147 (932)	1298 (1499)	1147 (1662)
Risk attitude				
Highly risk loving (share)	0.13 (0.34)	0.11 (0.32)	0.17 (0.37)	0.14 (0.34)
Very risk loving (share)	0.03 (0.18)	0.01 (0.10)	0.06 (0.23)	0.04 (0.19)
Highly risk averse (share)	0.07 (0.26)	0.06 (0.23)	0.06 (0.23)	0.06 (0.24)
Stay in bed (share)	0.40 (0.49)	0.41 (0.49)	0.36 (0.48)	0.38 (0.48)
Choice consistent individuals (share)	0.96 (0.18)	0.75 (0.43)	0.71 (0.45)	0.62 (0.48)

Mean are presented on the first row, Standard deviation () on the second row

First, it worth mentioning that inter-class heterogeneity is not very high regarding the variables considered here. However, we can still observe some informative insights.

We see that risk lovers (including highly risk loving and very risk loving individuals) are more likely to belong to class 3 (and to class 4, to a lesser extent). Indeed, we find 23% of them in class 3, against 12 and 16% in classes 1 and 2. Class 3 gathers respondents that pay low attention to a change in investment costs

The respondents in class 2 are more likely to have more than 5000 euros of savings. It is interesting to note that this "wealthier" class does not significantly value the increase of indoor temperature. Moreover, we find in classes 2 and 3, the highest share of respondents that are sensitive to environmental issue (see the characteristics *Environmental label is a significant criterion when buying appliances* in Table 10). In these two classes, respondents favor more energy efficiency alternative than the status quo (see the ASC coefficients in table 8).

Finally, individuals who have no opinion about the evolution of energy price over the next five years are more likely to be found in class 1 and 4. In both classes, the status quo is significantly preferred over energy efficiency measures while people who believe that the energy rate is going to increase are more likely to be found in class 2 and 3 that prefer the energy efficiency alternatives over the status quo. This result is consistent with the results of the mixed logit model.

7.3 Simulations

In this last section, we wish to interpret our results in a explicitly policy-oriented perspective. In European countries and specifically in France, policy makers are, indeed, particularly concerned about the low energy retrofit rate in the residential sector and efficient ways to raise it. Thus, testing the effect of the introduction of different measures – namely an insurance for quality of energy retrofits, a fixed energy price contract or a financial subsidy – on the energy retrofit rate could be an interesting insight to this end.

The estimate of average marginal effects offers a interesting tool to summarize regression results while illustrating the policy relevance of the main variables. A major shortcoming of our approach is the fact that averages of discrete choice experiment attributes do not reflect meaningful reference point because data from discrete choice experiments are based on hypothetical alternatives and not real choice sets (i.e as offered in the real world) (Achtnicht and Madlener, 2012). However, in a policy-oriented perspective, investigating how a small

variation in attributes levels would influence the predicted probability to choose the insulation offer seems to us a useful exercise.

To do so, we first have to consider a reference scenario, from which one will make vary the levels of attributes. These variations with respect to the reference scenario correspond to different alternative scenarii. We will calculate for each scenario (reference and alternative scenarii) the probability to choose the insulation offer against the status quo. Comparing the energy renovation rate (number of retrofit decisions) across scenarii will allow us to illustrate the effect of changing the level of an attribute on the choice probability to invest in this specific thermal insulation measure.

As we are interested in testing the effect on the energy renovation rate of the introduction of particular energy renovation alternatives while taking into account a potential trade-off induced by a change in the investment costs, we elaborate 40 different scenarii. We consider one reference scenario and 4 alternative scenarii (Table 11); for each one, the attribute Investment cost takes 8 values[69].

Table 11: Presentation of the scenarii considered in the simulation procedure

Attributes **Scenario**	**Investment costs**	**Energy savings**	**Insurance for quality**	**Fixed energy price contract**	**Increased indoor temperature**
Reference	3000€ to 25 000€	30%			x
Insurance for quality	3000€ to 25 000€	30%	x		x
Fixed energy price	3000€ to 25 000€	30%		x	x
Both insurance schemes	3000€ to 25 000€	30%	x	x	x
Increased energy savings	3000€ to 25 000€	50%			x

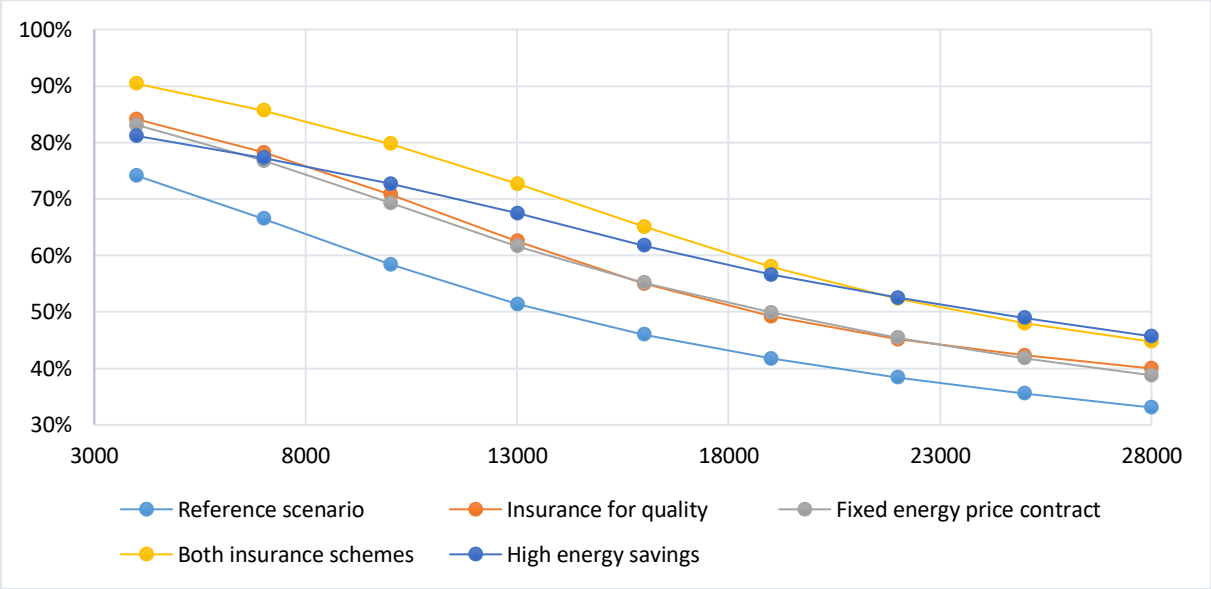
Note for the reader: The energy renovation alternative offered in Scenario 1 includes an energy savings potential of 30% and the increase of the indoor temperature. Investment costs vary from 3000 to 28000 euros. It does not include any insurance for quality neither fixed energy price contract..

For each of this scenario, we predicted the probability to invest in energy efficiency against choosing the status quo for eight values of the investment costs (from 3000 euros to 25 000 euros). We use the estimates issued from the mixed logit model and the mixlpred command. The mixlpred- likelihood is averaged over simulated draws conditional on the coefficient

[69] Thus, 5 x 8 = 40 scenarii

distribution estimates. We display in Figure 7 the probality to invest for each of these scenari (retrofit rate) as a function of the investments costs (x absciss).

Figure 7: Simulated average choice probabilities and effects for the mixed logit model



Note for the reader: For investment cost equals to 13000 euros, the retrofit rate is 52% for the reference scenario", 64% for the scenario insurance for quality, 62% for the scenario fixed energy price contract, 68% for the scenario increased energy savings; 73% for the both insurance schemes.

By reading the graph, several facts are noticable. First, we can note that even for very high investment costs (25000 euros), the probability to choose the reference scenario is still high (almost 40% of respondents would choose this scenario) compared to what we expect would be observable on the real world energy retrofit market. This is explained by the fact that we are in hypothetical choice situations that do not have any repercussions on real life choices. Moreover, as expected, the probability to invest is a deacreasing function of the investment costs, which confims the potential positive role of finanical subsidies on the energy efficiency rate. For instance, decreasing the investment costs by 10 000 euros (from 18 000 euros to 8 000 euros) would increase the energy renovation rate by approximately 20%.

The introduction of the insurance for quality or the fixed energy price contract in the energy efficiency offers increases the probability to invest in wall insulation by 5 to 10% in comparison to the benchmark (reference scenario) for the same level of investment costs. If they are both introduced, the change in the probability to invest is about +15%. This is an interesting insight for policy makers regarding the potential effect of the introduction of these new measures on the energy retrofit rate.

Thus, combining a decrease of investment costs and the indroduction of insurance schemes could have an important effect on the energy retrofit rate.

Finally, the graph shows that we are likely to obtain the same increase in the rate of retrofit (around 10%) by decreasing investment cost by 5000 euros (from 18000 to 13000 euros, for instance) or by introducing a insurance for quality (compared to the reference scenario). Two remarks come from this observation.

The first one is that the introduction of the insurance for quality or fixed energy price contract will still involve a positive effect on the renovation rate even if it leads to an additional cost (which could reflect the internalization in renovation costs of the cost of insurance paid by building professionals). For instance, if the insurance for quality involves, on average, an additional cost lower than 5000 euros, the effect of the introduction of this insurance on the retrofit rate remains positive. As a result, the introduction of the insurance for quality could be costly but below a certain threshold to have a positive effect on the retrofit rate.

The second observation refers to the efficiency of public expenditures. If the introduction of the insurance for quality and a fixed energy price contract have a positive effect on the energy renovation rate, (in some cases, greater than the one get by the decrease of investment costs), then, it could be interesting for policy makers to consider it as it can also reduce the need for public expenditures (subsidies for energy renovation) to achieve the same rate of energy renovation.

This latter issue raises the question of the implementation of such contracts. Sutherland (1991) identifies the lack of aggregate insurance against energy-related risk as a reason to justify the need for government support. In line with this, the insurance scheme for quality of retrofit work could be inspired by the french compulsory ten-year warranty that exists to cover defects for new construction and structural work existing in buildings. Based on such a scheme, households would be insured against the non stability of the energy retrofit works carried out, over 10 years, if something happens. However, offering this ten-year warranty could have a lower effect on the retrofit rate than predicted by the simulation exercice since this guarantee scheme is less strict than the one presented to households in our discrete choice experiment. Indeed, in contrary to what is offered in our DCE, the ten years warranty does not include an ex-post audit of the energy performance of the retrofits, certifying the quality of retrofits works. Stricter insurance schemes could help increasing substantially the number of energy retrofits (WTPs for insurance on quality are positive and relatively high) but are more challenging to implement. For instance, the dissemination on the market of techological solutions as the intrinsec measure of the energy performance of the dwelling (that are currently in development

in certain buildings companies) could be a trigger to the development of private insurance contracts insuring the achievement of a certain level of theoretical energy savings trough the realization of energy retrofits (i.e, which could be a proxy of the quality of the retrofits). On the other hand, insurance schemes allowing to insure real energy savings (on the bill) of energy retrofits could have a even more important impact on the number of retrofits as they could allow the development of third party funding[70]. In the tertiary sector, such contracts already exist under the name of energy performance contracts[71] (contrat de performance énergétique). It works as follows. A goal of energy savings achievable trough the energy works is set by the energy providers. Then, the final energy consumptions before and after the energy retrovation are compared. If the goal is not achieved, penalties apply. However, in the residential sector, a major limitation to the development of such contracts is the existence of the rebound effect (behavioural change from households after retrofits) that may reduce drastically future energy savings (see Chapter 4, we estimate that rebound effect for heating use is about 50-60%) and thus, discouraging funders.

Regarding the second type of insurance scheme, the fixed energy price contract over a period of 5 years, the challenges are different. If we consider the two main heating energy sources, electricity and gas (respectively 32% and 37% of our sample heat their homes with electricity and gas), such contracts seem feasible at first sight since they already exist on the market for shorter period (fixed rate contract, excluding tax) but their further development could be limited by nature (rate depends on production, transit, commercial costs and tax, which vary over time). Regarding electricity, the historical general trend shows a quasi continuous increase of the rate which is likely to continue in the future[72]. Thus, the provision by the market of fixed electricity price contracts over medium –long term seems difficult to be considered as a credible option even if subzidized by public policies (which could be expensive, since electricity is consumed by all households, as it is used for other energy uses such specific electricity). Moreover, it is interesting to recall that 63% of the homeowners in our sample among those who use electricity as heating energy do not have opinion about the evolution of future rate of electricity despite the past increasing trend.

[70] Third party funding: banks fund energy retrofit and are reimbursed thanks to future energy savings.
[71] See the following web link for more details: http://atee.fr/management-de-lenergie-contrat-de-performance-energetique-et-tiers-financement
[72] See the trend of the different sources of heating energy over the past years in France: https://www.quelleenergie.fr/magazine/prix-energie/evolution-prix-energie-55871/. The electricity rate depends on production, transit, commercial costs and tax.

As a result, the implementation and the relevance of both insurance schemes should be deeper investigate to make them be a substantial way to increase the energy retrofit rate.

8.Conclusion and perspectives for academic research

This research aims at fulfilling some of the gaps found in the existing literature regarding the risk and uncertainty barrier to energy efficiency investment. We focus in this study on testing the role of uncertainty regarding energy price and quality of retrofit work. To do so, we conduct a discrete choice experiment addressed to 3000 French homeowners. As attributes of our energy efficiency investments alternatives, we included two insurance schemes –an insurance for quality of energy retrofit and a fixed energy price contract. We then develop a mixed logit and a latent class models to investigate the nature of systematic heterogeneity in household preferences for the attributes of energy retrofit solutions (especially, the preferences for reduced uncertainty) and its link with some individual characteristics. We link this heterogeneity in preferences to individual characteristics such as risk aversion and opinion on the evolution of future energy price.

Our research confirms the previous findings of Alberini (2013) and goes deeper in the analysis. First, we provide evidence that uncertainty in future energy price is an important concern investment in energy retrofit by French residential homeowners. Our results also provide new insights: the quality of energy retrofit is also found to be a significant concern. Indeed, uncertainty about these two parameters provides a negative utility with regard to energy efficiency investments. As presented in our discrete choice experiment, the concern regarding quality of retrofit work is, on average, slightly more important than the one for energy price uncertainty. The willingness to pay for the insurance on retrofit quality is estimated as high as 6000 euros on average, while the one for a fixed energy price contract is about 4000 euros. However, this varies across respondents. We have distinguished four groups of respondents with relatively homogeneous preferences, which provided us further insights on the relative preferences for the two insurance schemes. Moreover, we find that risk averse individuals are more negatively affected by uncertainty during the energy efficiency decision-making process, which is consistent with the theoretical literature. Finally, on average, the implicit discount rate is found to be about 13,6% which would confirm the perceived risky nature of insulation retrofit.

Simulation based on the mixed logit model provides key insights for policymaking regarding the potential effect of new measures on the energy retrofit rate. This opens the discussion on the implementation and the cost-effectiveness of such measures. We show that reduced uncertainty about the quality of energy retrofits and future energy price evolution could increase significantly the likelihood to invest in energy efficiency (up to 15-20%), even if these measures are costly. To this end, more work is required first for a cost-benefit analysis of the development of such measures and contracts, then to investigate how these insurance schemes could be introduced on the market and consider potential rationales for political intervention. Concerning the role of uncertainty about future heating energy price, it is worth recalling that in december 2017, 60% of our sample declared having no opinion about the future 5 years trend of energy prices. Moreover, we found that the respondents are predominantly risk averse.

The role of attributes such as the investment costs, the energy savings potential and the improvement of comfort is also crucial in explaining energy efficiency investment. Decreasing the retrofit cost would have a significant impact on the energy retrofit rate; thus, subsidies for energy efficiency investment are useful and should remain a major focus for policy makers in order to increase the energy efficiency rate. However, with regard to the concern of the efficiency of public expenditures, the introduction of new measures and contracts on the two attributes could be considered as an additional effective way to increase the energy renovation rate.

Finally, the results confirm that comfort improvement is a significant driver of energy efficiency investment for most of the population, which is consistent with household declarations in the survey. This suggests that rebound effect could be a real side effect of energy efficiency improvement.

To go further in the understanding of the sources of uncertainty that could affect individual decision for energy retrofit, the role of the uncertainty on the time-persistence of financial incentives and political context could be an interesting track to follow in the future. Moreover, further investigation is needed to understand how dwellings and other individual characteristics of respondents could have a role in explaining the probability to invest in energy efficiency (such as the satisfaction with actual thermal comfort, age of the respondent, the age of the buildings, etc) or in explaining risk perception in energy retrofit (for instance trought the calculation of individual implicit discount rates). It could also be interesting to contrast individual perception about the future evolution of energy prices with actual trends in order to provide evidence of the presence or not of behavioural bias. Finally, understanding how the

design of the insurance schemes influence the utility provided by these measures could also be a key insight to focus on in the near future.

Moreover, even if DCE or stated preferences method place individual in hypothetical choice situations (that could be far from the reality[73]) that can conduct to hypothetical biais in the results, these methods are to be considered because they allow to test the preferences of homeowners in energy retrofit situations for original attributes. An extension of their uses to other types of energy investments (appliances, heating systems) to check for consistency across energy efficiency measures will be a interesting contribution in order to fullfill the analysis.

[73] See (Fowlie et al., 2015) to have an example of the real retrofit rate that can be achieved through the implementation of a free energy efficiency program in Michigan

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Appendix

A – Additional results – whole sample

Table 12: Conditional Logit and Hausmann test

	(b) partial	(B) all	(b-B) Difference	S.E.
Investment costs	-0.00011***	-0.00011***	-0.000008	0.000003
Energy savings (%)	0.034***	0.034***	-0.0003	0.0013
Insurance for quality	0.40***	0.36***	0.034	0.013
Fixed price contract	0.35***	0.30***	0.051	0.013
Increased indoor temperature	0.21***	0.20***	0.003	0.014
ASC	-0.67***	-0.63***	-0.042	0.061

Standard errors in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

(b) Model with a missing alternative (alternative B)

(B) Model with complete choice experiment, Log pseudolikelihood = -21951.141

Test: Ho: difference in coefficients not systematic

chi2(5)= 23.58

Prob>chi2 =0.0003. We reject H0.

The Haussmann test confirms that the IIA hypothesis does not hold.

Table 13: Mixed logit model results (including the savings over the energy bills instead of energy savings potential) to calculate the implicit discount rate

Mean	Coefficients	Standard errors
Investment costs	-0.00011***	0.000002
Savings over the energy bill	0.0015***	0.00007
Insurance for quality	0.66***	0.02
Fixed price contract	0.78***	0.020
Increased indoor temperature	0.45***	0.02
ASC	-2.7***	0.12
Standard deviation		
Insurance for quality	0.013***	0.11
Fixed price contract	0.36***	0.04
Increased indoor temperature	0.59***	0.03
ASC	4.09***	0.12

Log likelihood = -17678.897

Standard errors in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 14: Latent class model for the whole sample

	27% **class 1**	19% **class 2**	17% **class 3**	10% **class 4**	6% **class 5**	19% **class 6**
Investment costs	-0.0003***	-0.0002***	-0.00007***	-0.00027***	-0.00027	0.000001
	(0.00002)	(0.00001)	(0.00001)	(0.00005)	(0.0001)	(0.0000000)
Energy savings (%)	0.08***	0.04****	0.03***	0.063***	-0.0057***	0.026****
	(0.005)	(0.004)	(0.004)	(0.017)	(0.024)	(0.003)
Insurance for quality	0.65***	1.13***	4.94*	1.45****	1.24***	0.31***
	(0.06)	(0.06)	(5.07)	(0.29)	(0.31)	(0.04)
Fixed price contract	0.79***	0.97***	4.50	0.60**	1.73***	0.21***
	(0.09)	(0.06)	(5.07)	(0.28)	(0.63)	(0.04)
Increased indoor temperature	0.42***	0.54***	0.17***	0.56**	4.63***	0.05
	(0.07)	(0.06)	(0.06)	(0.23)	(0.89)	(0.04)
ASC	-2.79***	1.77***	1.82	4.55***	-0.95	-1.61***
	(0.23)	(0.17)	(5.07)	(0.81)	(1.1)	(0.19)

Standard errors in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Note that the same group patterns as the 4 classes Latent Class model over the whole sample are observable. For information, we tried different numbers of classes for the latent class model to see if heterogeneity across classes was stronger (regarding descriptive statistics of explanatory variables) when reducing the number of class. However, results are not conclusive.

Appendix B - Robustness analysis on Choice-consistent respondents

1. Descriptive statistics – Choice consistent individuals

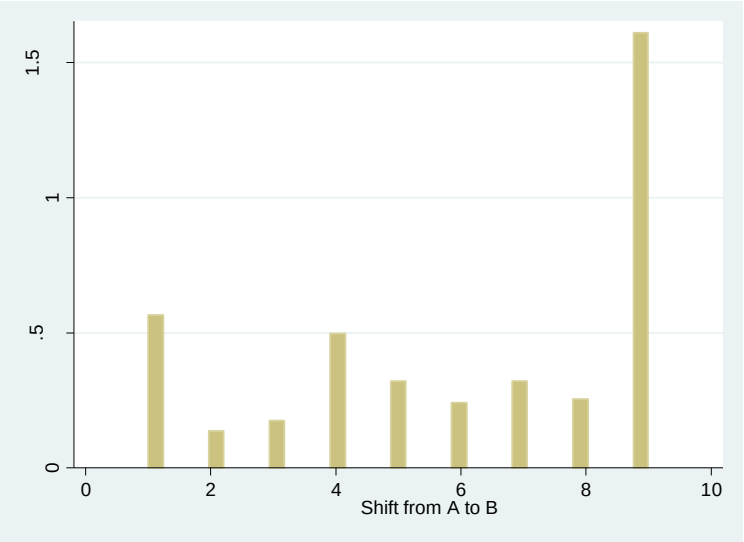
25% of the respondents are non-consistent across the choice experiment. As inconsistency can come from different reasons (inattention, learning effect, etc.) and can potentially induce bias, a robustness analysis of our estimates was implemented using the sample of consistent respondents. First descriptive statistics for this sample are presented in table 15. We note that this sample gathers respondents that are more likely to be risk averse (compared to the whole sample).

Table 15: Descriptive statistics for choice-consistent individuals.

	Mean	**Std. deviation**
Characteristics of individuals		
Male	0.45	0.49
Age of the respondent (in years)	50.5	13.7
Households who has a loan in progress (main residence purchase)	0.51	0.50
Landlords (renting out a property)	0.14	0.34
Risk averse Individuals *	0.75	0.43
Perception of the energy context		
Perception of quality of retrofits works (1: non-conformity never happens. 10: non-conformity is always an issue	6.5	1.9
Individuals having no idea about the trend of the future energy price	0.62	0.48
Environmental label is a significant criterion when buying appliances	0.49	0.50
Individuals that are fully satisfied with the current level of thermal comfort	0.24	0.43
Dwelling characteristics		
Owners living in a house	0.78	0.41
Surface of the dwelling (m2)	121	74
Energy bill (euros)	1185	1201
Heating energy source (%)		
Electricity	0.33	0.47
Gas	0.37	0.48
Wood	0.12	0.32
Fuel	0.11	0.31
Retrofit		
Household having implemented at least one energy measure (envelope) since move-in	0.44	0.5

*According to this dummy variable, we note that consistent individuals are more likely to be risk averse than non-consistent individuals

Figure 8: Risk aversion measure – Share of switches from safe to risky choice at each choice situation



2. Estimates

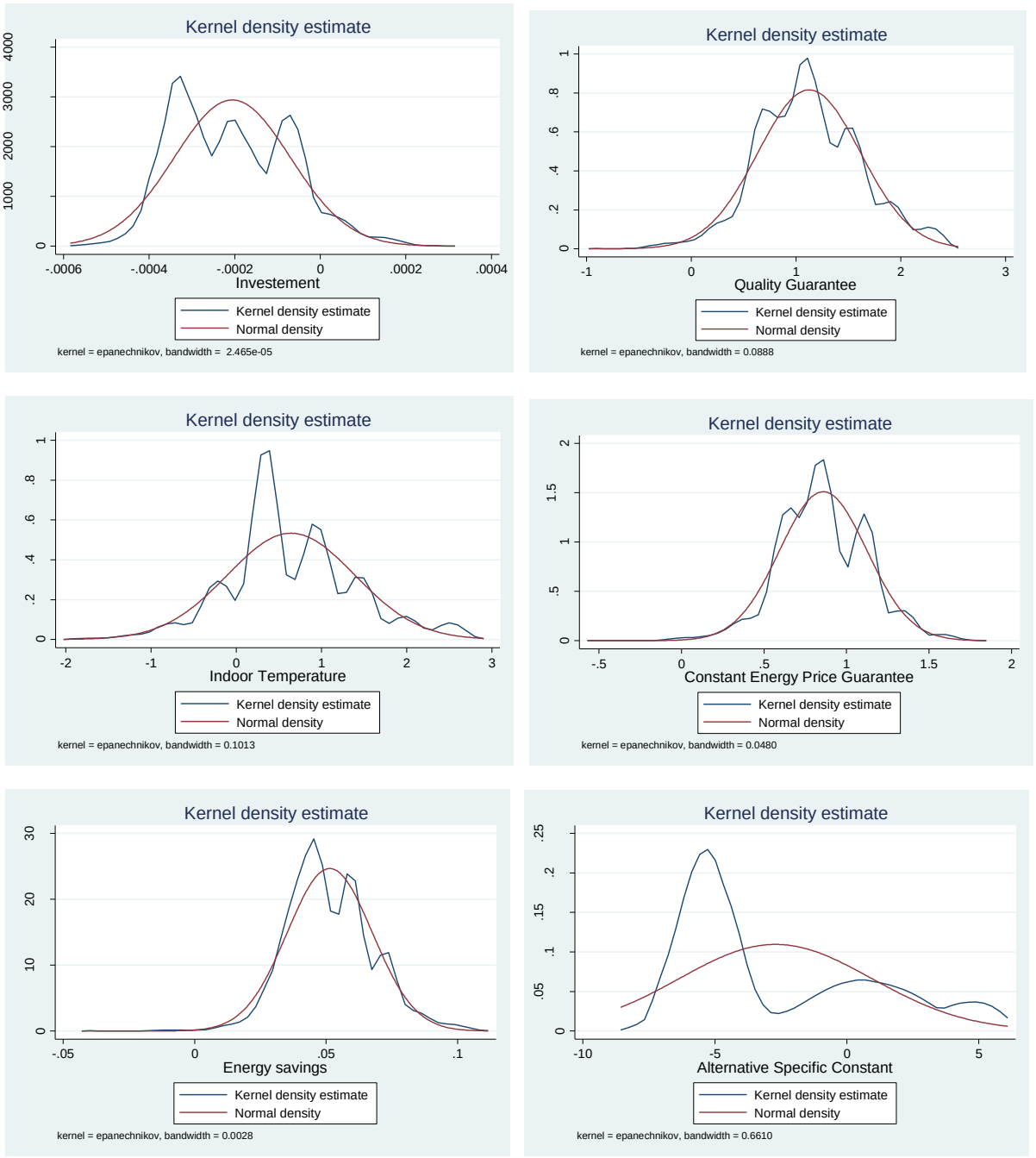
Table 16: Mixed logit model results (consistent respondents)

	Coefficients
Investment	-0,0002***
	(0.00000)
Insurance for retrofit quality	1.13***
	(0.039)
Fixed energy price contract	0.843***
	(0.033)
Indoor temperature	0.64***
	(0.038)
Energy savings	0,05***
	(0.002)
ASC	-2.533***
	(0.181)
Standard Deviation of coefficients	
Investment	0,0002***
	(0.00000)
Insurance for retrofit quality	0,848***
	(0.048)
Fixed energy price contract	0,589***
	(0.053)
Indoor temperature	1.10***
	(0.050)
Energy savings	0,0352***
	(0.004)
ASC	5.28***
	(0.23)
Number of obs = 52 886[74]	LR chi2(6) =8979

[74] Number of observations equals number of respondents x number of choice situations x number of alternatives in each choice situation

Standard errors in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Figure 9. Kernel density plots, mixed logit model (normal distribution, consistent respondents)



We note identical pattern regarding the distribution of simulated coefficients in comparison to the results over the whole sample (see section 7.1 Results in the main body of the chapter).

Table 17: 4 classes Latent Class model – Consistent individuals (2203 respondents)

Class share (%)	***18***	***13***	***26***	***43***
	class 1	**class 2**	**class 3**	**class 4**
Initial investment	-0.0002*** (0.00001)	-0.00026*** (0.00005)	-0.0004*** (0.00003)	-0.00003*** (0.000000)
Energy savings (%)	0.05*** (0.004)	0.08*** (0.017)	0.08*** (0.008)	0.03*** (0.002)
Insurance for quality	1.23*** (0.07)	1.61*** (0.30)	0.89*** (0.09)	0.67*** (0.03)
Fixed price Guarantee	1.03*** (0.07)	0.86*** (0.28)	0.96*** (0.11)	0.49*** (0.03)
Increased indoor temperature	0.75*** (0.07)	0.58* (0.23)	-0.042 (0.11)	0.48*** (0.03)
ASC	1.75*** (0.22)	5.35*** (0.81)	-3.85*** (0.36)	-2.22*** (0.17)

Standard errors in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$ LLF = -11893.311

Table 18: WTP for attributes

	Class 1	**Class 2**	**Class 3**	**Class 4**
Insurance for quality	6268 [5361 ; 7015]	6160 [3022 ;9298]	2382 [1753 ;3011]	19 939 [13115 ; 26763]
Fixed energy price contract	5260 [4397 ; 6123]	3290 [1324 ;5255]	2576 [2047 ; 3105]	14614 [9564 ;19664]
Energy saving	236 [188 ; 283]	293 [130 ;455]	228 [195 ; 261]	788 [528 ; 1046]
Increased indoor temperature	3826 [3073 ; 4580]	2227 [393 ; 4062]		14058 [8532 ;19584]

[] confidence interval at 90% level

Table 18: Descriptive statistics 4 classes (consistent sample- 2203 respondents)

Class	**1**	**2**	**3**	**4**
Savings between 0 and 5000 euros	0.26 (0.44)	0.24 (0.42)	0.21 (0.41)	0.30 (0.45)
No opinion about future energy price over the next 5 years (share)	0.64 (0.48)	0.70 (0.45)	0.60 (0.49)	0.61 (0.49)
Belief that energy price will increase over the next 5 years (share)	0.28 (0.45)	0.20 (0.40)	0.34 (0.47)	0.33 (0.47)
Environmental label is a significant criterion when buying appliances	0.47 (0.50)	0.42 (0.49)	0.47 (0.50)	0.53 (0.50)
Is fully satisfied with the thermal comfort of its dwelling	0.24 (0.43)	0.30 (0.46)	0.22 (0.41)	0.24 (0.43)
Men (share)	0.49 (0.50)	0.54 (0.49)	0.61 (0.50)	0.53 (0.50)
Heating bill (euros/year)	1097 (901)	948 (672)	1144 (1048)	1311 (1465)
Highly risk loving (share)	0.11 (0.31)	0.14 (0.35)	0.11 (0.31)	0.16 (0.37)
Very risk loving (share)	0.02 (0.16)	0.03 (0.16)	0.01 (0.12)	0.05 (0.21)
Highly risk averse (share)	0.07 (0.26)	0.08 (0.27)	0.06 (0.24)	0.05 (0.22)
Stay in bed (share)	0.39 (0.49)	0.39 (0.49)	0.41 (0.49à	0.38 (0.48)

() standard deviations

The models run in this section provide similar pattern in terms of results as ones provided by models run over the whole sample.

Appendix C - Questionnaire

Questionnaire : Préférences individuelles et rénovation énergétique

Ce questionnaire s'inscrit dans le cadre d'un travail de recherche sur les décisions de rénovation énergétique par les ménages français. Les réponses ne seront exploitées qu'à des fins de recherche et traitées de façon anonyme. Merci de votre participation !

Le questionnaire est composé de deux parties : la première, constituée des sections 1 et 2, vous propose des mises en situation dans lesquelles il vous est demandé de réaliser des choix contextualisés ; dans la seconde (sections 3 et 4), il s'agit de questions plus usuelles sur vous, votre logement de résidence principale, vos actions de rénovation énergétique.

Echantillon et consignes pour le déroulement de l'enquête en ligne :

2000 individus représentatifs des propriétaires (date de construction du logement et localisation aire urbaine)

Section 1 : Mesure de l'aversion au risque des individus et de la préférence pour le présent

Dans cette partie, l'objectif est d'évaluer votre comportement face aux situations d'incertitude et de votre préférence pour le présent dans le contexte de gains financiers. Il s'agit d'un protocole expérimental éprouvé.

Introduction

Placez-vous dans une situation où vous devez louer un appartement pour une durée d'un an. On vous propose deux appartements identiques sur tous les points excepté sur l'efficacité énergétique de leur système de chauffage (équipement de chauffage A dans l'appartement A et équipement de chauffage B dans l'appartement B).

Les systèmes de chauffage A et B se distinguent sur le montant des économies d'énergie annuelles sur facture qu'ils apportent par rapport à un appareil classique.

1) Merci de parcourir dans l'ordre (haut vers le bas) les 9 situations proposées. A partir de quelle situation préférez-vous l'équipement de chauffage B plutôt que le A ? Merci de reporter le numéro de la situation correspondante ci-dessous

Réponse 1 à 9

	Equipement A	OU	Equipement B	
Situation 1	20% de chance d'économiser 400€ et 80% de chance d'économiser 320€	OU	20% de chance d'économiser 770€ et 80% de chance d'économiser 20€	Votre choix : Equipement A ou B ? ⇨ Si vous préférez A, passez à la situation suivante, et refaites un choix ⇨ Si c'est B, veuillez reporter le numéro de la situation, le test est fini
Situation 2	30% de chance d'économiser 400€ et 70% de chance d'économiser 320€	OU	30% de chance d'économiser 770€ et 70% de chance d'économiser 20€	
Situation 3	40% de chance d'économiser 400€ et 60% de chance d'économiser 320€	OU	40% de chance d'économiser 770€ et 60% de chance d'économiser 20€	
Situation 4	50% de chance d'économiser 400€ et 50% de chance d'économiser 320€	OU	50% de chance d'économiser 770€ et 50% de chance d'économiser 20€	
Situation 5	60% de chance d'économiser 400€ et 40% de chance d'économiser 320€	OU	60% de chance d'économiser 770€ et 40% de chance d'économiser 20€	
Situation 6	70% de chance d'économiser 400€ et 30% de chance d'économiser 320€	OU	70% de chance d'économiser 770€ et 30% de chance d'économiser 20€	
Situation 7	80% de chance d'économiser 400€ et 20% de chance d'économiser 320€	OU	80% de chance d'économiser 770€ et 20% de chance d'économiser 20€	
Situation 8	90% de chance d'économiser 400€ et 10% de chance d'économiser 320€	OU	90% de chance d'économiser 770€ et 10% de chance d'économiser 20€	
Situation 9	100% de chance d'économiser 400€ et 0% de chance d'économiser 320€	OU	100% de chance d'économiser 770€ et 0% de chance d'économiser 20€	

2) Imaginez la situation suivante : vous venez d'effectuer un investissement en efficacité énergétique assez important pour votre logement et les pouvoirs publics vous proposent une aide financière. Vous avez à choisir entre deux modalités :

- un chèque de 1000 euros reçu dans 1 mois (paiement A)
- ou un chèque plus élevé mais dont l'échéance de réception est de 1 an. (paiement B)

Considérez les 17 situations suivantes où le montant du chèque B évolue. Parcourez les dans l'ordre (haut vers le bas) : A partir de quelle situation, préférez-vous renoncer au paiement A reçu dans 1 mois pour bénéficier du paiement B reçu dans 1 an ?

Réponse de 1 à 17

Situations n°	Paiement A dans 1 mois Montant	Paiement B dans 1 an Montant
1	1000 euros	1 019 euros
2	1000 euros	1 037 euros
3	1000 euros	1 057 euros
4	1000 euros	1 076 euros
5	1000 euros	1 096 euros
6	1000 euros	1 116 euros
7	1000 euros	1 137 euros
8	1000 euros	1 158 euros
9	1000 euros	1 179 euros
10	1000 euros	1 201 euros
11	1000 euros	1 258 euros
12	1000 euros	1 317 euros
13	1000 euros	1 443 euros
14	1000 euros	1 581 euros
15	1000 euros	1 733 euros
16	1000 euros	1 989 euros
17	1000 euros	2 501 euros

Questions d'introduction à la partie B suivante

3) Comment anticipez-vous l'évolution du prix de votre énergie de chauffage pour les 5 ans à venir ?

Je ne sais pas

Je sais

Si je sais (curseur à placer sur axe avec graduation <-10% < prix actuel <+10%<+20%<…+100%)

4) Pensez-vous que les malfaçons sont des problèmes courants lors de la réalisation de travaux par des entreprises du bâtiment ?

Note de 0 à 10, 0 ce n'est jamais un problème, 10, les malfaçons sont systématiques

5) Avez-vous déjà subi une expérience malheureuse de malfaçon lors de la réalisation de travaux par un prestataire dans un de vos biens immobiliers ?

Aucune

1

Plusieurs

6) Pouvez-vous estimer le montant de votre facture énergétique de chauffage annuelle (en euros) ? (Dans le cas du chauffage tout électrique, la facture de chauffage représente 60% en moyenne de la facture d'électricité)

XX numérique

Section 2 : Travaux de rénovation dans une situation hypothétique

Contexte

Les actions de rénovation énergétique apportent des économies d'énergie ; cependant le montant effectif économisé sur facture après rénovation peut être sujet à une certaine incertitude. Des facteurs externes peuvent conduire à un écart entre les économies effectivement réalisées grâce aux travaux de rénovation énergétique des économies prévues ou affichées par les ingénieurs du bâtiment.

Pour réduire les incertitudes sur les bénéfices de la rénovation énergétique et tenter d'encenser la demande en travaux, les entreprises du bâtiment, pouvoirs publics et industriels réfléchissent à de nouveaux types de contrats incluant des garanties sur les gains issus de la rénovation énergétique.

Imaginez la situation suivante…

Vous habitez dans votre logement actuel.

Des entreprises du bâtiment vous proposent d'améliorer l'isolation des murs de votre logement en réalisant ou améliorant l'isolation thermique par l'extérieur de votre logement*

*On fait l'hypothèse que cela ne pose pas de problème d'un point de vue urbanistique et que vous n'ayez pas déjà réalisé cette opération de rénovation.

L'isolation thermique extérieure est un bardage constitué d'une structure métallique et de l'apport d'un isolant venant recouvrir la paroi de la maison. Il permet de supprimer les ponts thermiques, défauts d'isolation d'une paroi à la jonction des murs et des planchers.

L'opération permet également de rénover aussi les enduits de façades très vétustes et ne nécessite pas de demande de permis de construire. Les travaux sont peu gênants (pas de mobilisation de l'intérieur de la maison, pas de perte de surface) et permettent d'améliorer l'isolation acoustique et le confort thermique (frais en été, disparition des sensations de froid dues aux pertes de chaleur).

On vous propose alors de choisir entre plusieurs offres : l'alternative A et l'alternative B, qui proposent l'isolation par l'extérieur des murs de votre logement avec 5 modalités de réalisation, et l'alternative « ne rien faire ». Les alternatives proposant la rénovation se distinguent selon 5 caractéristiques détaillées ci-après :

- L'investissement nécessaire pour réaliser les travaux (exprimé en euros), net de toutes aides et à payer avant le début des travaux.

- Le potentiel d'économies d'énergie moyen de l'opération de rénovation, exprimé en % de réduction de votre consommation d'énergie de chauffage annuelle actuelle et valable sur 30 ans (durée de vie de l'équipement). Il est fourni à titre indicatif et reflète le niveau de prestation choisi.

- La souscription ou non à une garantie de performance énergétique, valable 10 ans. En cas de souscription, la bonne qualité énergétique finale des travaux est garantie contractuellement. Elle fait l'objet d'un contrôle par un auditeur agréé externe.

- La souscription ou non à une garantie « prix de l'énergie constant » sur 5 ans. Les pouvoirs publics proposent de faire bénéficier les ménages d'un prix de l'énergie constant sur 5 ans s'ils s'engagent dans la rénovation énergétique. Ce prix correspond à celui de l'année de réalisation des travaux. Après 5 ans, les pouvoirs publics peuvent réviser le système de prix.

- L'augmentation ou non de la température intérieure de votre logement en hiver après les travaux.

Dans chacune des 9 situations suivantes, laquelle des alternatives choisiriez-vous ?

Les situations sont à considérer de façon indépendante les unes des autres

Situation 1	Offre A Isolation thermique	Offre B Isolation thermique	
Investissement net	16 000 €	7 000 €	Pas de changement par rapport à la situation actuelle
Potentiel d'économies d'énergie moyen	-40%	-25%	
Garantie « performance énergétique » des travaux	✗	✓	
Garantie « prix de l'énergie constant »	✓	✗	
Température intérieure	Température augmentée	Température inchangée	
Choix	□	□	□

7) Choix1 : Quelle alternative choisissez-vous ?
A, B, pas de changement par rapport à la situation actuelle

Situation 2	Offre A Isolation thermique	Offre B Isolation thermique	
Investissement net	10 000 €	13 000 €	Pas de changement par rapport à la situation actuelle
Potentiel d'économies d'énergie moyen	-25%	-40%	
Garantie « performance énergétique » des travaux	✗	✓	
Garantie « prix de l'énergie constant »	✗	✓	

Température intérieure	Température inchangée	Température augmentée	
Choix	□	□	□

8) Choix 2 : Quelle alternative choisissez-vous ?
A, B, pas de changement par rapport à la situation actuelle

Situation 3	Offre A Isolation thermique	Offre B Isolation thermique	
Investissement net	16 000 €	7 000 €	Pas de changement par rapport à la situation actuelle
Potentiel d'économies d'énergie moyen	-25%	-40%	
Garantie « performance énergétique » des travaux	✓	✗	
Garantie « prix de l'énergie constant »	✗	✓	
Température intérieure	Température augmentée	Température inchangée	
Choix	□	□	□

9) Choix 3 Quelle alternative choisissez-vous ?
A, B, pas de changement par rapport à la situation actuelle

Situation 4	Offre A Isolation thermique	Offre B Isolation thermique	
Investissement net	13 000 €	10 000 €	Pas de changement par rapport à la situation actuelle
Potentiel d'économies d'énergie moyen	-40%	-25%	
Garantie « performance énergétique » des travaux	✗	✓	
Garantie « prix de l'énergie constant »	✗	✓	
Température intérieure	Température inchangée	Température augmentée	
Choix	□	□	□

10) Choix 4 Quelle alternative choisissez-vous ?
A, B, pas de changement par rapport à la situation actuelle

Situation 5	Offre A Isolation thermique	Offre B Isolation thermique	
Investissement net	7 000 €	16 000 €	

Potentiel d'économies d'énergie moyen	-40%	-25%	Pas de changement par rapport à la situation actuelle
Garantie « performance énergétique » des travaux	✓	✗	
Garantie « prix de l'énergie constant »	✗	✓	
Température intérieure	Température augmentée	Température inchangée	
Choix	□	□	□

11) Choix 5 Quelle alternative choisissez-vous ?

A, B, pas de changement par rapport à la situation actuelle

Situation 6	Offre A Isolation thermique	Offre B Isolation thermique	
Investissement net	10 000 €	13 000 €	Pas de changement par rapport à la situation actuelle
Potentiel d'économies d'énergie moyen	-40%	-25%	
Garantie « performance énergétique » des travaux	✓	✗	
Garantie « prix de l'énergie constant »	✓	✗	
Température intérieure	Température inchangée	Température augmentée	
Choix	□	□	□

12) Choix 6 Quelle alternative choisissez-vous ?

A, B, pas de changement par rapport à la situation actuelle

Situation 7	Offre A Isolation thermique	Offre B Isolation thermique	
Investissement net	7 000 €	16 000 €	Pas de changement par rapport à la situation actuelle
Potentiel d'économies d'énergie moyen	-25%	-40%	
Garantie « performance énergétique » des travaux	✗	✓	
Garantie « prix de l'énergie constant »	✓	✗	
Température intérieure	Température augmentée	Température inchangée	
Choix	□	□	□

13) Choix 7 Quelle alternative choisissez-vous ?

A, B, pas de changement par rapport à la situation actuelle

Situation 8	Offre A Isolation thermique	Offre B Isolation thermique	
Investissement net	13 000 €	10 000 €	
Potentiel d'économies d'énergie moyen	-25%	-40%	Pas de changement par rapport à la situation actuelle
Garantie « performance énergétique » des travaux			
Garantie « prix de l'énergie constant »			
Température intérieure	Température inchangée	Température augmentée	
Choix	□	□	□

14) Choix 8 Quelle alternative choisissez-vous ?

A, B, pas de changement par rapport à la situation actuelle

Situation 9	Offre A Isolation thermique	Offre B Isolation thermique	
Investissement net	16 000 €	7 000 €	
Potentiel d'économies d'énergie moyen	-40%	-25%	Pas de changement par rapport à la situation actuelle
Garantie « performance énergétique » des travaux			
Garantie « prix de l'énergie constant »			
Température intérieure	Température augmentée	Température inchangée	
Choix	□	□	□

15) Choix 9 : Quelle alternative choisissez-vous ?

A, B, pas de changement par rapport à la situation actuelle

Section 3 : Caractéristiques du ménage et du logement

1.Ménage (s'adresse à une personne de référence >18 ans)

16) Etes-vous ?
un homme
une femme

17) Quelle est votre année de naissance ?
XXXX numérique

18) De combien de personnes se compose votre foyer ?

XX numérique

19) Quelle est votre situation ? (plusieurs réponses possibles)
Célibataire sans enfants
Célibataire avec un ou des enfants d'âge inférieur à 25 ans présents dans le logement
Couple seul
Couple avec un ou des enfants d'âge inférieur à 25 ans présents dans le logement
Couple accueillant une/d'autre(s) personne(s) de la famille

20) En quelle année êtes-vous arrivé dans votre logement actuel ?

XXXX numérique

21) Envisagez-vous un déménagement dans les prochaines années ?
Oui, dans les 2 ans
Oui, dans 2 à 5 ans
Oui , dans 5 à 10 ans
Non
Je ne sais pas

22) Quel est le code postal de votre lieu de résidence principale?

XXXX numérique

23) Dans quel type d'unité urbaine se situe votre logement ?
L'unité urbaine est une commune ou un ensemble de communes qui comporte sur son territoire une zone bâtie d'au moins 2 000 habitants où aucune habitation n'est séparée de la plus proche de plus de 200 mètres. En outre, chaque commune concernée possède plus de la moitié de sa population dans cette zone bâtie.
Commune rurale
Unité Urbaine < 20 000 habitants.
Unité urbaine de 20 à 100 000 habitants
Unité urbaine > de 100 000 habitants.
Agglomération parisienne

24) Quelle est le type de la zone géographique dans laquelle votre logement se situe
Paris
En centre-ville

Dans le péri-urbain/ banlieue d'une ville
Zone rurale

25) Quelle est votre profession ? (6 classes possibles)
Agriculteurs exploitants
Artisans, commerçants et chefs d'entreprise
Cadres et professions intellectuelles supérieures
Professions Intermédiaires *(Professions intermédiaires de la santé et du travail social, Clergé, religieux, Professions intermédiaires administratives de la fonction publique,)* Professions intermédiaires administratives et commerciales des entreprises, *Techniciens, Contremaîtres, agents de maîtrise*
Employés *(Employés civils et agents de service de la fonction publique, Policiers et militaires, Employés administratifs d'entreprise, Employés de commerce, Personnels des services directs aux particuliers*)
Ouvriers
Autre

26) Quelle est votre situation actuelle ?
Occupe un emploi
Chômeur
Etudiant(e),
Retraite(e) (ancien salarié) ou Pré-retraite(e)
Retire(e) des affaires
Au foyer (y compris congé parental)
Autre inactif y compris les personnes ne touchant qu'une pension de réversion et les personnes invalides

2.Logement et performance énergétique

27) Quelle est la surface habitable de votre logement (m2)?

XX numérique

28) Votre logement de résidence principale est il… ?
Une maison
Un appartement
Autre

29) Quelle est l'année de construction de votre logement ? <u>en numérique</u>

XXXX numérique

30) Quelle est l'année de construction de votre logement ? <u>(en classe)</u>
avant 1949
entre 1949 et 1974
entre 1975 et 1999
après 1999

31) Le logement est-il… ? (plusieurs réponses attendues)
Un bâtiment Isolé

Mitoyen sur un côté
Mitoyen sur (au moins) deux côtés
Plein pied
Sur deux niveaux (un étage)
Sur trois niveaux ou plus (deux étages ou plus)
Possède des combles/grenier

32) Votre logement a-t-il été l'objet d'un diagnostic par experts (audit énergétique, DPE, label, etc) ?
Oui, c'est un logement très performant d'un point de vue énergétique (étiquette A ou B si DPE ou équivalent)
Oui, c'est un logement assez performant d'un point de vue énergétique (étiquette C si DPE ou équivalent)
Oui, la performance énergétique du logement est moyenne (étiquette D si DPE ou équivalent)
Oui, la performance énergétique du logement est faible (étiquettes énergétiques E, F ou équivalent)
Oui, la performance énergétique du logement est très faible (étiquette énergétique G ou équivalent)

Non, le logement n'a pas fait l'objet d'un diagnostic énergétique

33) Votre logement possède-t-il des fenêtres en double-vitrage ou triple vitrage ?
Toutes
Partiellement
Non

34) Les murs de votre logement sont-ils… ?
Non isolés thermiquement
Isolation moyenne
Bonne isolation
Je ne sais pas

35) Le sol de votre logement est-il… ?
Non isolés thermiquement
Isolation moyenne
Bonne isolation
Je ne sais pas

36) Le toit/les combles de votre logement est/sont-il(s)… ?
Non isolés thermiquement
Isolation moyenne
Bonne isolation
Pas de toit/combles
Je ne sais pas

37) Quelle est votre énergie de chauffage principale ?
Électricité
Gaz
Fioul
Bois
Réseau de chaleur

Renouvelable
Autre

38) Votre chauffage principal est…
Chaudière individuelle ou installation centrale individuelle
Chauffage ou chaufferie collective
Chauffage mixte
Chauffage tout électrique individuel
Appareil(s) indépendant(s)
Autre moyen de chauffage
Aucun moyen de chauffage

39) Si vous possédez un moyen de connaître votre température de chauffage en hiver, de combien est-elle en moyenne ? En °C
xx

40) Possédez-vous un dispositif de climatisation et comment l'utilisez-vous ?
Oui, j'en possède un et je l'allume le moins possible et seulement en cas de très grosses chaleurs (canicules)
Oui, j'en possède un et je l'allume souvent en période estivale
Oui, j'en possède un et je l'allume de façon continue en période estivale ; j'ai une préférence individuelle forte pour le frais
Je n'ai pas de dispositif de climatisation

41) Pouvez-vous estimer le montant de votre facture d'électricité annuelle (en euros)?
XX numérique

42) Pour votre facture d'électricité, s'agit-il?

D'une facture individuelle pour le logement
D'une facture collective pour l'immeuble répartie dans les charges
Autre

3.Comportement et préférences individuelles

43) Estimez-vous que le confort thermique de votre logement soit satisfaisant ? (un mauvais confort thermique entraîne des sensations de froid, humidité, courant d'air, etc)
Oui , tout à fait
Oui, cela me convient
Non, pas du tout

44) Sinon, quel est, selon vous, la raison principale de cet inconfort ? (plusieurs réponses possibles)
Panne ou vétusté du matériel de chauffage ou matériel insuffisant (système de chauffage)
Mauvaise isolation des murs, fenêtres, etc
Intempéries
Restriction à cause du coût
Autre

45) Vous restreignez vous sur votre consommation de chauffage ?
Oui pour des raisons Ecologiques
Oui pour des raisons Economiques
Non

46) Pour votre usage du chauffage pouvez-vous évaluer votre type de consommation ? note de 1 à 10 ou curseur
1 : je me restreins énormément (température de chauffage basse, réduction des périodes de chauffage, coupure systématique du chauffage pendant l'absence),
5 : j'estime que mon comportement concernant la consommation de chauffage est « normale », sans extrême
10 : j'ai un niveau de préférence pour le confort élevé pour l'usage chauffage (température intérieure particulièrement élevée, longue période de chauffage, etc)

47) Dans les domaines suivants, avez des comportements « verts, écologiques » volontaires ? (plusieurs réponses possibles)
Tri des déchets
Nombre et intensité d'utilisation des appareils électroménagers, informatiques, etc
Achats alimentaires
Transport domicile-travail (utilisation des transports en commun, covoiturage, etc)
Transport de loisir (utilisation des transports en commun, covoiturage, etc)
Participation active au sein d'une association environnementale
Profession (orientation « verte »)

48) Etes-vous attentifs à l'étiquette énergétique de vos équipements domestiques lors de leurs achats ?
Oui, critère majeur de choix
Oui, critère mineur de choix
Non

4. *Travaux énergétiques*

49) Avez-vous réalisé des travaux de rénovation énergétique sur votre logement d'habitation depuis emménagement (isolation thermique mur, combles, fenêtres, changement du système de chauffage, énergie renouvelable) ?
Oui
Non

(si « oui »=> question suivante, si « non » question 77)

Si réalisation de travaux de rénovation énergétique

50) Quel a été le coût global de ces travaux de rénovation énergétique ?

Xx euros

51) Qui a décidé de la réalisation ces travaux de rénovation énergétique?

Vous-même
La copropriété

52) Avez-vous réalisé une Isolation thermique des murs ?
Oui, Isolation thermique par l'intérieur
Oui, Isolation thermique par l'extérieur
Non

53) Montant total des travaux d'isolation des murs ? (euros)

XX Numérique

54) Surface des murs concernée ? (m2)

55) Avez-vous réalisé une Isolation des combles/toiture ?
Oui
Non

56) Montant total de l'isolation des combles/toiture ? (euros)

XX Numérique

57) Avez-vous réalisé une Isolation thermique des sols ?
Oui
Non

58) Montant total des travaux d'isolation du sol ? (euros)

XX Numérique

59) Avez-vous réalisé une Pose de double/triple vitrage sur certaines de vos fenêtres/baies ?
Oui, pour 100% des fenêtres/baies
Oui pour plus de 50% des fenêtres/baies
Oui, pour quelques fenêtres/baies
Non

60) Montant de l'opération de changement de fenêtres/baies ? (euros)

XX numérique

61) Pour les travaux mentionnés ci-dessus (isolation de l'enveloppe, pose de double/triple vitrage), quelles ont été votre ou vos motivations principales ? (classement possible, jusqu'à trois motivations ?)
Confort thermique
Confort acoustique
Économies d'énergie (bénéfice économique)
Bénéfice environnemental
Vétusté de mon logement
Augmenter la valeur du bien immobilier
Rénovation suite à emménagement (remise en état)
Autre raison
Je n'ai pas réalisé ce type de travaux

62) Avez-vous réalisé un Remplacement du système de chauffage ?
Non
Oui, Chaudière à condensation,
Oui, Chaudière hybride,
Oui, Pompe à chaleur,
Oui, Micro-cogénération gaz,
Oui, Énergie hydraulique,
Oui, Énergie éolienne,
Oui, Énergie solaire,
Oui, Autre dont système de chauffage « classique »

63) Pour quelle raison avez-vous changé votre système de chauffage ?
Panne
Motif économique : gains sur facture,
Motif économique : en prévision d'une valorisation patrimoniale (vente du bien)
Motif écologique
Autre raison
Je n'ai pas réalisé ce type de travaux

64) Montant de l'opération du changement de système de chauffage ?
XX numérique

65) En quelle année les derniers travaux ont-ils été réalisés ?

XX numérique

66) Qui a financé ces travaux ?
Vous-même
La copropriété
Assurance
Autre
NSP

67) Avez-vous bénéficié d'aides publiques pour votre rénovation énergétique ? (plusieurs réponses possibles)
Aide de l'Anah
Crédit d'impôt pour la transition énergétique (CITE)
Déduction fiscale
Autre
Non

68) De quel montant total avez-vous bénéficié pour les aides à la rénovation énergétique (réduction d'impôt comprise) ? (euros)

XX numérique

69) Auriez-vous réalisé ces travaux sans aide ?
Non, je n'aurais rien entrepris
Oui, mais le volume de travaux aurait été moindre
Oui, mais les travaux auraient été repoussés dans le temps
Oui, mais je ne serais pas passé par un professionnel
Oui, ces aides n'ont rien changé

NSP

70) Avez-vous utilisé un crédit pour la réalisation de ces travaux ?
Oui
Oui, Eco-prêt à taux zéro
Non, autofinancement direct

71) Avez-vous fait ces travaux à l'occasion d'autres travaux (embellissement, agrandissement, isolation phonique, etc)?
(Plusieurs réponses possibles)
Agrandissement, extension du logement
Ravalement de façades
Rénovation
Isolation phonique
Aménagement d'espace intérieur (nouvelle pièce, salle d'eau, salle de bain, WC)
Embellissement
Système de ventilation
Couverture et étanchéité
Pas d'autres travaux

72) Avez-vous fait réaliser ces travaux par un professionnel ?

Oui totalement
Oui, en partie
Non

73) Avez-vous évalué la rentabilité financière de votre projet de rénovation avant décision (même grossièrement)?
Oui
Non, je ne disposais pas d'assez d'informations,
Non car je ne sais pas faire
Non car je n'étais pas intéressé
Non, autre raison

74) Etes-vous satisfaits des travaux réalisés ? (qualité, déroulé)
Oui
Moyennement
Non

75) Pouvez-vous donner un ordre de grandeur de l'évolution de vos dépenses de chauffage annuelles depuis la réalisation des travaux de rénovation? (en%)

Curseur entre – 100% et + 100 %

76) Avez-vous gagné en confort ? (plusieurs réponses possibles)
Aucun gain de confort
Une meilleure répartition de la chaleur dans le logement
Qualité de l'air
Température plus élevée dans le logement l'hiver
Température moins élevée dans le logement l'été
Moins de perdition de chaleur

Autre
NSP

(suite question 82 pour ceux qui ont fait de la rénovation énergétique)

Si pas de travaux de rénovation énergétique

77) Avant aujourd'hui, avez-vous déjà réfléchi à faire des travaux de rénovation énergétique pour le logement actuel?
Oui
Non

78) Pour vous, quels sont les bénéfices principaux que vous associez à la rénovation thermique de votre logement ? (classer en ordre d'importance si possible pour les bénéfices connus)
Economies d'énergie
Confort thermique
Bénéfice environnemental
Confort acoustique
Bénéfice sanitaire
Valorisation patrimoniale du bien immobilier
Autre
Aucun

79) Prévoyez-vous de faire des travaux de rénovation énergétique dans les 2 prochaines années ?
Oui, Changement de système de chauffage
Oui, Isolation thermique des murs
Oui, Isolation thermique des combles /toit
Oui, Isolation du sol
Oui, Isolation des fenêtres
Oui, Energie renouvelable
Oui, Autre
NSP
Aucun

Si non, questions suivantes : 80, 81, 82
Si oui => aller directement question 82

80) Si non, pourquoi n'avez-vous pas réalisé de travaux de rénovation énergétique? Raison(s) principale(s) (3 choix possibles ou classement possible pour les freins concernés)
Je suis satisfait de mon état actuel
Le logement est neuf
Ce type d'investissement n'est pas dans mes priorités et préférences
Sujet techniquement trop complexe, j'ai peur de me tromper
L'investissement nécessaire est trop élevé
C'est impossible compte tenu du contexte légal (copropriété, code urbanistique, etc)
Je ne suis pas certain que les gains financiers suivront
Je n'ai pas confiance en la qualité des travaux réalisés
Le dérangement occasionné est trop important

Déménagement prochain
Je ne suis pas sûr que la rénovation énergétique de mon logement soit valorisée dans le cas d'une vente
Je n'ai pas trouvé d'offres/ d'artisans
Autre

81) Quels sont les éléments principaux qui pourraient vous faire changer d'avis ? (plusieurs réponses possibles)

A l'occasion de la réalisation d'autres types de travaux, je pourrais envisager les travaux de rénovation énergétique (mutualisation des coûts et gêne)
La meilleure reconnaissance de la valeur patrimoniale de la performance énergétique du logement
De l'information personnalisée : par exemple, les conseils d'un expert objectif pour la réalisation de mes travaux
La garantie de la réalisation des gains économiques prévus au moment de la décision de rénovation énergétique
Des aides publiques plus facilement accessibles
L'augmentation importante annoncée du prix de l'énergie dans les futures années
Un dérangement occasionné par le chantier moins important
Un système de financement des travaux plus souple. Par exemple : emprunt et tiers financeur qui se rembourse sur les économies d'énergie réalisées
Aucune de ces raisons
Rien

A tous

82) Estimez-vous que les travaux de rénovation énergétique constituent un investissement «risqué » ? c'est-à-dire, considérez-vous qu'il existe un risque de perdre de l'argent ou de ne pas rentabiliser votre projet quand vous investissez en rénovation énergétique (plusieurs choix possibles)

Aucun risque
Risque/Incertitude sur la rentabilité future du projet dans l'environnement économique présent et futur incertain.
Risque sur la qualité finale des travaux énergétiques par rapport à ce qui est annoncé
Risques opérationnels. On ne connait pas de façon certaine les coûts réels de ces travaux car possibilité d'imprévus (faillite de l'entreprise, coût additionnels)
Risque de non valorisation immobilière. A la vente du bien, les travaux énergétiques réalisés peuvent ne pas être valorisés à leur juste prix dans son prix de vente.
Autre

5. Ménage bis : situation financière, patrimoine et placements financiers

Les informations financières demandées par la suite ne seront utilisées qu'à des fins de recherche dans le cadre d'une étude sur la réalisation de travaux de rénovation énergétique et seront traitées de façon **complètement anonymes** ; elles permettront de reconstituer une information sur le portfolio type du ménage occupant, **merci de contribuer à notre travail !**

83) Quel est le revenu mensuel net de votre ménage ? (y compris les salaires nets, allocations familiales, pensions et autres revenus)

XXXX numérique

84) Pourriez-vous nous indiquer dans quelle tranche se situe le montant total de l'épargne détenue par tous les membres de votre ménage (hors biens immobiliers) ?

Moins de 500 €
500 à moins de 1 000 €
1 000 à moins de 2 000 €
2 000 à moins de 3 000 €
3 000 à moins de 5 000 €
5 000 à moins de 10 000 €
10 000 à moins de 15 000 €
15 000 à moins de 30 000 €
30 000 à moins de 50 000 €
50 000 à moins de 100 000 €
100 000 à moins de 150 000 €
150 000 € à moins de 200 000 €
200 000 € et plus
Refus
NSP

85) A combien évalueriez-vous votre bien : résidence principale ? (num)

86) A combien évalueriez le reste de votre patrimoine immobilier ? (num)

87) Pour l'achat de votre logement principal (ou l'achat du terrain et la construction de votre logement), avez-vous un ou plusieurs prêts en cours ?

Oui, le remboursement s'étend encore sur une période inférieure à 5 ans
Oui, le remboursement s'étend encore sur une période comprise entre 5 et 10 ans
Oui, le remboursement s'étend encore sur une période comprise entre 10 et 20 ans
Oui, le remboursement s'étend encore sur une période supérieure à 20 ans
Non

88) Si vous avez un ou des prêts en cours pour votre résidence principale, quel est l'ordre de grandeur de vos mensualités ?

Conclusion et transition vers le Chapitre 2

Ce premier chapitre a montré le rôle de l'incertitude sur le future coût de l'énergie et sur la qualité des travaux de rénovation énergétique comme frein à la rénovation énergétique chez les propriétaires français. Par ailleurs, les résultats de l'analyse mettent en évidence que l'hétérogénéité des ménages vis-à-vis de leurs caractéristiques, de leurs préférences et de leurs croyances peut avoir un rôle important pour comprendre les décisions de rénovation énergétique. Par l'originalité de l'approche et des données utilisées, cet article fournit une contribution originale à la littérature sur le paradoxe énergétique.

Cependant, l'efficacité énergétique n'est pas le seul déterminant de la consommation énergétique résidentielle. Bien que son poids explicatif est important, la spécificité du secteur est que la consommation énergétique repose sur le rôle déterminant de l'usager. L'adéquation entre les caractéristiques des ménages, des logements et de leur environnement peut conduire à des comportements énergétiques particuliers qu'il faut identifier avant de vouloir faire évoluer.

Ainsi, l'objet de ce second papier est d'identifier les déterminants de la consommation énergétique résidentielle et les schémas de la décision énergétique à l'échelle du ménage tout en prenant en compte les spécificités du cas français. En cohérence avec la vision du premier papier, nous intégrons dans notre cadre d'analyse que le niveau d'efficacité énergétique du logement peut dépendre d'un choix (antérieur) réalisé par les ménages, ce choix dépendant de leurs caractéristiques individuelles. Par ailleurs, nous nous intéressons particulièrement au rôle des préférences pour le confort pour expliquer la consommation énergétique excessive.

Chapitre 2

Energy Consumption in the French Residential Sector: How Much do Individual Preferences Matter?*

*Cet article a été écrit en collaboration avec Dorothée Charlier[75]. Il a été accepté dans la revue *Energy Journal* en décembre 2018 et sera disponible sous peu.

Abstract

The aim of this research is to understand the impact of preference heterogeneity in explaining energy consumption in French homes. Using a discrete-continuous model and the conditional mixed-process estimator (CMP) enable us to address two potential endogeneities in residential energy consumption: energy prices and the choice of home energy characteristics. As a key contribution, we provide evidence that a preference for comfort over saving energy does have significant direct and indirect impacts on energy consumption (through the choice of dwelling), particularly for high-income households. Preferring comfort over economy or one additional degree of heating implies an average energy overconsumption of 10% and 7.8% respectively, up to 18% for high-income households. Our results strengthen the belief that household heterogeneity is an important factor in explaining energy consumption and could have meaningful implications for the design of public policy tools aimed at reducing energy consumption in the residential sector.

Keywords: Residential energy consumption; Household preferences; Discrete-continuous choice method; Conditional mixed-process.

JEL CODES: Q41; D12; C26; C21

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1.Introduction

Reducing the final energy consumption of the European Union has been included in the EU energy strategy for 2030, with the goal of achieving 27% of energy savings compared to the business-as-usual scenario. Among all sectors, decreasing the energy consumption of the buildings sector is one of the most challenging tasks. Despite the fact that the sector has been identified as having the greatest potential for energy savings at the global scale (IEA, 2017), in EU countries the achievement is for the most part subject to the good will and behavior of billions of households living in these buildings (namely, the residential sector)[76]. Nowadays, observed energy savings are below the expectations of technical and economic models (Jaffe and Stavins, 1994; Sunikka-Blank and Galvin, 2012; Sorrell and O'Mallay, 2014), which could be a strong indicator of this behavioral bias. In that context, projecting future energy consumption of the sector or changing its trajectory in the expected direction seems complex in the absence of a complete understanding of household behavior.

In terms of policymaking, the task is to implement efficient policies able to stimulate changes at the household level to improve upon international energy consumption targets. Renovation measures and social intervention to encourage more efficient use of energy have been identified as potential solutions for reducing energy consumption in the residential sector (Lopes et al. 2012). Gaining a better understanding of energy consumption patterns in the housing sector is necessary to implement such solutions in an effective way.

Statistical bottom-up studies conducted by economists have revealed that 40% of energy consumption in the residential sector is determined by technical factors (Belaïd 2016). A large share of the remainder would be explained by socioeconomic and individual characteristics such as income, age of household members, tenure and energy-related preferences and choices (Belaïd 2016; Belaïd and Garcia 2016; Cayla et al. 2011). Although understanding the determinants of energy consumption has been a recurring theme in economics, distinguishing the effects of individual factors on the final quantity of energy consumed, which would enable characterization of energy behavior and consumption patterns, is still a complex issue. In particular, the topic suffers from limitations due to a lack of appropriate data to control both for socio-economic characteristics, individual preferences and the technical characteristics of dwellings. Consequently, engineering models that almost exclusively use technical building

[76] In 2016, the residential and building sectors represented respectively 25.4 % and 40% of the final energy consumption in the EU. Source: Eurostat and European Commission.

characteristics and engineering calculations as inputs to predict energy consumption are still widely used. However, they reveal limitations in non -including and -modeling the effect of individual heterogeneity and occupant behavior in engineering models (Galvin and Sunikka-Blank 2014; Delzendeh and al., 2017). Combining the benefits of both approaches, namely, integrating both energy-related preferences and theoretical energy performance of housings in research, is an essential step to deepen understanding of the energy consumption spectrum in the residential sector and clarify the role of household behavior.

To advance the academic literature and provide relevant recommendations to policy-makers, additional empirical research is needed to identify individual determinants and their interaction with building characteristics, and to describe energy consumption patterns. Energy savings and energy-intensive behaviors are derived from individual energy use preferences. Analyzing the effect of such preferences is crucial for understanding the importance of household heterogeneity in explaining variability in energy consumption and identifying leverage actions. The issue has generally been neglected in the economics literature (Lopes et al. 2012), particularly due to the lack of relevant data.

This research aims to partially fill this gap. Our main hypothesis is that individual stated preferences regarding household energy use do have a role in explaining energy consumption in French homes. We used a discrete-continuous model based on McFadden's pioneering work (1984) to test this assumption, and account for the growing empirical concern related to the interactions between dwellings and household characteristics when modeling energy demand. We assumed that individual energy consumption preferences may be manifested in two ways. We examined whether household comfort preferences and socioeconomic characteristics influence both the features of their home (in this case the energy-efficiency level of the dwelling chosen by the household at the time of purchase or rental), and the amount of final energy they consume. Our research is based on the French PHEBUS[77] survey conducted in 2012, which includes complete thermal data, Energy Efficiency Certificates (energy-efficiency classifications), and socioeconomic characteristics for more than 2000 dwellings, as well as newly available information about household behavior and stated preferences.

[77] Performance de l'Habitat, Équipements, Besoins et USages de l'énergie (Phébus) http://www.statistiques.developpement-durable.gouv.fr/sources-methodes/enquete-nomenclature/1541/0/enquete-performance-lhabitat-equipements-besoins-usages.html

This paper thus contributes to the broader literature on the determinants of energy consumption by providing an original analytical framework, thanks to the use of an innovative dataset. A key result is evidence of the existence of several energy consumption patterns in the residential sector that manifest themselves through energy-related preferences and economic characteristics of households. Then, we provide evidence that individual energy use preferences are a significant driver of energy consumption for high-income households, both directly and indirectly. Our main results show that preferring comfort over economy for two or three types of energy use implies energy overconsumption of 10% on average. If we consider the subpopulation of households belonging to the three highest income deciles, surplus energy consumption from high and medium preferences for comfort lies between 18.1% and 21.8%. For low-income households, we find no significant effect of preferences but a lower energy price elasticity.

Our study differentiates energy consumption patterns by income level, and contributes to the integration of behavioral inputs in modeling exercises, which should be of interest to policymakers. Accordingly, we suggest that policymakers consider low-income and high-income households separately when developing and implementing policies to reduce energy consumption in the residential sector. This is particularly important for reducing potential inequalities and bias. Finally, through our methodology we confirm the necessity of accounting for indirect determinants when assessing the drivers of energy demand in the residential sector.

The paper is organized as follows. Section 2 presents the literature review. Section 3 describes the model. The data and the results are presented in section 4 and 5 respectively. Section 6 concludes with policy recommendations.

2.Literature review

The final energy consumption of a dwelling is explained by three main determinants: technical building characteristics including the local environment, household characteristics (socioeconomic characteristics, individual preferences, income, etc.), and the price of energy. The literature review also calls attention to the dearth of studies focusing on the share of energy consumption attributed to individual heterogeneity with regard to energy consumption preferences.

Household characteristics

The impact of socio-demographic characteristics on energy consumption has been demonstrated in the literature. Concerning occupancy status, contrary to the theory that posits that tenants are likely to consume more energy than owners (misaligned incentives), empirical research fails to find a consensus on the effect of tenure status on energy consumption (Belaïd 2016; Charlier 2015; Jones et al. 2015; Yohanis 2012). Family structure and its position in the life cycle, however, does have an impact on energy demand. The number of occupants has a positive impact on energy consumption (Leahy and Lyons 2010; Vaage 2000), and there is a cyclical effect based on the age of the reference person: energy consumption is comparatively higher for dwellings whose occupants are between 45 and 65 than for other age classes (Belaïd 2016; Brounen and Kok 2011; Brounen et al. 2013).

Regarding income elasticity (see Table 1), the effect is positive in most studies, which is consistent with the "normal good status" of energy consumption: income elasticity often lies between 0.01 and 0.15. This frequent low income elasticity is often attributed to the correlation between income and other characteristics such those of the home (Alberini et al. 2011) and occupancy status. However, the effect of household income is sometimes more complex. Although low income households use less energy, they have a relatively smaller opportunity to change their appliances and heating and cooling systems. Positive elasticity may mainly involve the purchase of more energy-efficient appliances, which will induce lower energy consumption (Cayla et al. 2011; Labandeira et al. 2006; Nesbakken 2001; Santamouris et al. 2007). Income elasticity may also depend on income level: in 2013, Meier et al. (2013) investigated the relationship between household income and expenditures on energy services in the United Kingdom. A key finding of their study was that the income elasticity of electricity and gas demand is contingent on household income. Households with low-income exhibit a rather low-income elasticity of energy demand (about 0.2). Households at the top end of the income distribution exhibit an income elasticity of up to about 0.6. Finally, in the recent work of Hache et al. (2017), the authors demonstrated with a non-linear approach (CHAID clustering method) that income level and global energy expenditures were intimately related in the French residential sector.

Technical building characteristics and environment

Technical building characteristics and environment can account for more than half of the energy consumption variability in the residential sector. Indeed, much attention has been paid to the

impact of the technical properties of housing (insulation, year of construction, building materials, design of the building) on energy consumption. The size effect is positive if we look at its influence on total consumption but is negative if we consider consumption per square meter ("returns to scale effect"). Some estimates indicate that up to 57% of total heating energy consumption can be due to the size effect (Baker and Rylatt, 2008; Estiri, 2015; Harold et al., 2015b; Risch and Salmon, 2011). Newer buildings tend to consume less energy, and housing type is an important variable (Nesbakken 2001; Santin 2011; Vaage 2000). Apartments generally consume less than single-family homes because of their smaller heat loss surface (Rehdanz 2007; Vaage 2000; Wyatt 2013). The influence of a dwelling's construction date on energy consumption (electricity excluded) is not universal, but older buildings generally consume more energy than newer ones (Rehdanz, 2007; Risch and Salmon, 2011; Vaage, 2000). Dwelling insulation (attic or cavity walls or global insulation) reduces energy consumption from -10% to -17% (Brounen et al., 2012; Hong et al., 2006). Finally, local climate also has an impact: in western countries, the longer the heating period is, the more energy a dwelling consumes (Kaza 2010; Belaïd 2017; (Mansur et al. 2008).

Individual preferences regarding energy use

Individual energy use preferences refer here to the intrinsic disposition of individuals to save energy in their everyday life (Lopes and al. 2012); we do not include individual preferences that are manifested in one-time actions such as the purchase of energy-efficient appliances. Depending on their nature, individual preferences can induce a wide range of everyday behaviors, from energy-saving behavior (energy conservation, restriction) to energy-intensive behavior. The tendency of households to save energy in the residential sector is a multi-dimensional phenomenon resulting from a trade-off between diverging motivations; it is positively linked with environmental awareness and normative concerns or economic motivation and negatively affected by immediate welfare considerations (Lindenberg and Steg 2007). The work of Hamilton et al. (2013) demonstrates that energy consumption may differ greatly (by up to three times) among dwellings with similar technical characteristics. Thus, assessing the extent of the effect of individual preferences is a crucial step in better understanding the impact of individual heterogeneity on real energy consumption variability. However, individual preferences have generally been neglected in the economics literature (Lopes et al. 2012) in particular because of the lack of appropriate data. Assessing the effect of

individual energy use preferences on energy consumption variability is complex, and the estimate greatly depends on the indicator used and the scope considered.

Some researchers have approached the issue of preference heterogeneity in energy use by studying the relationship between the effective intensities of energy use for several energy services (e.g. observed energy behaviors such as heating temperature, the running time of appliances, the frequency of use of some energy services, etc.), household and dwelling characteristics, and energy consumption (Belaïd and Garcia 2016; Santin 2011; Yun and Steemers 2011). Santin (2011) found that the number of hours of heating at maximal temperature explains 10.3% of the variability in heating energy consumption. However, in many cases, researchers model energy savings behavior as an end in itself and not as a proxy for individual heterogeneity able to explain energy consumption variability. The major results of these studies show that energy savings actions are context-dependent (Belaïd and Garcia 2016; Lopes et al. 2012): living in an energy inefficient dwelling and facing higher energy prices induce more energy-efficient behavior.

Moreover, in the specific case where a household implements energy retrofits to improve the energy efficiency of its housing, the observed savings are sometimes significantly below what can be expected on engineering grounds. Several assumptions can be made to explain this gap. First, measurement errors can occur such as uncertainties in the calculation method used by engineers to assess theoretical energy consumption (Allibe 2012; Galvin and Sunikka-Blank 2013, 2014). Second, another conclusion is that there is a strong behavioral bias. Martinaitis et al. (2015) conducted five different studies to highlight that buildings did not perform as predicted, even when the energy simulation was very accurate. They concluded that human behavior and occupant preferences were important contributors to the gap between the predicted and actual building energy performance. Indeed, a household's demand for an energy service (or preferences) can evolve over time: this dynamic phenomenon, called *direct rebound effect,* is well-known in economics literature and research on this topic is widely available. In the residential sector, it is characterized by the increase in thermal comfort after improvement of the energy efficiency of a dwelling. When it occurs, a share of the energy savings potential expected by the implementation of energy retrofits is lost due to behavioral change (Aydin et al., 2017; Sun, 2018). Direct rebound effect for heating could reach 60% (Sorrell 2009). Finally, the energy savings potential induced by a change in energy related behavior, attitudes or preferences has also been addressed in field experiment studies.

Some small-sample studies on the effect of energy-saving information on energy consumption found that more informative bills and advice about reasonable energy use results in a 10-percent energy savings for electricity (Ouyang and Hokao, 2009; Wilhite and Ling, 1995). Lopes et al. (Lopes et al., 2012), found that the savings potential from a change in energy-saving behavior ranges from 1.1% to over 29%.

Energy prices

Price elasticity is always found to be negative, but estimates vary widely from -0.20 to -1.6. Energy price elasticities from the literature are listed below. However, it is important to emphasize that the price elasticity of energy demand may depend on the energy considered, the methodology, etc. In their 2017 meta-study Labandeira et al. (2017) gathered the energy price elasticities results of 428 papers (multi-sector, multi-level, multi-energy sources, multi-country) produced between 1990 and 2016. They showed that the estimates could vary according to the sector, methodology used, level of aggregation of data, nature of the energy source considered, evaluation method, country, etc. For example, their findings provided evidence that micro-level studies tend to find higher price elasticity expressed in absolute values than research based on aggregate models.

Energy price elasticity is also found to be related to income level. For the residential sector in micro-based studies, findings are not unanimous on this issue. For instance, disaggregation of households by expenditure and socioeconomic composition reveals that behavioral response to energy price changes is weaker (stronger) for low-income (top-income) households (Schulte and Heindl 2017a). However, Alberini et al. (2011) found that the price elasticity of electricity demand declines with income, but that the magnitude of this effect is small.

Table 1: Income and price elasticities in the literature

Authors	Country	Level of analysis	Price elasticity	Income elasticity
Parti and Parti (1980)	US	San Diego county	Electricity: -0.58	0.15
Dubin and McFadden (1984)	US	Household	Electricity: -0.26	0.02
Baker et al. (1989a)	UK	Household	Electricity: -0.758 Gas: -0.311	-
Bernard et al. (1996)	Canada	Household	Electricity short-run: - 0.67	0.14
Nesbakken (1999)	Norway	Household	All energy types: -0.50	0.01
Vaage (2000)	Norway	Household	Heating energy: -1.24	
Nesbakken (2001)	Norway	Household	All energy types: -0.21	006
Halvorsen and Larsen (2001)	Norway	Household	Short-run: -0.43	---
Labandeira et al. (2006)	Spain	Household	Electricity: -0.79 Gas: -0.04	
Rehdanz (2007)	Germany	Household	Oil: [-2.03; -1.68] Gas: [-0.63; -0.44]	
Meier and Rehdanz (2010)	Germany	Household	Oil: -0.4 Gas: [-0.34; -0.36]	
Alberini and Filippini (2011)	US	State level data	Electricity: [− 0.860; − 0.667] Gas: [− 0.693; − 0.566]	0.02
Bernard et al. (2011)	Canada	Household	Electricity short-run: [- 0.51]	0.08
Fan and Hyndman (2011)	South Australia	State level data	Electricity: [-0.36; -0.43]	
Brounen et al. (2012)	Germany	Household	Electricity: -0.4310 and Space heating: -0.5008	
Meier et al. (2013)	UK	Household	Electricity price on energy spending: 0.7360	[0.2; 0.6]
Filippini et al. (2014)	EU	EU member countries	All energy types: [-0.26; -0.19]	
Krishnamurthy and Kriström (2015)	11 OECD countries	EU member countries	Electricity: [−0.16; -1.4] France: −0.6523	[0.07; 0.108]
Miller and Alberini (2016)	US	Household	All energy types: [-0.56; -0.76]	

Risch and Salmon (2017)	France	Household	All energy types: -0.485	0.0295
Schulte and Heindl (2017a)	Germany	Household	Electricity: -0.4310 and Space heating: -0.5008	
Campbell (2017)	Jamaica	Sectorial	-0.42	0.42
Damette et al. (2018)	France	Household	Wood [-1.553;-2.394] Electricity: -1.33 Gas: -1.22	[0.0294;0.0443]

3. Data and descriptive statistics

3.1 Data

This research uses data from the PHEBUS survey, a national household energy survey conducted by the Department of Observations and Statistics (SOeS), a subdivision of the French Ministry of Ecology and Sustainable Development. The survey includes 2,040 observations including individual dwelling energy audits performed by the same company in 2012 to study theoretical energy-efficiency measures, real energy consumption (based on energy bills), and reported social, economic, and behavioral data of dwelling occupants. The survey provides cross-sectional annual data (2012) and is representative of the French dwelling stock according to regions, climate zones, dwelling types and building construction dates. The survey was conducted using face-to-face interviews.

Energy performance certificates and building characteristics

Data sets available through this survey are quite innovative as they provide uniform assessments of Energy Performance Certificates (EPC) for each dwelling. These certificates have been produced by a single organization, which reduces any potential subjective bias in performance assessment. In our database, housing energy efficiency is classified into seven energy categories (according to French legislation): A, B, C, D, E, F, G (from the most energy efficient to the least, see Figure 6 in appendix C.2). In accordance with the literature review, we also introduced the following control variables: housing type, construction period, surface area, the location and climate zone.

Real energy consumption

Information on real energy consumption for each dwelling was also available in the PHEBUS survey. For each source of energy consumed at household level, the quantity of energy was assessed from 2012 energy invoices and expressed in kilowatt hours. Sources of energy used in French dwellings include electricity (31%[78]), gas (40%), domestic fuel (16%), wood (3.5%), urban heating (5%), etc.

Household characteristics, preferences, and length of tenure

We used income, number of persons, length of occupancy, the number of days of housing vacancy during the heating period, and the number of appliances belonging to each household to control for household characteristics. Information on household stated preferences is available from the PHEBUS survey. Households were asked the following question: "When it comes to indoor heating, do you prefer …?". This question was asked after gathering information about energy-saving behavior.

For each type of end use (heating, hot water, and electricity), a binary variable makes it possible to know whether households favor comfort or energy savings. People can choose to have comfort preferences for one end use and energy saving preferences for another. It is therefore possible to have a scale of preferences. A strong preference for comfort will be measured as a declared preference for each end use, a medium preference as a declared preference for two out of three end uses, and finally a low preference as a single declared preference for comfort. To establish the consistency between stated preferences and energy-saving behavior, we provide Table 2 below.

[78] The percentage corresponds to the share of households that consume this source of energy as main source of heating energy. Source: Phebus 2012

Table 2: Households' stated preferences

	Preference for...[1]	
Heating end use	**Comfort**	**Saving energy**
Last winter, were you in the habit of regularly lowering the temperature or turning off the heating in the bedrooms …		
During daylight	0.28	0.35
At night	0.46	0.52
During the last heating period, when your dwelling was unoccupied, did you …turn off the heat?		
Yes	0.36	0.43
When you open the window to ventilate a room, do you turn down or off the heating of the room?		
Always	0 .37	0.45
Most of the time	0.43	0.50
Do you limit your heating consumption?		
Yes	0.10	0.42
Electricity end use	**Comfort**	**Saving energy**
Number of appliances	16.93	15.49
Hot Water end use	**Comfort**	**Saving energy**
Number of showers (per cu[2])	7.57	7.14
Number of baths (per cu)	0.61	0.47

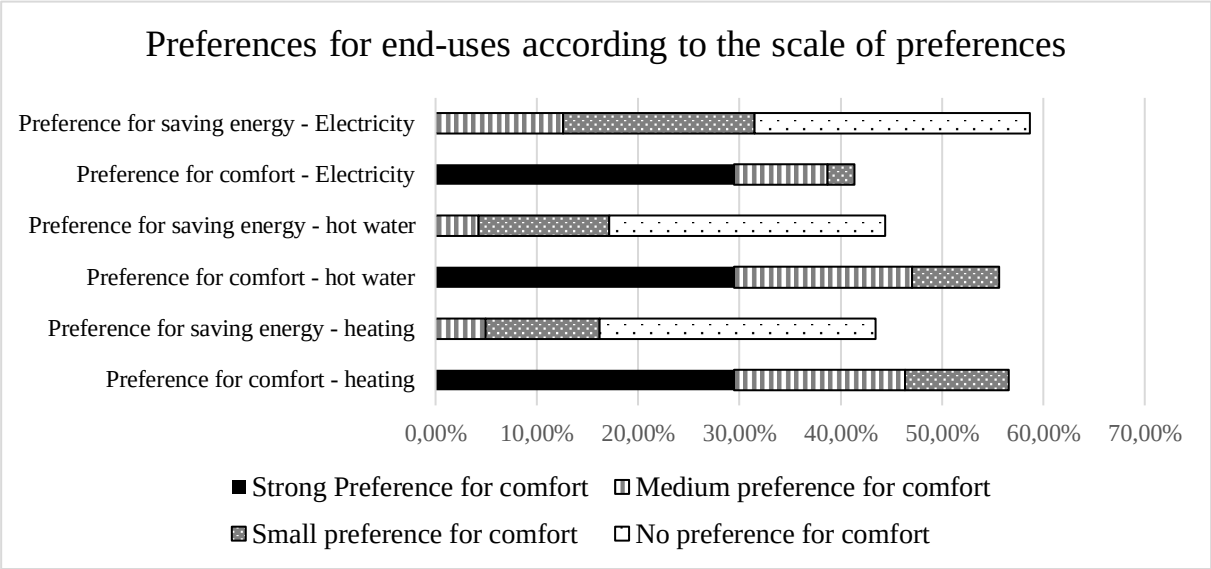
[1]The null hypothesis of equality of proportions cannot be rejected at the 90% confidence level. All the rest of the proportions are statistically different at the 90% confidence level or more.

[2]Index for the number of persons

Note for the reader: This table assesses the consistency between stated behaviors and stated preferences of respondents regarding energy use. Numbers correspond either to proportions of respondents in each category, either to counting numbers (number of baths, of appliances, etc.). For instance, respondents that declared preferring saving energy over comfort are more likely to behave in a more energy saving way regarding the three energy uses: there is a higher share of respondents preferring energy saving over comfort in the category of people that turn down/off the heat when they open the window, this people take a lower number of showers in a week (7.14<7.57) and own a lower number of appliances (15.49 < 16.93).

We also compared the preferences for each end use according to our scale (see Figure 1 below). Unsurprisingly, it is not possible to have a strong preference for comfort and a preference for saving energy. For households who have a low preference for comfort, their preference for comfort is mainly for thermal comfort.

Figure 1: Preferences for end uses according to the scale of preferences



Note for the reader: Respondents that declared preferring comfort over energy saving for only one of the three energy uses (small preference for comfort) favour heating use first, then hot water use in second position. Respondents that declared preferring comfort over energy saving for two energy uses (medium preference for comfort) are more likely to favour heating and hot water uses than specific electricity use.

We do not have 100% if we consider each bar separately but if we consider the sum of the answers of the two categories "preference for saving energy" and "preference for comfort" for the same energy use, the result is 100%. Indeed, for each energy use, each respondent had to choose between preferring saving energy or comfort.

Finally, when people want to save energy, it is mostly for electricity. For example, among households who have medium preferences for comfort, 12.6% want to save electricity compared to only 4.26% for hot water and 4.95% for heating. Moreover, other variables can also be used as a proxy for comfort, for example, the heating temperature (Charlier and Legendre 2017). SOFRES-ADEME (2009) revealed that an additional one degree Celsius implies an overconsumption of 7.8%.

Energy prices

Unfortunately, the PHEBUS database does not provide energy price information directly. Other information can help determine the energy cost for each household to fill this gap. Indeed, the PHEBUS data set provides information on the type and amount of energy consumed by each dwelling according to each type of fuel, but also on the type of contract (for gas and electricity) and the power required per type of fuel used in kVA (electricity, gas, oil). The power required

depends on the type of fuel used for the heating system (i.e. the energy mix) as well as the number of rooms (or the surface area) and the number of appliances. For instance, the power required for electricity is not the same if the heating system is electric or uses another energy source. Thus, it is possible to have different energy power per energy-mix composition and the end use of each type of energy among households. Moreover, for gas and electricity, households can choose the type of contract they want (an energy market supplier or not). Finally, the PHEBUS data set also provides information on the quantity consumed in peak hours and in off-peak hours.

The only information which is not provided is the energy cost itself. To complete the PHEBUS data set, we looked at the PEGASE database (provided by the French Ministry of Energy, see Appendix A, Table 6) to obtain the energy and subscription cost for each type of energy (oil, gas, electricity, and wood) per the amount of power required and the type of contract in 2011 and 2012. Thus, we have information about the price of energy which corresponds to (i) the amount of power required, (ii) the type of fuel, (iii) energy cost in off-peak and peak hours and (iv) the type of contract. We were thus able to fill the gap in the PHEBUS database (see Figure 5 which sums up the methodology in the appendix). Finally, it is possible to calculate a weighted energy cost for each household based on the energy mix and the structure of energy consumption, notably the number of kilowatt hours consumed in off-peak and peak hours. Thus, with a weighted energy cost, we have a specific cost of energy for each household. The equation is as follows:

$$energy\ price_i = \sum_{i=1}^{n} \frac{volume\ in\ kwh_{ift} \times energy\ price_{ft}}{total\ volume\ in\ kwh_i} \quad (1)$$

where f represents the type of fuel, i the household, and t the type of rate for a specific energy (electricity or gas).

3.2 Descriptive statistics

The main descriptive statistics of the variables used in the model are summarized in Appendix C1 (Table 7). Based on these observations, we noted several trends in our data. The average income, surface area, occupancy status, etc. seem to be linked in some way with the energy class of each dwelling, which supports the underlying assumption of our model: the potential

interaction between home thermal characteristics and household characteristics (Table 3). This is consistent with the contribution of Santamouris et al. (2007). We also observed interactions between preferences, income level, and consumption (Figure 2, Figure 3, Figure 4, Table 4 and Table 8a in the appendix). Finally, to complete the descriptive analysis, we ran *t*-tests based on the preference variable, available in the appendix in Table 8b. We found that households with high comfort preferences live in dwellings that are statistically more energy efficient. This observation seems consistent with the rebound effect that describes the fact that a cheaper energy cost (due to increased energy efficiency) involves a greater demand for this very same service. Here, the greater demand would mean preferring comfort over saving energy for a specific energy use. Other *t*-tests confirm the highly significant relationship ($p<0.01$) between energy consumption, a strong preference for comfort, and income. The overall descriptive statistics argue in favor of the real need to properly control for thermal, economic, and individual characteristics when modeling energy demand in the residential sector.

Table 3: Descriptive statistics by dwelling energy efficiency classification

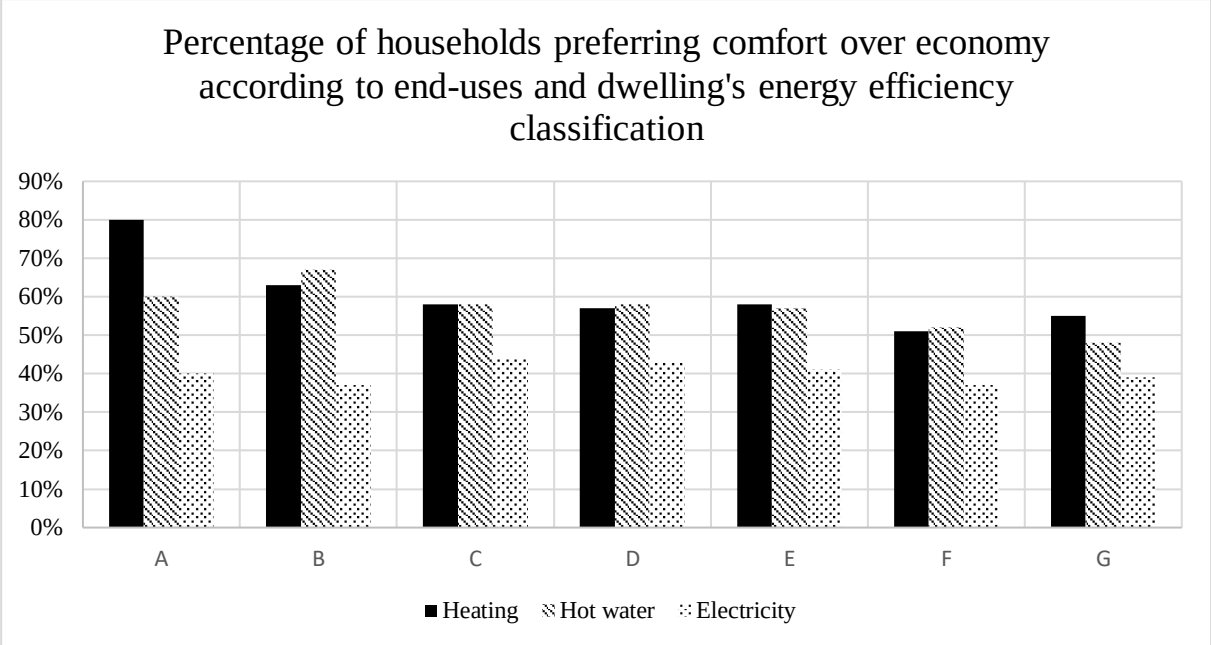
Energy class*	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Number of observations	***5***	***43***	***281***	***564***	***598***	***301***	***248***
Average annual disposable income per household	51068	50099	46097	43970	38632	37877	31201
	(22293)	(39645)	(28396)	(25085)	(20893)	(25569)	(18808)
Average number of occupants	3.2	2.9	2.9	2.7	2.5	2.3	2.2
	(1.6)	(1.2)	(1.2)	(1.3)	(1.2)	(1.1)	(1.1)
Percentage of individual houses (%)	100	84	79	78	84	81	74
Percentage of renter-occupied dwellings (%)	0	16	18	19	21	25	35
Mean surface area (m^2)	172	151	127.7	118.7.	110	97.5	90.5
	(63.3)	(92.2)	(49.7)	(45.7)	(47.1)	(40.6)	(44.0)
Number of years spent in the current dwelling	10.4	10.3	13.1	15.7	18.5	19.5	20.7
	(5.8)	(9.7)	(11.0)	(12.8)	(15.3)	(16.0)	(19.9)
Average number of appliances	19.8	22.2	17	16.7	16.6	14.7	12.7
	(5.4)	(22.5)	(11.3)	(10.1)	(18.4)	(11.5)	(5.9)

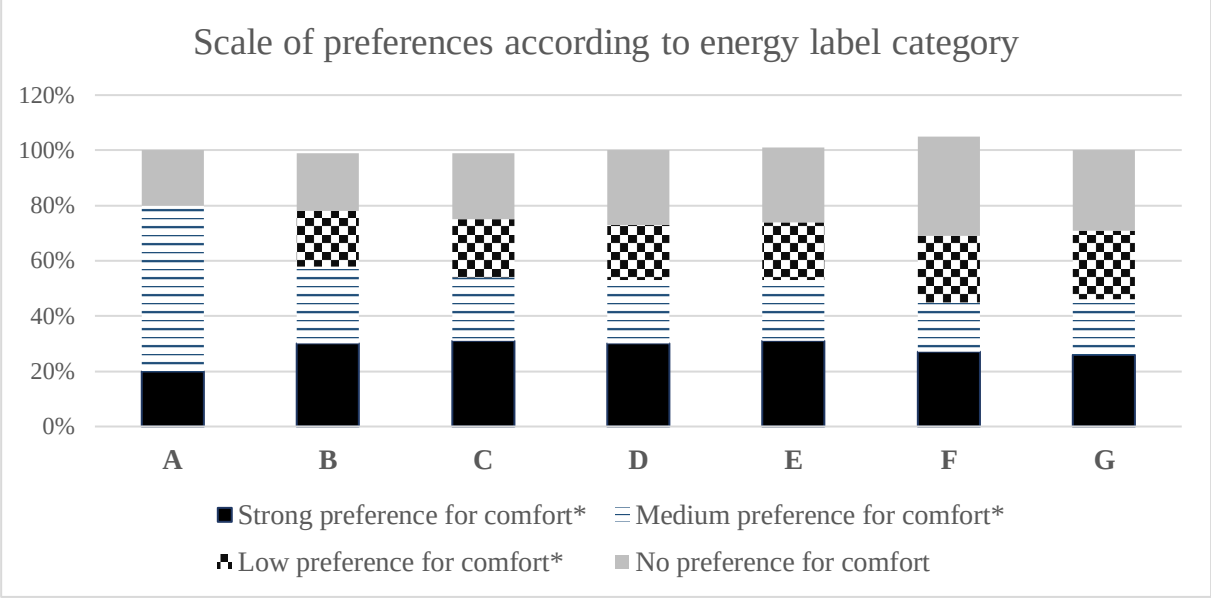
Source: PHEBUS Survey 2012, authors' calculations. () corresponds to standard deviation

*Housing energy classes are defined in Appendix C (see Figure 6 in appendix C.2). *Energy Performance Certificates (EPCs) are a rating scheme to summarize the energy efficiency of dwellings. Information about energy efficiency is given as: a numerical value of the energy performance of the dwelling (theoretical energy consumption expressed in kilowatt-hours per square meter) calculated with an engineering model from observed technical characteristics*

a ranking into categories of energy performance based on the previous numerical value. Seven categories are defined from G (low energy efficiency) to A (high energy efficiency)

Figure 2: Preferences and dwelling energy efficiency classification



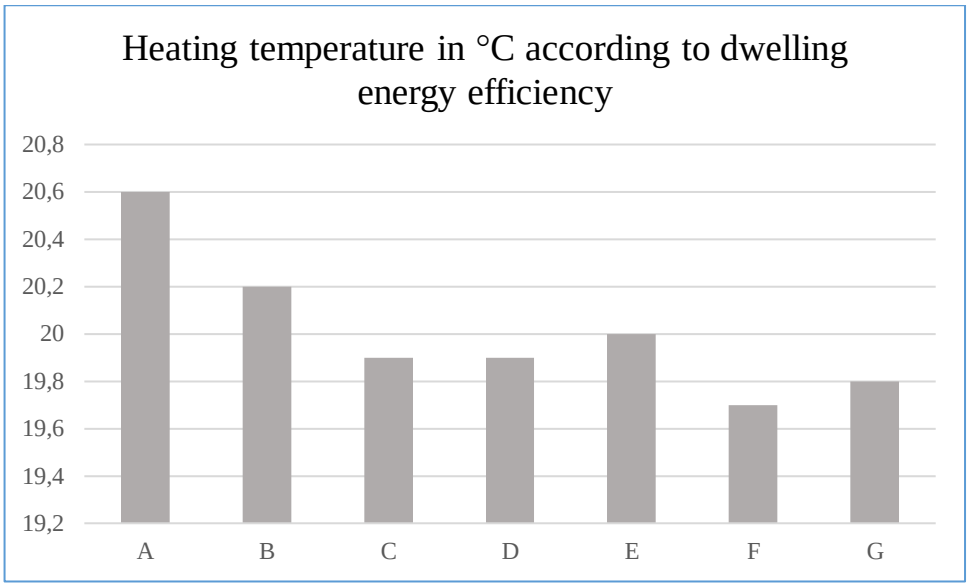


Source: PHEBUS Survey 2012, authors' calculations.

The scale of preferences is compounded from PHEBUS data: strong preference for comfort means that a household declared that it prefers comfort over economy for all three energy uses:, electricity, heating, and hot water; a medium preference means that this preference for comfort concerns two of the three energy uses; and finally, a low preference means that the preferences for comfort concerns only one energy use. Energy efficiency classification are defined in Figure 6, appendix C.2.

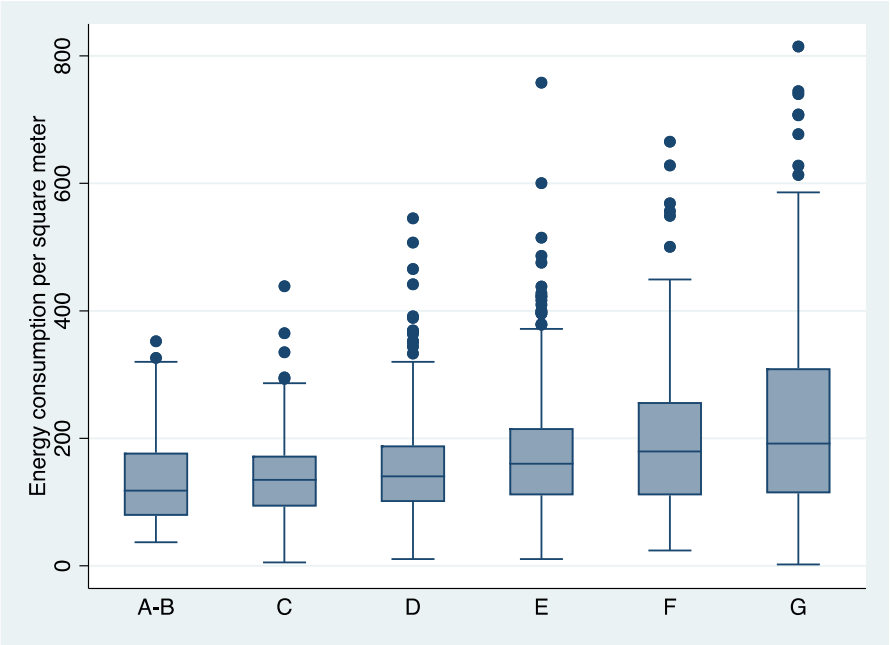
Note for the reader: This graph shows that the percentage of respondent preferring comfort over energy savings for all or two of the energy uses (strong preference for comfort and medium preference for comfort) is increasing when we move to the left, e.g when the dwelling is more energy efficient. Thus, energy efficiency of the dwelling is associated with more frequent preference for comfort, which can be an indirect evidence of rebound effect in energy efficient dwellings. This is also an evidence of restriction behavior regarding energy consumption in low energy efficient dwellings.

Figure 3: Heating temperature in °C and dwelling energy efficiency



Source: PHEBUS Survey 2012, authors' calculations

Figure 4: Energy consumption according to dwelling energy efficiency



Source: PHEBUS Survey 2012, authors' calculations

Table 4: Descriptive statistics between preferences and income decile

	Energy consumption in kwh/m²		Strong preference for comfort		No preference for comfort		Preference for comfort for heating		Preference for comfort for electricity		Preference for comfort for hot water	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
D1*	308.3	171.8	27.47%	44.75%	41.76%	49.44%	42.10%	49.49%	37.57%	48.55%	47.63%	50.07%
D2	309.8	206.4	17.77%	38.32%	30.78%	46.27%	45.88%	49.95%	30.66%	46.22%	50.66%	50.12%
D3	263.0	166.1	29.21%	45.59%	32.83%	47.07%	52.50%	50.06%	37.60%	48.56%	52.40%	50.06%
D4	260.9	140.9	26.70%	44.35%	28.89%	45.44%	53.33%	50.01%	36.19%	48.17%	56.12%	49.75%
D5	264.8	134.5	31.58%	46.60%	27.06%	44.53%	58.70%	49.36%	42.27%	49.52%	53.91%	49.97%
D6	248.7	115.8	27.19%	44.60%	33.22%	47.22%	54.25%	49.94%	33.13%	47.18%	57.27%	49.59%
D7	253.3	132.3	36.13%	48.16%	19.41%	39.65%	62.64%	48.49%	50.54%	50.12%	63.32%	48.31%
D8	241.5	112.4	32.46%	46.94%	18.59%	39.00%	66.07%	47.46%	47.56%	50.06%	60.02%	49.11%
D9	235.7	128.3	33.56%	47.34%	18.73%	39.11%	62.10%	48.63%	51.63%	50.10%	61.16%	48.86%
D10	229.08	115.30	38.78%	48.84%	18.77%	39.15%	61.43%	48.79%	54.85%	49.89%	66.74%	47.23%

Source: PHEBUS Survey 2012, authors' calculations

*Income is defined by deciles: D1 (decile 1) to D10 (decile 10)

4. Model

4.1 Theoretical background

For several decades, the framework of conditional demand analysis that employs the two-step discrete-continuous model initiated by Dubin and McFadden (1984) has been used to account for the role of preferences or behavior when modeling energy consumption. More recently, new approaches such as covariance structure analysis or structural equation modeling approach have also been used to integrate indirect determinants of energy consumption. In using these approaches, researchers assume the existence of implicit choices and preferences in terms of home characteristics or energy appliances and their effects on energy consumption. In using discrete-continuous models, researchers also assume that appliance or thermal equipment choices and consumption choice are bound (Dubin and McFadden 1984; Risch and Salmon 2017; Vaage 2000) and use these models to address selectivity biases in data sets with endogenously partitioned observational units (Frondel et al. 2016). These models are thus often used in the field of energy consumption due to the interactions and endogeneity between independent explanatory variables. Models using the discrete-continuous framework assume that household characteristics could play a twofold role in explaining energy consumption: first, they influence the choice of home characteristics or appliances (indirect effect on energy consumption); second, once the appliances or home characteristics are considered, they also have a direct influence, all things being equal. Kriström (2006) explained that households do not demand energy *per se*, but demand is combined with other goods such as “capital goods” (housing units, equipment units). Empirical evidence using the discrete-continuous framework has confirmed this assumption: for example, Baker et al. (1989b) applied a two-stage model of energy demand to British expenditure data. Durable good appliances are first modeled, which then determines the energy demand of households. Vaage (2000) and Nesbakken (2001) demonstrated that analyzing energy demand conditionally to appliance or heating system choice is relevant in the residential sector. In the case of France, Stolyarova et al. (2015) modeled two discrete choices: the choice of end-use combinations by energy source or the choice of heating system by dwelling type.

Recently, researchers have demonstrated further interest in addressing the issue of interactions. Ewing and Rong (2008) showed that higher-income households are more likely to live in big

homes that consume more energy. Estiri (2015) called attention to the major interactions between building characteristics and lifecycle and socioeconomic household characteristics and quantified the direct and indirect roles of each in energy consumption with a covariance structure analysis. He reached the conclusion that the main effects of socioeconomic and lifecycle characteristics are observed via building characteristics (expressed with a latent variable that includes surface area, number of rooms, and tenure status). Using a general linear model and a path analysis, Yun and Steemers (2011) investigated the significance of behavioral (the proxy used is frequency of AC use), physical, and socioeconomic characteristics on cooling energy consumption. The findings suggest that such factors exert a significant indirect as well as direct influence on energy use, supporting the necessity of understanding indirect relationships. In the same vein, Belaïd (2017) used a structural equation modeling approach (PLS approach) on French data to elicit the indirect role of household characteristics on building characteristics in order to explain residential energy consumption. His results are consistent with housing consumption theories that socioeconomic household characteristics play an important role in determining the physical attributes of a dwelling. Finally, the importance of accounting for interactions between a dwelling's physical attributes and household characteristics is also supported by the findings of Santamouris et al. (2007) in the UK: their work demonstrates that income explains the presence of several dwelling characteristics, including insulation building envelopes and building age.

Based on the existing literature, the main assumption of this research is that individual preference for comfort has a significant positive impact on energy consumption. We assume that the household's decision is divided into two parts. In the first, the household decides to live in a housing unit according to its theoretical energy performance; then, in the second, it decides how much energy to consume according to its preferences.

To test this assumption, we used a discrete-continuous choice model framework to take into account the assumed interactions between household characteristics and the dwelling's energy-efficiency level, using a conditional mixed process. The specification of household fuel demand is based on a utility model with R* the stochastic indirect utility function of the households, which we assume to be unobserved. Indirect utility V depends on the price of energy P, income Y, household characteristics (including preferences) Z and building characteristics (including locality) W and is defined conditionally on the choice of energy label classification. Therefore:

$$R_{ij}^{*} = V_{ij}[P_i, Y_i, Z_i, W_i] + v_{ij} \quad (2)$$

where j=1, ..., J is the index of category, i=1, ..., N that of the individuals, and v_{ij} the error term. The Roy's identity gives us the household's Marshallian demand function for energy:

$$X_{ij}(P_j, Y_i, Z_i, W_i) = \frac{\partial V_{ij}(P_j, Y_i, Z_i, W_i)/\partial P_j}{\partial V_{ij}(P_j, Y_i, Z_i, W_i)/\partial Y_i} \quad (3)$$

When simplified, the energy demand function conditional on energy category *j* by household *i* can be written as follows:

$$q_{ij} = \gamma_{ij} z_{ij} + \nu_{ij} w_{ij} + \beta_{ij} P_{2012i} + \eta_{ij} \quad (4)$$

where q_{ij} is the quantity of energy consumed by household *i* in an energy classification *j*, z_{ij} is a vector of household characteristics (including preferences, income, and mode of occupation), P_{2012i} is the energy price, w_{ij} is a vector of building characteristics (including locality), γ_{ij} and ν_{ij} are vectors of the related parameters, and η_{ij} the error term taking into account the influence of unobservable parameters.

4.2 The econometric methodology: a discrete-continuous choice

In our research, an original data set was used to apply this discrete-continuous choice method as we faced two potential problems of endogeneity related to the choice of the dwelling's thermal performance (energy classifications, see Figure 6 in Appendix C.2) and endogeneity due to energy prices (proof in Appendix D.1). As a choice variable for the discrete choice, we used the theoretical energy performance of the dwelling by energy-efficiency classification. This classification, from an EPC assessment, was chosen as a proxy for the theoretical energy-efficiency level of the dwelling. Thus, we studied which characteristics determine a household's probability of belonging to an energy-efficient classification level with an ordered probit. Energy classifications have also been introduced in the continuous choice as explanatory variable; this enables us to capture interactions between energy efficiency and households while identifying direct drivers of energy consumption.

Thus, for the discrete choice of the model, we use an ordered probit because energy performance classifications arise sequentially (Cameron and Trivadi 2010). For individual *i*, we specify:

$$y_i^* = x_i'\beta + u_i$$
(5)

with y^*a latent variable which is an unobserved measure of the dwelling's energy performance; x the regressors. For low y^*, energy performance is very high; for $y^* > \alpha_1$ corresponding to the energy classification threshold A-B to C, energy performance is somewhat lower; for $y^* > \alpha_2$ corresponding to the change from C to D, energy efficiency is even lower, etc. For an m-alternative ordered model (here $m = 6$ because of the 6 energy classifications we consider), we define:

$$y_i = j \quad if \;\; \alpha_{j-1} < y_i^* \leq \alpha_j, \qquad j = 1, \ldots, m$$
$$\Pr(y_i = j) = \Pr(\alpha_{j-1} < y_i^* \leq \alpha_j)$$

The regression parameters β and the m-1 threshold parameters $\alpha_1, \ldots, \alpha_{m-1}$ are obtained by maximizing the log likelihood with $p_{ij} = \Pr(y_i = j)$. Energy classes are also introduced in the second equation and used as regressors of final energy consumption expressed in kW/m^2/year with other explanatory variables. The model captures the possibility of correlation between unobservable variables in the discrete and continuous stages.

Conditional on the discrete choice, a household decides on the quantity of energy to consume. Therefore, in the continuous choice, the total energy consumption (the logarithm of the energy consumption in kWh/m ^{2}) is estimated, conditional on the dwelling's thermal performance (energy-efficiency classification) and a set of explanatory variables (energy price, income, individual preferences, housing characteristics, etc). This is the "energy consumption choice," which we estimate using a least-square model.

On the other hand, , we suspect a risk of endogeneity of the energy price variable in 2012 (P_{2012i}) in the continuous choice due to simultaneity. Simultaneity arises when at least one of the independent variables is jointly determined by the dependant variable. Here we suspect silmutaneity between the quantity of energy consumed by housings (q_{ij}) and the price of energy (P_{2012i}). To correct for this potential endogeneity, we implement an instrumental regression (IV) by introducing as instruments the lag of energy prices (P_{2011i}) that is assumed to not be correlated with the error term ε_i (cause lagged values are less likely to be influenced by current shocks), and the type of energy rate for electricity $(TARIFF_i)$, that accounts for the type of contract choosen for electricity and determines if the energy price is a market or

regulated price. According to Robert (2015), estimation strategies using IV are effective when lagged values of the endogenous explanatory variable are used as instruments if the instruments (i) did not appear as explanatory variables in the structural equation and (ii) are well correlated with the simultaneously-determined dependent variable. So, the choice of contract made when the household decides to move in cannot be directly influenced by consumption in the year considered. Finally, some studies which analyze energy consumption using energy prices adopt the same methodology (Risch and Salmon 2017).

We therefore have:

$$q_{ij} = \gamma_{ij} z_{ij} + \nu_{ij} w_{ij} + \beta_i P_{2012_i} + \varepsilon_i \quad (6)$$

with

$$P_{2012_i} = \alpha_1 P_{2011_i} + \alpha_2 TARIFF_i + \nu_{i,k} \quad (7)$$

where q_{ij} is the final energy per square meter consumed and z_{ij} and w_{ij} the regressors. We estimate the model using a double least-squares model, which enables us to correct for the endogeneity issue of energy prices.

Finally, we have a system composed of a three-simultaneous-equations model (5) (6) and (7). The model contains variables which are assumed to explain both choices: the choice of a dwelling with a certain energy-efficiency level and the choice of energy use. However, some exclusion (or selection) variables have also been introduced in each equation: the duration since move-in and detached house for equation 1 (discrete choice) and the number of appliances and number of days of housing vacancy during the heating period for equation 2 (continuous choice).

4.3 The estimation process

In order to estimate our three equations simultaneously, we have used the conditional mixed process (CMP) proposed by Roodman (2011). A CMP framework can be required to jointly estimate three equations with linkages among their error processes. The CMP also allows relationships among their dependent variables. This process fits a large family of multi-equation, multi-level, conditional mixed-process estimators and is particularly useful in the simultaneous equation framework with endogenous variables (as is the case here), or in a

seemingly unrelated regressions (SUR)[79] configuration, where dependent variables are generated by processes that are independent but with correlated errors that are not.

Thus, the CMP modeling framework is essentially that of SUR, but in a much broader sense. The individual equations need not be classical regressions with a continuous dependent variable; they also may be estimated by ordered probit. A single invocation of CMP may specify several equations, each of which may use a different estimation technique. Furthermore, CMP allows each equation's model to vary by observation. The main advantage of the CMP estimator to the SUR estimator is *recursivity* and *full observability* that work for a larger class of simultaneous-equation systems. The conditional mixed process is suitable for estimates in which there is simultaneity but where instruments allow for the construction of a recursive set of equations, as in two-stage least square (2SLS). In this case, the CMP is a limited-information maximum likelihood (LIML) estimator. The use of the maximum likelihood approach to estimate the three equations as a system rather than as a two-step estimator implies efficiency gains.

5. Results

5.1 Drivers of energy consumption: discrete-continuous choice model

The results of the two steps are presented in Table 5 below. Complementary results with other measures for preferences and proofs of the quality of estimations are provided in Table 11 in the appendix.

[79] See Arnold Zellner, 'An Efficient Method of Estimating Seemingly Unrelated Regressions and Tests for Aggregation Bias', *Journal of the American Statistical Association*, 57/298 (1962), 348-68.

Table 5: Results of the discrete-continuous model

	All Samples		Decile 1-2-3		Decile 8-9-10	
	Discrete choice	Continuous choice	Discrete choice	Continuous choice	Discrete choice	Continuous choice
	(1)	(2)	(3)	(4)	(5)	(6)
Energy price in 2012 (log)	0.153**	-0.552***	-0.0195	-0.437***	0.523***	-0.714***
	(0.0736)	(0.0608)	(0.128)	(0.111)	(0.153)	(0.110)
Income (log)	-0.112**	0.0921**	-0.164	0.0928	0.284*	-0.0775
	(0.0529)	(0.0443)	(0.127)	(0.111)	(0.160)	(0.103)
Strong preference for comfort	-0.00153	0.102**	0.0974	0.0630	-0.226*	0.181**
	(0.0631)	(0.0518)	(0.114)	(0.0992)	(0.123)	(0.0802)
Medium preference for comfort	-0.0609	0.100*	0.103	-0.0127	-0.360***	0.218**
	(0.0677)	(0.0558)	(0.126)	(0.110)	(0.131)	(0.0896)
Low preference for comfort	-0.0532	0.0621	0.0276	0.0848	-0.365***	0.156*
	(0.0675)	(0.0555)	(0.116)	(0.101)	(0.139)	(0.0947)
No preference for comfort (reference)	-	-	-	-	-	-
Number of appliances (log)		0.146***		0.183***		0.110**
		(0.0324)		(0.0671)		(0.0515)
Number of days of housing vacancy during heating period (log)		-0.0299***		-0.0548***		-0.00775
		(0.00910)		(0.0172)		(0.0152)
Control for individual characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Control for building characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Control for locality	Yes	Yes	Yes	Yes	Yes	Yes
Control for building energy class		Yes		Yes		Yes
Control for price endogeneity	Yes	Yes	Yes	Yes	Yes	Yes
N	2,040	2,040	613	613	612	612

Standard errors in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

The dependent variable of the discrete choice (ordered probit) is the energy label classification, from G to A-B. The dependent variable for the continuous choice is the energy consumption expressed in kilowatt hour per square meter for the year 2012 (expressed in log).

The thresholds, or cut-off points, reflect the predicted cumulative probabilities at covariate values of zero. They are all significant at $p<0.01$

Estimates by subgroup of explanatory variables are given in Table 11 in the appendix to confirm the robustness of our results. Marginal effects are given in Table 12.

Individual characteristics include: number of occupants and duration since last move-in

Building characteristics include: detached or non-detached house, building construction period, surface area

Locality characteristics include: climate zones. In metropolitan France, three main climate zones are considered, they consist of territories with similar temperatures and meteorological conditions (including solar resource). Urban demographic information is also included in locality.

Building energy class includes EPC energy classes.

5.1.1 Ordered probit (A-B is the reference class)

Results (Table 5) show that household and dwelling characteristics have a significant influence on the propensity to live in an energy-efficient dwelling. Considering the global sample (first column of Table 5), income has a significant negative effect: households with higher income are more likely to live in energy-efficient homes than poor households. This could be linked to the higher price of real estate with better energy efficiency, i.e. "green value" (Hyland et al., 2013). This result is also in line with Santamouris et al. (2007). However, if we consider the subpopulations of the first three income deciles on the one hand (column 3), and of the three last income deciles on the other hand (column 5), income elasticities may differ. We observe that households at the top end of the income distribution are more likely to choose less energy-efficient dwellings; wealthier households generally live in big detached houses which consume more and are less energy-efficient. This result is still valid if we remove the individual preferences for comfort.

Variable energy price has a significant positive effect on the probability of belonging to an energy inefficient dwelling in the global model and the model for deciles 8-9-10, meaning that energy cost can be a driver to choose an energy inefficient dwelling. Energy price could be assumed to reflect the nature of the main energy source of each dwelling, i.e. the heating energy. According to the energy class, the nature of the heating energy differs. Indeed, inefficient dwellings are the dwellings that have the more costing energy sources. For instance, dwellings in class G have fuel and electricity as more frequent main sources of heating energy (Figure 7) and these sources of energy are the more expensive. Thus, a higher energy cost is associated with energy-inefficient dwelling (mostly dwellings heat by electricity and fuel). In average, the cost of fuel is around 0.091 euros per kilowatt-hour, 0.11 for electricity, 0.083 for gas and 0.071 for wood., a higher energy cost is associated with energy-inefficient dwelling.

As the price of energy is higher for the main energy sources of the inefficient dwellings (electricity and fuel), it seems consistent that energy price has a significative positive effect on the fact to belong to an energy inefficient dwelling (see figure 7 in appendix). Concerning other variables, effects for the global sample are summarized below and are in line with the literature. The age of the reference person has an impact: for the two higher age classes, households are more likely to live in a non-efficient dwelling than those under 44, the effect being higher for households in the last category (over 66 years).

Moreover, dwelling occupancy period has a significant link with the energy efficiency of the dwelling. The more recent the move-in date is, the more likely households are to live in efficient dwellings. Two assumptions can be made: the greater availability of energy-efficient dwellings on the current real estate market (new dwellings are more energy efficient because of thermal regulations) and/or greater attention paid by households to residential energy information (for several years, EPC information has been provided to potential renters and buyers). Some environmental characteristics are also correlated with the energy performance of dwellings. Concerning neighborhood, the less isolated the dwelling (in terms of shared walls), the more energy efficient it is likely to be. Urban area types also have an impact; compared to Paris and big cities, dwellings in rural areas are more likely to be energy inefficient; this result is consistent with (Belaïd 2016). Moreover, energy-efficient dwellings are more likely to be found in cooler climate zones. Finally, size and building type effects are also significant; the bigger the dwelling is, the more energy efficient it is likely to be; living in a bigger house increases the probability of being in an energy-efficient dwelling. A dwelling's energy efficiency is thus not only determined by household characteristics but also by its environmental and technical characteristics.

Finally, preferences for comfort over economy have a significant effect only in the model applied to households in the three lowest income deciles. Households declaring a preference for comfort for at least one of the three energy uses considered (heating, hot water, or electricity) are more likely to live in more energy-efficient dwellings. For a wealthier household, having a strong preference for comfort raises the probability of living in an energy-efficient dwelling (class B) compared to others, from 3.93% to 6.26% (see Table 12 in the appendix).

5.1.2 Direct drivers of energy consumption

Energy price elasticity is significant in our three models (columns 2, 4 and 6), ranging from -0.43 to – 0.714; it is consistent with previous findings presented in our literature review. Results show that the magnitude of the price elasticity differs between low and high levels of revenue. It is lower for low-income households (-0.43 in column 4) and higher for high-income households (-0.714 in column 6), meaning that poor households are less responsive to an increase in energy prices. This could be explained by the fact that they are already restricting their energy consumption to their basic requirements; thus, any increase in energy prices does not affect this subsistence consumption. This differentiation in energy price elasticities according to income level is consistent with the work of Nesbakken (1999) and Schulte and Heindl (2017b). Income elasticity in the model on the global sample is + 0.09 (column 2), which is consistent with the findings in the literature for countries with similar climate and development characteristics, which range from 0.02 to 0.15. We did not find significant effects of income in the two other models.

Concerning our core assumption about the effect of individual preferences with regard to energy consumption, our model confirms our hypothesis: individual preferences for comfort over economy are highly significant and have a direct positive effect on energy consumption. When the global sample is considered, preferring comfort over economy for two or three energy uses implies energy overconsumption of 10% on average (column 2). If we consider the subpopulation of households belonging to the three highest income deciles (column 6), the effect is significant and even higher: Energy overconsumption from high and medium preferences for comfort lies between 18.1 and 21.8%. Moreover, this result is strengthened by those obtained with the indoor heating temperature (see Table 11 in Appendix). A one Celsius degree increase implies an overconsumption of 7.8%. Similar results are presented by SOFRES-ADEME (2009), which showed an overconsumption of 7%.

This result is interesting in terms of public policy development (see section 6). By linking the results of the discrete choice presented above and the descriptive statistics (Table 13 in the appendix), we can provide a more complete picture of our findings: we demonstrate that richer households are more likely to live in energy-efficient dwellings according to their preferences for comfort among other factors. The effect of individual preferences on energy consumption

for these households is positive and higher than that for the global population. Preferences for comfort could induce up to +18% additional energy consumption. This result could be considered to be evidence for the existence of a direct rebound effect even in cross-sectional data. It shows that there is a considerable scope of action for public policies to develop regarding the reduction of energy consumption by behavioral changes for this target population (i.e. wealthier households living in energy-efficient dwellings). Regarding poorer households, we highlight two important facts: they are more likely to live in energy inefficient dwellings where energy is more expensive. Moreover, their response to energy price is low, suggesting that they only address their basic needs regarding energy consumption. The appliance rate of households has also a significant impact on energy consumption. An increase in this rate implies an overconsumption of 14.6%. All these results are consistent with the literature review of Lopes et al. (2012).

Finally, regarding behavioral variables, we see that the duration of absence during the day has, unsurprisingly, a negative significant effect on total energy consumption. The number of appliances is significant and positive in explaining energy consumption. In contrast, the number of days of housing vacancy during heating periods is significant and negative, which is not unexpected. People who work during the day consume less energy.

In terms of dwelling characteristics, energy-efficiency classifications have the expected effects, significant and negative. The more efficient the home is, the less occupants consume energy. This suggests that, in our sample, the EPC measures available in our survey are at least partially representative of the levels of real energy consumption observed. Living in a more energy-efficient dwelling implies a lower effective energy consumption, all things being equal. Finally, climate zone explains both direct and indirect consumption. Living in a cold zone compared to a hot zone has a positive effect on the probability of living in an energy efficient dwelling. Living in cold zone has a positive and significant effect on energy consumption. This result is consistent with the literature, which shows that climate positively influences energy consumption (Kaza 2010; Belaïd 2017; Mansur et al. 2008).

6. Conclusion and policy implications

This research provides new evidence of the significant role of individual characteristics in energy consumption. The key result of this research is to provide a preliminary estimate of the magnitude of the effect of heterogeneity in preferences in explaining energy consumption variability. In summary, our research makes the following contributions:

- It confirms the role of common drivers of energy consumption for the French residential sector: energy price, income, age, environmental characteristics, energy efficiency of the dwelling, etc. However, our research also supports the existence of a differentiation of energy price elasticity according to household income level.
- It demonstrates that individual preferences for comfort over economy have a significant positive effect on energy demand for the global population: preferring comfort over economy implies on average a 10% increase in individual energy consumption, all else being equal. We show that this effect is higher in magnitude for high-income households, who are otherwise more likely to live in more energy-efficient dwellings.
- We provide new evidence of the importance of the role of energy label categories when analyzing the drivers of energy consumption. Our methodology applied the well-known discrete-continuous model framework pioneered by McFadden (1984) with a new perspective to account for the complexity of energy consumption. Our modeling of housing choice via the dwelling's energy-efficiency level (energy classification) is an important contribution. By using a nonlinear methodology to understand the drivers of residential energy demand, our approach, accounting for dwelling/household interactions, is in line with recent work (Estiri 2015, Belaïd 2017). In particular, we provided evidence that basic household and dwelling characteristics (surface area, location, etc.) can determine thermal housing attributes, conditioning final energy consumption.

Based on the findings presented above, in the next paragraph we set out several ways of integrating our research into public policy.

Financial incentives for energy refurbishment

As a result of the discrete choice step of our model, we are in a position to provide a better mapping of the match between household characteristics and the energy characteristics of dwellings. This enables us to formulate policy recommendations aimed at reducing energy consumption through energy efficiency. They are detailed below.

First, we provide evidence that poorer households are more likely to live in energy inefficient dwellings; this means that poorer people live in dwellings that need to be renovated for improved energy efficiency. For these households, the high investment costs of energy retrofits could be a significant barrier to action, which could partly justify the energy efficiency gap observed in the residential sector and well discussed in the academic literature (Gillingham and Palmer 2014).

Second, if we focus on high-income households that are more likely to live in more energy efficient dwellings, attention should be paid to the significant effect of a change in comfort preferences on energy consumption: preferences for comfort could induce up to +18% additional energy consumption. A connection can be made with the well-known "rebound effect" (Gillingham, Rapson, and Wagner 2016) that accompanies better energy performance of a dwelling and leads to a reduced amount of energy savings due to the improvement in comfort resulting from retrofits. In such cases, the household consumes more energy than expected by engineering calculations after the implementation of the energy retrofit. If the rebound effect occurs and is significant, providing financial incentives for energy refurbishment is no longer a cost-effective measure for policymakers. Similarly, Alberini et al. (2016) provided additional elements relative to the cost-effectiveness of energy retrofits rebates in the residential sector of Maryland (US) and demonstrated that an extreme rebound effect related to electricity heating and cooling consumption was found among incentive takers. His results also suggest that, above a certain level of rebate, the reduction of energy consumption induced by improved energy efficiency no longer exists.

Thus, our research highlights the fact that financial incentives for energy retrofits should be allocated with caution and should target two specific issues: poverty and the cost-effectiveness of public expenditures. In such a context, targeted financial incentives for energy refurbishment should be conditional based on the income level of the household (higher financial incentives for lower income households), on the initial energy-efficiency level of the housing (households living in the least energy efficient dwellings should receive priority) and on the energy-saving potential of the retrofit works to be implemented.

In France, the *Live better* program funded by the ANAH (National Agency for the improvement of housing) has been part of this approach for several years, offering two levels of income-differentiated incentives to foster energy efficiency in the residential sector. Between 2010 and

2017, about 250,000 dwellings[80] were retrofitted with a minimum theoretical energy efficiency gain set at 25%.

Information and behavioral treatment

Our research highlighted the significant role of a preference for comfort to explain the energy consumption of high-income households. In such a context, the role of behavioral incentives to reduce energy consumption should not be ignored by policy-makers. In line with this recommendation, Zivin and Neidell (2013) used cooling data in the US to argue in favor of the more frequent use of behavioral treatments to reduce energy consumption; they considered these to be just as effective as energy efficiency improvements in bringing about energy savings. Thus, designing information campaigns promoting reasonable energy use and focused on intensive energy consumers unaware of environmental impacts would be an effective complementary tool to reduce energy consumption (Ouyang and Hokao, 2009; Wilhite and Ling, 1995).

Alternatively, the use of smart meters providing real-time feedback on energy consumption and costs could be a significant way to induce energy-saving behavior (Faruqui et al. 2010) provided that their widespread deployment can be achieved at a reasonable cost. Numerous studies have demonstrated that improving information about energy consumption can lead to energy efficiency gains (Arrow and Fisher 1974; Brounen et al. 2013; Carroll et al. 2014; Di Cosmo et al. 2014; Ehrhardt-Martinez et al. 2010; Grimes et al. 2016; Jessoe and Rapson 2014; Matsukawa 2004; Pon 2017; Wolak 2011) Finally, smart metering could also be considered as a tool to fight climate change.

Energy and carbon taxation

Economic tools such as energy taxes or carbon taxation are often considered in the debate as levers for decreasing energy consumption in the short- or long-term. However, some sensitive issues must be carefully addressed regarding our results. We highlighted a lower energy price elasticity for low-income households and a higher cost of energy in less energy efficient dwellings where they are more likely to live: thus, low-income households should be less responsive to economic tools like carbon taxation that increases the energy price and are potentially more affected by its financial consequences. We suggest that policymakers wishing to tax energy or CO2

[80] https://www.actu-environnement.com/ae/news/cour-comptes-efficacite-gestion-programme-habiter-mieux-anah-stabilite-budget-31017.php4

emissions to be careful not to increase fuel poverty in these households. Specifically, the issue of the redistributive effects of carbon taxation should be carefully addressed by policy makers and academic research. A differentiated energy or carbon tax rate defined according to income level could be envisaged to reduce the redistributive effects mentioned above while taking into account the behavioral patterns observed in high-income households. This could be achieved without extra-cost but could address the issue of social acceptance.

In conclusion, following the results of the research of Hache et al. (2017), we recommend that policymakers aiming to promote social welfare and achieve effective public policies keep in mind that low-income and high-income households should be considered separately when developing and implementing policies to reduce energy consumption in the residential sector.

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Appendix

Energy prices

Table 6: Energy prices provided by the PEGASE database

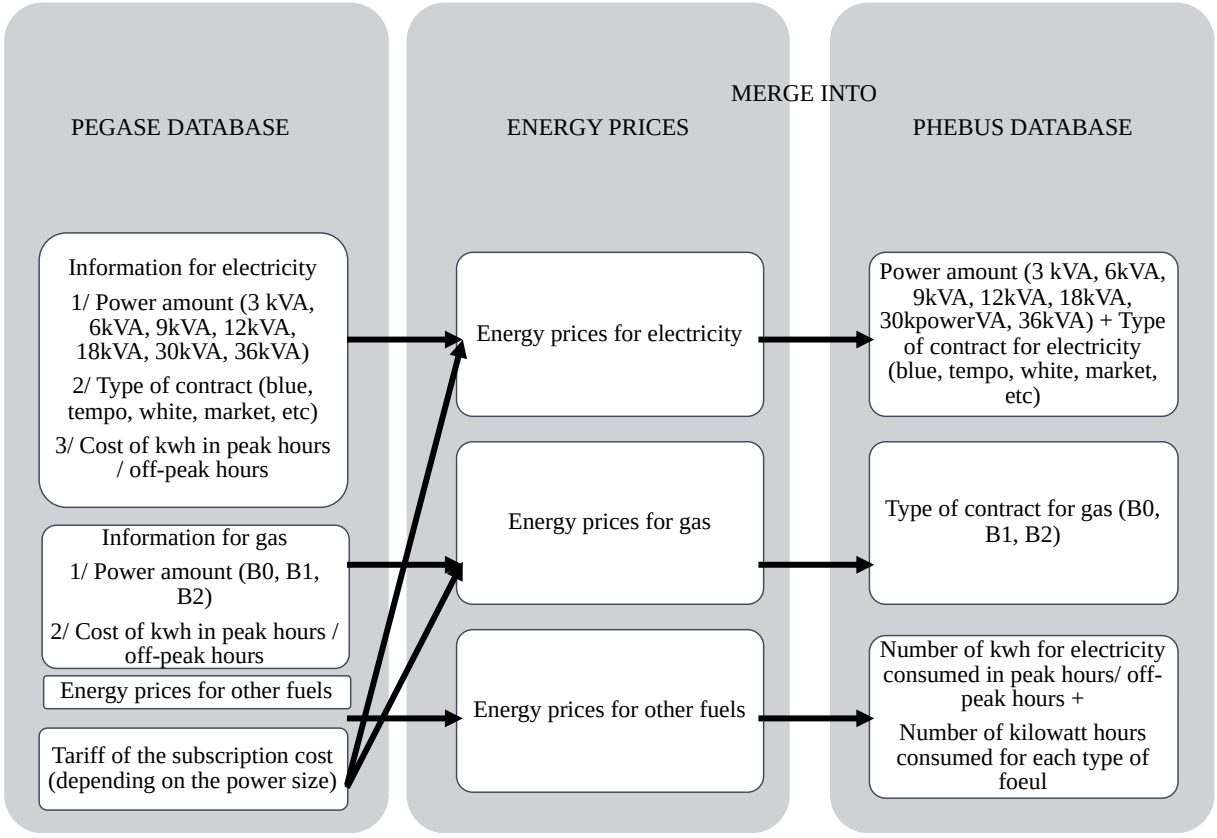
	2011	2012
ELECTRICITY TARIFF		
Electricity. blue rate. base option in euros (tax included)		
Annual subscription cost 3 kVA	64.94606	67.40325
Annual subscription cost 6 kVA	77.45169	80.36592
Annual subscription cost 9 kVA	90.3377	93.76717
Annual subscription cost 12 kVA	142.84527	148.13392
Annual subscription cost 15 kVA	164.85725	171.04758
Annual subscription cost 18 kVA	219.2238	227.44092
Price for 100 kWh (power 3 kVA)	17.02237	17.7994
Price for 100 kWh (power 6 kVA)	16.23193	16.9816
Electricity. blue rate. peak hours rate in euros (tax included)		
Annual subscription cost 6 kVA	93.13223	96.59658
Annual subscription cost 9 kVA	111.76704	115.91475
Annual subscription cost 12 kVA	189.49559	196.56458
Annual subscription cost 15 kVA	223.04773	231.32342
Annual subscription cost 18 kVA	254.38013	263.81675
Annual subscription cost 24 kVA	529.87303	549.78758
Annual subscription cost 30 kVA	652.50116	677.02358
Annual subscription cost 36 kVA	754.42164	782.73067
100 kWh peak-hours	12.91385	13.54292
100 kWh off-peak	8.76965	9.23933
Price for 100 kWh (power 6 kVA)	14.03546	14.70435
Price for 100 kWh (power 9 kVA)	13.02266	13.65389
Price for 100 kWh (power 12 kVA)	12.77758	13.39973
Electricity. blue rate. tempo option in euros (tax included)		
Annual subscription cost 9 kVA	109.04157	113.022
Annual subscription cost 12 kVA	203.35865	210.90942
Annual subscription cost 30 kVA	456.64613	473.54025
Annual subscription cost 36 kVA	566.42158	587.43975

100 kWh blue days and off-peak	6.8142	7.2111
100 kWh blue days and peak-hours	8.20155	8.65528
100 kWh white days and off-peak	9.8401	10.35061
100 kWh white days and peak-hour	11.7537	12.33594
100 kWh red days and off-peak	18.5589	19.40033
100 kWh red days and peak-hour	49.16455	51.17409
Electricity. market rate. in euros (tax included)		
All rates	13.41974	13.82434
DA rate	24.45679	25.13133
DB rate	15.8404	16.3847
DC rate	14.02566	14.45913
DD rate	12.84391	13.2134
DE rate	12.54369	12.91665
GAS RATE		
Natural Gas. price in euros (tax included)		
Annual subscription cost - base rate	43.8933	46.92645
Annual subscription cost - B0 rate	58.0092	61.97075
Annual subscription cost - B1 rate	185.18415	195.4546
Annual subscription cost - B2I rate	185.18415	195.4546
100 kWh PCS - base rate	9.3988	9.96987
100 kWh - B0 rate	8.0742	8.51871
100 kWh- B1 rate	5.58353	5.86163
100 kWh - B2I rate	5.58353	5.86163
Price for 100 kWh B0 rate	11.74238	12.42551
Price for 100 kWh B1 rate	7.08853	7.44654
Price for 100 kWh B2I rate	6.79365	7.13536
DOMESTIC OIL RATE		
Tariff of one ton of propane in tank	1670.297	1791.087
100 kWh PCI (Lower calorific value) propane in tank	12.96815	13.90596
Price of one ton of propane	1670.297	1791.087
100 kWh PCS (Higher calorific value) of propane	12.1036	12.97889
100 kWh PCI of propane	13.06961	14.01476
Bottle of 13 kg butane	30.19	31.75
100 liters of oil at Rate C1	88.79	96.88

100 kWh oil PCI at Rate C1	8.90482	9.71618
WOOD RATE		
One ton of bulk pellets	250	260
One stere of logs	63	67
100 kWh PCI of bulk wood	3.70588	3.94118

Source: PEGASE database, French Ministry of Energy

Figure 5: Methodology used to merge energy prices



C. Descriptive statistics – Energy performance class

C.1 Main descriptive statistics

Table 7: Main descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
Energy consumption in kwh/m²	170.562	99.901	2.258	814.740
Energy price in 2012	0.094	0.028	0.006	0.382
Energy price in 2011	0.090	0.027	0.006	0.308
Regulated rate with no subsidy	0.703	0.457	0.000	1.000
Regulated rate with subsidy	0.010	0.101	0.000	1.000
Disposable income	40394.0	24639.4	307.0	277601.0
Number of persons	2.544	1.298	1	10
Strong preference for comfort	0.295	0.456	0	1
Medium preference for comfort	0.218	0.413	0	1
Low preference for comfort	0.215	0.411	0	1
No preference for comfort	0.272	0.445	0	1
Heating temperature	19.916	1.465	8	30.0
Number of appliances	16.082	13.511	1	341.0
Number of days of housing vacancy during heating period	7.783	16.104	0	210.0
Duration since move-in	17.255	15.019	0	89.0
Non-detached house	0.437	0.496	0	1
Surface area	111.8	49.3	15.0	600.0
Climate zone H1 - coldest	0.575	0.494	0	1
Climate zone H2	0.361	0.480	0	1
Climate zone H3	0.063	0.243	0	1
Town < 2000 inhabitants	0.274	0.446	0	1
Town between 2,000 and 10,000 inhabitants	0.132	0.339	0	1
Town between 10,000 and 50,000 inhabitants	0.148	0.355	0	1
Town between 50,000 and 200,000 inhabitants	0.110	0.313	0	1
City between 200,000 and 2,000,000 inhabitants	0.243	0.429	0	1
Paris	0.093	0.291	0	1

Construction period				
Before 1919	0.170	0.376	0	1
1919 to 1945	0.090	0.286	0	1
1946 to 1970	0.174	0.379	0	1
1971 to 1990	0.325	0.468	0	1
1991 to 2005	0.175	0.380	0	1
2006 and after	0.066	0.249	0	1
Energy class				
A	0.024	0.152	0	1
B	0.138	0.345	0	1
C	0.276	0.447	0	1
D	0.293	0.455	0	1
E	0.148	0.355	0	1
F				
G	0.122	0.327	0	1

Table 8a: Analysis of preferences: Correlation between individual preferences and socio-economic characteristics

	Age	**Number of consumption units**	**Revenue**	**Strong preference for comfort**	**Medium preference for comfort**	**Low preference for comfort**
Number of consumption units	-0.4104*					
Revenue	-0.1131*	0.3718*				
Strong preference for comfort	0.0242	-0.0262	0.1086*			
Medium preference for comfort	-0.0568*	0.0687*	0.0602*	-0.3414*		
Low preference for comfort	-0.0347	-0.0011	-0.0396	-0.3384*	-0.2766*	
Preference for comfort for heating use	0.0060	0.0224	0.1111*	0.5663*	0.2210*	-0.0947*

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 8b: *Analysis of preferences: t test*

	Obs	Mean		*t*	Critical probability
		0 (No)	1 (Yes)		
Revenue, by preference for comfort for heating	2040	37271.82	42791.16	*t* = -5.0449	0.00000
Revenue, by strong preference for comfort	2040	38665.47	44532.82	*t* = -4.9310	0.00000
Revenue, by preference for comfort for hot water	2040	37430.96	44601.38	t = -6.5383	0.00000
Revenue, by preference for comfort for electricity	2040	37265.54	42888.56	*t* = -5.1529	0.00000
Real energy consumption, by strong preference for comfort	2040	164.389	175.3014	*t* = -2.4484	0.0072
Real energy consumption, by preference for comfort for heating	2040	170.3639	171.0365	*t* = -0.1386	0.4449
Theoretical energy consumption, by strong preference for comfort	2040	208.7363	190.8599	*t* = 2.9913	0.0014

C.2 Energy class

Figure 6: EPC energy-efficiency classifications

Energy classification is based on Energy Performance Certificates (EPCs). EPCs are a rating scheme to assess the energy efficiency of dwellings. Information about energy efficiency is given as:

• a numerical value of the energy performance of the dwelling (theoretical energy consumption expressed in kilowatt-hours per square meter) calculated with an engineering model from observed technical characteristics

• a ranking into categories of energy performance based on the previous numerical value. Seven categories are defined gradually from G (lower energy efficiency) to A (higher energy efficiency)

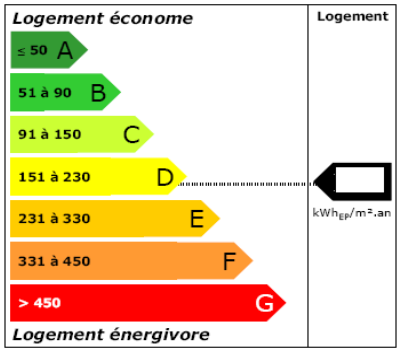


Table 9: Distribution of national dwelling stock into energy-efficiency classifications

Energy Class	Number of observations	At national scale	Share of housing stock (%)
A-B	48	439 585	2
C	281	2 724 895	12.6
D	564	5 483 573	25.4
E	598	6 322 821	28.3
F	301	3 361 569	15.6
G	248	3 257 038	15

Regressions

D.1 Quality test of instruments

First, we performed tests to determine whether endogenous regressors in the model are in fact exogenous. After a 2SLS estimate with an unadjusted VCE, the Durbin (Jiang et al. 2014) and Wu–Hausman (Hausman 1978; Wu 1974) statistics were reported.

We checked the consistency of the results with a VCE estimate. In all cases, if the test statistic is significant, then the variables being tested must be treated as endogenous.

Table 10: Test of endogeneity

H_0: variables are exogenous	
Durbin (score) χ^2 = 14.7703	p = 0.0001
Wu-Hausman F (1.2012) = 14.6739	p = 0.0001
Robust score χ^2 = 8.18694	p = 0.0042
Robust regression F (1.2012) = 9.12298	p = 0.0026

We now explore the degree of correlation between the additional instruments (energy prices in 2011 and electricity rates) and the endogenous regressor (energy prices in 2012). Our exogenous variable can be considered a valid instrument if it is correlated with the included endogenous regressors but uncorrelated with the error term. Using a Stock and Yogo (2005) test, we discuss the validity of the instruments. The null hypothesis of each of Stock and Yogo's tests is that the set of instruments is weak. To perform the Wald tests, we choose a relative

rejection rate of 5%. If the test statistic exceeds the critical value, we can conclude that our instruments are not weak. In our model, the *F* statistic is 459.896 and largely exceeds the critical value. Our instruments are not weak.

Minimum eigenvalue statistic = 459.896

	5%	10%	20%	30%
2SLS relative bias	13.91	9.08	6.46	5.39
2SLS Size of nominal 5% Wald test	22.30	12.83	9.54	7.80
LIML Size of nominal 5% Wald test	6.46	4.36	3.69	3.32

Finally, to confirm our results, we perform tests of overidentifying restrictions. With the 2SLS estimator, Sargan's (Sargan 1958) and Basmann's (Basmann 1960) χ^2 tests are reported. A statistically significant test statistic always indicates that the instruments may not be valid. Here, the tests are not significant, so our instruments are valid.

Sargan (score) χ^2 (2) = 2.45102	p = 0.2936
Basmann χ^2 (2) = 2.41909	p = 0.2983

In order to ensure the quality of the lag of energy prices as instrument, we test also as instrument the energy prices in 2010. The Durbin score and the Wu-Hausman score test rejects the null hypothesis of the absence of endogeneity. Sargan's (Sargan 1958) and Basmann's (Basmann 1960) χ^2 tests still indicate the validity of instruments."

D.2 Estimates

Table 11a: Model estimates by subgroup of variables (following page)

	Whole Sample		With heating temperature		Subgroup 1		Subgroup 2		Subgroup 3		Subgroup 4	
	DC	CC	DC	CC	DC	CC	DC	CC	DC	CC	DC	CC
Energy price in 2012	0.153**	-0.552***	0.139*	-0.521***	0.150**	-0.482***	0.127*	-0.474***	0.135*	-0.491***	0.141*	-0.504***
	(0.0736)	(0.0608)	(0.0739)	(0.0603)	(0.0738)	(0.0412)	(0.0736)	(0.0430)	(0.0737)	(0.0453)	(0.0740)	(0.0472)
Income (log)	-0.112**	0.0921**	-0.0965*	0.0830*	-0.0751		-0.119**	0.0623**	-0.123**	0.0700**	-0.127**	0.0790**
	(0.0529)	(0.0443)	(0.0526)	(0.0435)	(0.0488)		(0.0520)	(0.0312)	(0.0524)	(0.0337)	(0.0524)	(0.0342)
Preference for comfort: high	-0.00153	0.102**			0.0717		-0.00260	0.103***	-0.00201	0.102***	-0.00415	0.104**
	(0.0631)	(0.0518)			(0.0579)		(0.0632)	(0.0381)	(0.0632)	(0.0395)	(0.0631)	(0.0408)
Preference for comfort: medium	-0.0609	0.100*			-0.0200		-0.0605	0.0707*	-0.0636	0.0780*	-0.0554	0.0738*
	(0.0677)	(0.0558)			(0.0622)		(0.0679)	(0.0411)	(0.0679)	(0.0425)	(0.0678)	(0.0439)
Preference for comfort: low	-0.0532	0.0621			-0.0306		-0.0547	0.0424	-0.0577	0.0479	-0.0462	0.0384
	(0.0675)	(0.0555)			(0.0618)		(0.0677)	(0.0408)	(0.0677)	(0.0422)	(0.0677)	(0.0436)
Heating temperature			-0.0463***	0.0789***								
			(0.0164)	(0.0135)								
Number of appliances (log)		0.146***		0.139***				0.131***		0.142***		0.139***
		(0.0324)		(0.0322)				(0.0322)		(0.0324)		(0.0323)
Number of days of housing vacancy during heating period (log)		-0.0299***		-0.0273***				-0.0285***		-0.0296***		-0.0294***
		(0.00910)		(0.00905)				(0.00911)		(0.00915)		(0.00908)
Control for individual characteristics	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Control for building characteristics	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No
Control for locality	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	No	Yes	Yes
Control for building energy class		Yes		Yes		Yes		Yes		Yes		Yes
Control for price endogeneity	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2040	2040	2026	2026	2040	2040	2040	2040	2040	2040	2040	2040

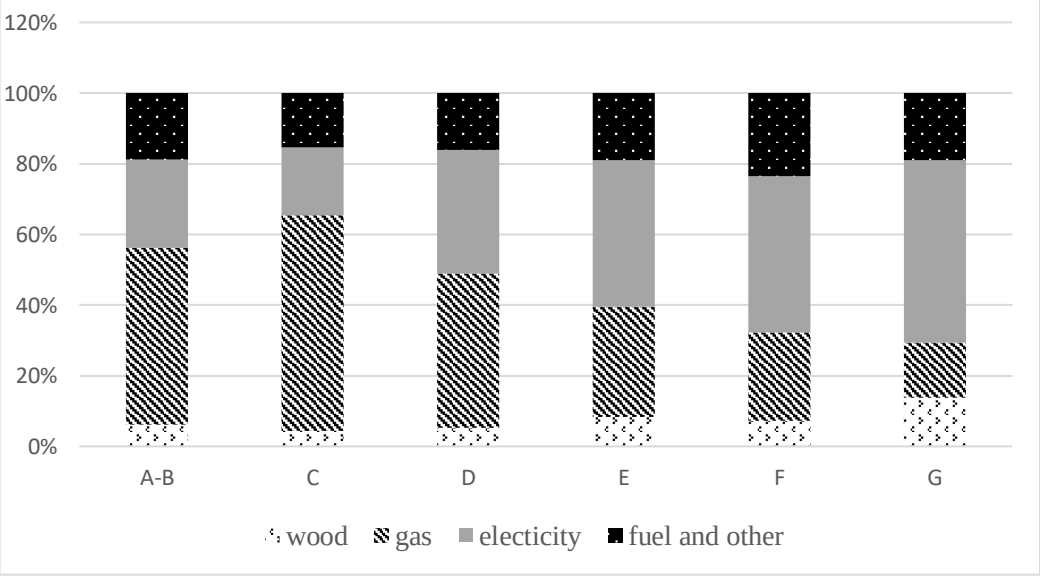
Standard errors in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$. The thresholds, or cut-off points, reflect the predicted cumulative probabilities at covariate values of zero. They are all significant at $p<0.01$.

Table 11b: Reduced form for the IV regression (whole sample)

Variables	(1) Energy price 2012 (log)
Energy price 2011 (log)	0.987***
	(0.00235)
Electricity rate 1	0.00867***
	(0.00174)
Electricity rate 2	-0.00391
	(0.00786)
Constant	0.0174***
	(0.00589)
Observations	2,040
R^2	0.989

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Figure 7: Percentage of each type of heating energy source by energy class



Source: PHEBUS Survey 2012, authors' calculations

Table 12: Marginal effects for the ordered probit model

Whole sample						
	Outcome 1	Outcome 2	Outcome 3	Outcome 4	Outcome 5	Outcome 6
Energy price in 2012	-0.0072	-0.0232	-0.0180	0.0073	0.0159	0.0251
Income (log)	0.0053	0.0170	0.0132	-0.0053	-0.0117	-0.0184
No. of persons	0.0023	0.0073	0.0057	-0.0023	-0.0051	-0.0080
Preference for comfort: high	0.0001	0.0002	0.0002	-0.0001	-0.0002	-0.0003
Preference for comfort: medium	0.0029	0.0092	0.0072	-0.0029	-0.0063	-0.0100
Preference for comfort: low	0.0025	0.0081	0.0063	-0.0025	-0.0055	-0.0087
Control for individual characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Control for building characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Control for locality	Yes	Yes	Yes	Yes	Yes	Yes
Decile 1-2-3						
	Outcome 1	Outcome 2	Outcome 3	outcome 4	Outcome 5	Outcome 6
Energy price in 2012	0.0006	0.0024	0.0026	0.0004	-0.0016	-0.0045
Income (log)	0.0048	0.0202	0.0221	0.0036	-0.0133	-0.0375
No. of persons	0.0028	0.0117	0.0127	0.0021	-0.0077	-0.0217
Preference for comfort: high	-0.0029	-0.0120	-0.0131	-0.0022	0.0079	0.0223
Preference for comfort: medium	-0.0030	-0.0127	-0.0139	-0.0023	0.0083	0.0236
Preference for comfort: low	-0.0008	-0.0034	-0.0037	-0.0006	0.0022	0.0063
Control for individual characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Control for building characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Control for locality	Yes	Yes	Yes	Yes	Yes	Yes
Decile 8-9-10						
	Outcome 1	Outcome 2	Outcome 3	outcome 4	Outcome 5	Outcome 6
Energy price in 2012	-0.0322	-0.0911	-0.0410	0.0494	0.0607	0.0543
Income (log)	-0.0175	-0.0494	-0.0222	0.0268	0.0329	0.0294
No. of persons	0.0020	0.0055	0.0025	-0.0030	-0.0037	-0.0033
Preference for comfort: high	0.0139	0.0393	0.0177	-0.0213	-0.0262	-0.0234
Preference for comfort: medium	0.0222	0.0627	0.0283	-0.0340	-0.0418	-0.0374
Preference for comfort: low	0.0224	0.0634	0.0286	-0.0344	-0.0423	-0.0378
Control for individual characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Control for building characteristics	Yes	Yes	Yes	Yes	Yes	Yes

Table 13: Distribution of income deciles for each energy-efficiency classification (%).

	A	B	C	D	E	F	G
D1	0	12	4	7	8	14	21
D2	0	5	7	6	11	15	16
D3	0	2	9	10	10	9	13
D8	20	14	14	10	11	6	6
D9	20	16	14	13	7	10	5
D10	20	12	14	13	8	9	5

Legend (upper table): 42% of the dwellings belonging to energy class B are occupied by households in the three highest income deciles. 50% of the dwellings of energy class G are occupied by households of the three lowest income deciles

Conclusion et transition vers le chapitre 3

Dans ce papier, nous avons mis en évidence la pluralité des facteurs qui déterminent la consommation énergétique résidentielle ainsi que la complexité de leurs interactions.

Notamment, nous avons montré que la performance énergétique du logement qui conditionne directement la consommation énergétique finale est elle-même déterminée antérieurement par les caractéristiques socio-économiques et les préférences individuelles des ménages français. Ces dernières variables influencent aussi directement la consommation d'énergie finale.
Suggérée par la littérature académique la plus récente, l'existence de ces relations à plusieurs niveaux doit être prise en compte systématiquement dans les travaux de recherche futurs pour ne pas mésestimer le poids relatif des différents déterminants de la consommation énergétique dans le logement. Dans ce contexte ; le cadre méthodologique et les spécifications économétriques utilisés démontrent leur pertinence.

Les résultats confirment que la consommation d'énergie résidentielle est conditionnée par la structure du parc (matching logement/ménage) qui se détermine en partie par le niveau de revenu. Pour aller plus loin dans l'analyse des obstacles à la réduction des consommations énergétiques résidentielles et affiner l'éclairage pour les décideurs publics, la mesure plus fine des écarts entre consommation énergétique théorique (et donc attendue) et réelle et l'identification et la compréhension des comportements sobres ou non en énergie sont nécessaires. Cela peut notamment permettre de mettre en exergue des comportements énergétiques caractéristiques portés par des types de consommateurs spécifiques. Cette problématique fera l'objet du deuxième article de la thèse.

Chapitre 3

The Role of Individual Preferences in Explaining the Energy Performance Gap[81]*

*Cet article a été écrit en collaboration avec Dorothée Charlier[82]. Il a été soumis à la revue *Energy Journal* (décembre 2018) et est disponible en Working paper et policy paper sur le site de la FAERE[83].

Abstract

The aim of this research is to understand the role of socioeconomic characteristics and individual preferences in explaining the energy performance gap in the residential sector. This gap reflects the difference between the theoretical energy consumption of homes assessed by engineering models and real energy consumption. Using the ratio of the two consumption amounts to measure the gap, we perform a quantile regression to tease out the effects of preferences on the entire distribution of the energy performance gap spectrum instead of focusing on the conditional average. As a result, this research provides an original contribution: depending on the direction of the gap, our findings suggest that significant drivers include individual preferences for comfort over economy, which explain up to 12% of the gap variability, and poverty. This context should serve as a reminder to public authorities regarding the issues of rebound effect and household welfare.

Keywords: Residential energy consumption; Household preferences; Energy performance gap; Quantile regression; Quantile treatment effect.

JEL CODES: Q41; D12; C26; C21

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[83] http://faere.fr/pub/WorkingPapers/Bakaloglou_Charlier_FAERE_WP2018.15.pdf

1.Introduction

In 2015, the residential sector represented 25.4 % of final energy consumption[84]; heating of space and water currently represents 79.2 % of that final energy consumed by households[85]. EU countries have agreed on a new 2030 Framework for climate and energy including at least 27% energy savings over a status quo scenario. Energy efficiency is a powerful driver for reducing energy consumption but may not be spreading quickly enough to achieve energy targets: this could be explained by the energy efficiency gap[86]. On the other hand, the role of the dwelling's occupant in energy consumption patterns is central and must not be underestimated.

Households often combine housing attributes, energy input and climatic conditions to obtain the dwelling unit comfort that they enjoy in final consumption (Quigley and Rubinfeld, 1989). In this context, it seems pertinent to carry out an empirical analysis of the *energy performance gap,* which indicates the discrepancy between theoretical energy consumption predicted by engineering calculations and real energy consumption, and then identify its behavioural determinants. Understanding the origin of extreme energy performance gaps could help explain deviant consumption patterns and thus be useful for policymakers. First, it could be useful to improve the accuracy of models of energy consumption used for ex-ante policy analysis. Second, policy evaluations must consider not just how much a policy increases energy efficiency, but what types of consumers can be induced to become more energy efficient (Allcott and Greenstone, 2012).

The present research aims at providing an empirical contribution to the identification of how individual drivers explain the energy performance gap in the residential sector. The major focus of our research is not only to quantify the gap but also to identify households characterized by low and high deviation regarding the *energy performance gap*. Among household

[84] Households use energy for various purposes: space and water heating, space cooling, cooking, lighting and electrical appliances and other end uses, which mainly cover household uses of energy outside the dwellings themselves.
[85] Statistics come from Eurostat. More information and statistics are available online, see (last visit in February 2019): https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households.
[86] Literature on the energy efficiency gap is abundant. For more details, see Allcott, H. and M. Greenstone. (2012). Is There an Energy Efficiency Gap? *Journal of Economic Perspectives*. 26(1):3-28, Blumstein, C. (1980). Program evaluation and incentives for administrators of energy-efficiency programs: Can evaluation solve the principal/agent problem? *Energy Policy*. 38(10):6232-6239, Gillingham, K. and K. Palmer. (2014). Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence. *Review of Environmental Economics and Policy*. 8(1):18-38, Jaffe, A. B. and R. N. Stavins. (1994). The Energy Paradox and the Diffusion of Conservation Technology. *Resource and Energy Economics*. 16(2):91-122, Jaffe, A. B. and R. N. Stavins. (1994). The energy-efficiency gap What does it mean? *Energy Policy*. 22(10):804-810, Metcalf, G. E. and K. A. Hassett. (1999). Measuring the Energy Savings From Home Improvement Investments Evidence From Monthly Billing Data. *Review of Economics & Statistics*. 81(3):516.

characteristics, we will focus on the role of individual preferences regarding energy use, energy price and revenue in explaining the gap.

Over the last decades, empirical research in energy economics has provided evidence that individual characteristics and occupant preferences have a crucial role in explaining final energy consumption in housing stock: by directly influencing energy consumption, these drivers could interfere with, moderate or even compromise the effects of energy-efficiency policies (Orea, Llorca and Filippini 2015). Technical data have been found to account for only 40% of final energy consumption in the residential sector (Belaïd, 2016), while socioeconomic characteristics such as revenue, household's age, tenure status, etc. account for about 33%. The specific effect of behavioural characteristics and preferences on energy consumption variability (Belaïd, 2016; Belaïd and Garcia, 2016; Cayla, *et al.*, 2011; Quigley and Rubinfeld, 1989) has frequently been highlighted. However, according to the literature review of Lopes (2012) research on the issue is rare and inconclusive. Identifying and characterizing energy consumption patterns and their link to behavioural information is still a major issue.

For now, this field of empirical research is still sparse, perhaps because it requires rich datasets. The recent *PHEBUS*[87] survey, which includes complete thermal data and Energy Performance Certificates (EPCs) for more than 2000 dwellings, allows us to better understand household behaviours and their influence on energy consumption variability by controlling for home energy-efficiency heterogeneity. Given access to a formal assessment of theoretical home energy consumption with limited heterogeneity in measurement, we were able to measure the energy performance gap at dwelling scale. Using the *intensity of energy use* indicator , i.e. the ratio between real and theoretical consumption (Wirl 1987; Cayla, Maizi, et Marchand 2011), we were able to identify under-consumption and overconsumption. We perform a quantile regression analysis to explain the energy performance gap spectrum, which lets us tease out the effects of preferences on the entire distribution on the energy performance gap spectrum instead of focusing on the conditional average. Finally, quantile treatment effects are implemented to how each specific variable of interest affects the gap.

As a result, this research contributes to the literature by demonstrating the prominent role of individual characteristics in explaining the energy performance gap. Depending on the scope of energy uses considered, our findings suggest that up to 12% of the gap is explained by

[87] See the description of the database here: https://www.casd.eu/source/enquete-performance-de-lhabitat-equipements-besoins-et-usages-de-lenergie-volet-dpe/ (last visit: February 2019)

individual preferences. Moreover, we provide evidence that poverty and financial resource availability are significant drivers that explain restriction behaviours regarding energy consumption, especially when the dwelling's energy performance is poor. On the other hand, this research demonstrates that strong preferences for comfort could explain energy overconsumption situations. These results contribute to a better understanding of the energy consumption spectrum, confirm past research assumptions and result in several public policy recommendations.

The paper is organized as follows. Section 2 presents the literature review. Section 3 describes the data. The model and the results are presented in section 4 and 5 respectively. In section 6 we discuss the results and present some policy implications. Section 7 concludes.

2.Literature review

1) Analytical framework: The energy performance gap, opposing theory and reality

The energy performance gap is defined in the literature as the difference between theoretical energy consumption assessed by engineering models after an energy audit and real energy consumption evaluated using energy bills (Allibe, 2012; Galvin, 2010; Galvin, 2014; Galvin and Sunikka-Blank, 2013). This gap has been highlighted in several studies over the past years, but little work has been done to identify the real factors influencing this gap.

In 2012, Galvin (2012) did a preliminary descriptive study with a European comparison. The authors focus on the case study of German dwellings and put forward policy implications. Their findings suggest the existence of not only an energy performance gap but also a systematic trend linking the theoretical measurement of heating energy consumption (Energy Performance Certificate measurement) and real energy consumption. The more energy efficient the dwelling is, the more the gap between the two measures grows in the direction of overconsumption. Galvin suggested that this trend would be partly linked with the rebound effect. Once dwellings have been renovated with energy-efficiency improvements, households adapt (i.e. increase) their heating comfort, leading to an increase in energy consumption. On the other hand, Galvin (2012) also introduces the concept of the "prebound effect": For less energy-efficient dwellings, real heating energy consumption is systematically lower than theoretical (on average 30% lower); this is assumed to be explained by restriction behaviours.

However, comfort preferences and behaviours are not the only reasons for a gap. Assumptions that have been made in the literature to explain the gap include the following:

- Uncertainties in the calculation method used by engineers to assess theoretical energy consumption (Allibe, 2012; Galvin and Sunikka-Blank, 2013; Galvin and Sunikka-Blank, 2014; Galvin et Sunnika-Blank 2012; Allibe 2012). This could be linked to errors in calculation, the thermal model used or incorrect assumptions (standardized occupancy, technical factors)
- Measurement uncertainties that could come from human error and subjectivity (when assessing quality or quantity of building materials or surfaces). According to experts, there is 20 to 30% uncertainty in the French EPC measure (Carassus, *et al.*, 2013).
- False assessment of the real quality of energy installations during the audit phase because of non-observability. Indeed, to stay economically affordable, EPC energy audits are probably not thorough enough to assess the real quality of dwellings' technical characteristics. This assumption comes from both technical studies (Carassus et al. 2013) and economics research (Allibe, 2012).
- Influence of socioeconomic and behavioural factors such as occupancy status, income level and number of occupants, which differs from EPC calculation assumptions or preferences (Cayla, *et al.*, 2011) .

The energy performance gap has been the focus of a few empirical studies, but until now, none has used econometric analysis to understand what determines it. In this research, we aim to contribute to the literature on the energy performance gap by determining the role of individual attributes. More particularly, we focus on testing the hypothesis of a positive effect of individual preferences for comfort over economy, revenue and energy price to explain the energy performance gap in the French residential sector.

2) Classic determinants of energy consumption

So that our analysis uses consistent determinants that can influence the energy performance gap, we briefly review the literature to build a list of the main individual factors explaining energy demand in the residential sector. Globally, there is consensus that income, energy price, number of occupants, age of the reference person, employment status and individual preferences have a significant role in explaining energy consumption variability (Belaïd, 2016; Brounen and Kok, 2011; Brounen, *et al.*, 2013) . We thus focus on the explanatory variables of interest: energy price, revenue and preferences for comfort.

Regarding income elasticity, the effect is positive in most of the studies, which is consistent with the normal good status of energy consumption; income elasticity remains low, often less

than 0.15 (Cayla, *et al.*, 2011; Labandeira, *et al.*, 2006; Nesbakken, 2001; Santamouris, *et al.*, 2007).

Energy price elasticity is always found to be negative, but estimates vary widely from -0.20 to -1.6. However, it is important to stress that price elasticity regarding energy demand may depend on the energy considered, the methodology used and the income level (Filippini, *et al.*, 2014; Krishnamurthy and Kriström, 2015; Miller and Alberini, 2016; Risch and Salmon, 2017; Schulte and Heindl, 2017; Campbell, 2017).

Individual preferences regarding energy use refer here to the intrinsic disposition of individuals to save energy in their everyday life (Lopes, *et al.*, 2012); it does not include individual preferences that are manifested through one-time actions like the purchase of energy-efficient equipment. Indicators used as proxies for energy-saving behaviour or preferences are quite heterogeneous in the literature. For example, Santin (2011) finds that the number of hours of heating at maximal temperature explains 10.3% of the variability of heating energy consumption. The work of Hamilton, *et al.* (2013) demonstrates that energy consumption may greatly differ (by up to three times) in dwellings with similar technical characteristics. Finally, it has been found that more informative bills and advice on reasonable energy use, implying a change in individual preferences regarding energy consumption, result in 10 percent energy savings for electricity (Ouyang and Hokao, 2009; Wilhite and Ling, 1995). In the literature review by Lopes and colleagues (Lopes, *et al.*, 2012), the synthesis shows that the savings potential from a change in energy-saving behaviours ranges from 1.1% to over 29%.

Finally, preferences for comfort can also evolve with the energy performance of the dwelling. Improving a dwelling's energy efficiency always leads to a decrease in energy consumption. However, this reduction is moderated due to the rebound effect. On average, 30% of the energy savings induced by an energy-efficiency improvement will be lost because of an increase in the comfort demand. In 2008, Sorrell and Dimitropoulos find in their literature review that the rebound effect for heating use could vary from 10 to 58% for the short-run rebound effect and from 1.4 to 60% for the long-run rebound. Erdal, *et al.* (2017) investigate the rebound effect in residential heating, using a sample of 563,000 households in the Netherlands. Using a quasi-experimental analysis through a large retrofit subsidy program, they confirm the important role of household behaviour in determining the outcomes of energy-efficiency improvement programs. They also demonstrate a significant heterogeneity in the rebound effect according to income level and actual energy use intensity. The rebound effect is strongest among lower-

income groups—these households are likely to be further from their satiation level in consumption of energy services, including thermal comfort.

This literature review suggests that, indeed, energy price, revenue and individual preferences for comfort may be good candidates in explaining the energy performance gap in the residential sector.

3.Data and descriptive statistics

1) Data

To study the determinants of the gap between theoretical performance and real energy consumption, this research uses data from the PHEBUS survey, a national household energy survey conducted by the Department of Observations and Statistics (SOeS), part of the French Ministry of Ecology and Sustainable Development. The survey contains over 2000 dwelling energy audits performed by the same company and launched in 2012; theoretical energy performance measures; real energy consumption (based on energy bills); and social, economic and behavioural data on dwelling occupants. Datasets available through this survey are quite innovative as they provide us with uniform assessments of Energy Performance Certificates (EPCs) for each dwelling.

EPC measure and main calculation assumptions regarding behavioural characteristics

The theoretical energy measure available in the PHEBUS survey is the Energy Performance Certificate (EPC). EPC certification includes an energy audit realized by an approved auditor (the same for all audits) based on visual inspection and collection of technical data followed by an assessment of the theoretical energy consumption calculated by engineering models with the assumption of standardized behaviours. This measure considers three energy uses: heating, hot water production and cooling. Neither lighting consumption nor domestic appliances are considered. Characteristics such as house construction data, window and wall insulation, heating system performance and climate data are collected and merged to obtain an aggregated measure of energy consumption.

The theoretical energy consumption of each dwelling is obtained from the 3CL method[88], which allows an estimate of the predicted dwelling energy consumption, expressed as C.

$$C = Cch + Cecs + Ccool \quad (1)$$

Cch is the theoretical heating energy consumption of the dwelling, $Cecs$ the theoretical energy consumption for hot water use and $Ccool$ the theoretical energy consumption for cooling use. The calculation of $Cecs$ and $Ccool$ are not detailed in this paper as they are minor sources of energy consumption in comparison to heating consumption. Cch consumption is calculated based on the heating needs of the building (Bch) multiplied by the inverse of the heating system power (Ich).

$$Cch = Bch \times Ich \quad (2)$$

where

$$Bch = SH.ENV.METEO.INT \quad (3)$$

Heating needs Bch are defined according to SH, habitable area; ENV, heating loss in the envelope and ventilation; $METEO$, which accounts for past environmental features due to dwelling location; and INT, an intermittence factor (INT), which accounts for indoor heating management (depending on heating system, building type, etc).

The main assumptions in the calculation are the following. Concerning environmental factors, the meteorological data used are the heating degree hours of the *département* (county) of reference to assess the heating needs of the building. Degree hours used are an average for the last 30 years for each *département*. Regarding heating management, 19°C is the conventional target heating temperature used in the calculation. The entire dwelling surface is considered as heated permanently during the heating period. Moreover, hot water needs are set according to the habitable area and the *département* where the dwelling is located.

In the end, this engineering calculation provides the theoretical energy consumption for each dwelling, expressed in primary and final energy, in kilowatt-hours per square meter.

[88] See the details of the 3CL methodology by following the web link: http://www.rt-batiment.fr/fileadmin/documents/RT_existant/DPE/DPE_outils/Nouvel_Algorithme_3CL-DPE_vf.pdf (Last visit in February 2019).

Measure of theoretical and real energy performance of dwellings: the intensity of energy use ratio

As explained above, the EPC result is a quantitative assessment of final energy consumption of the dwelling in kilowatt-hours per square meter. It ranks the dwellings into energy classes (seven classes, from A to G, available in appendix A Figure 6). One of the advantages of using the EPC values provided in the PHEBUS database is that all of the dwelling energy audits are carried out by the same firm, using the same calculation method, which gives us what seems to be uniform data. For this research, we use EPC measurements expressed in final energy to better match real energy consumption. Measurement of real energy consumption expressed in kilowatt-hours per square meter is based on energy bills for the year 2012. Real energy consumption measurement includes all energy consumption, regardless of the energy uses.

Thus, it is possible to calculate the intensity of energy use ratio (IEU). This indicator allows us to identify overconsumption and under-consumption situations.

The intensity of energy use indicator, first described by Wirl (1987) and then Cayla, *et al.* (2011), is defined as follows:

$$IEU = \frac{Final\ energy\ consumption\ (based\ on\ energy\ bills)}{Theoretical\ energy\ consumption\ (EPC)}$$

When the ratio becomes well above one, it means that the dwelling is "overconsuming" in comparison with its theoretical measure of energy consumption; if it is smaller, the dwelling is said to be to "under-consuming". The energy performance gap combines the instances when IEU significantly differs from one. This research aims to explain these high and low measures of the ratio using socioeconomic and environmental data.

However, we would like to make it clear that, in the analysis that follows, the scope of the energy uses included in the numerator and the denominator is not systematically the same. In addition to basic energy uses, real energy consumption includes specific electricity and cooking energy uses that are not considered by the theoretical measure of energy consumption assessed in the survey. EPC only includes main energy uses: hot water and heating energy[89]. Thus, when we consider the intensity of energy use indicator, only extreme values can be considered as interpretable in terms of the energy performance gap. Otherwise, it worth mentioning that the

[89] Heating and hot water energy uses account for approximately 61% and 12%, respectively, of dwelling global energy consumption

numerator and the denominator of the indicator are composite measures. In this context, some composition effect can arise and can lead to analytical errors (for instance, a compensation mechanism among energy uses can occur).

Thus, to complete our analysis, we also consider the IEU for a subsample of dwellings that are heated with gas and use gas for hot water. For this sample, we excluded all other energy uses in order to get a comparable basis between the EPC measure and real energy consumption in our IEU indicator. As this subsample includes only 517 observations, we use it to test the robustness of the analysis realized on the global sample.

Individual stated preferences for comfort

In the PHEBUS dataset, information is also available on households' stated preferences. For each end use (heating, hot water and electricity), it is possible to know whether households favour comfort or energy savings. Households were asked the following question: "*When it comes to indoor heating, do you favor comfort or energy savings?*". This question was asked for three types of end use (heating, hot water, and electricity). It is therefore possible to have a scale of preferences. A strong stated preference for comfort will be measured as a declared preference for each end use, a medium preference as a declared comfort preference for two out of three end uses and finally a low preference as a single declared preference for comfort. In this dataset, other variables can also be used as a proxy for comfort: for example, the stated heating temperature in winter.

We check the consistency between stated preferences and behaviour (see Table 6 in the appendix). While we are aware that behaviour is also reported, it is a way to control the consistency of the answers. In general, households that say they prefer comfort exhibit less economical behaviour. Moreover, households are distributed fairly evenly between the different levels of preference (between 21% and 28%) whatever the sample (whole or gas sample, Table 7).

More than 56% of households who have a stated preference for one end use have the same stated preference for the other two end uses (Table 8).

Energy price

The survey provides information on the type of energy cost (for gas and electricity) and the power required per type of fuel used (electricity, gas, oil). The power required and the type of

energy cost depend on the type of fuel used for the heating system and hence on the energy mix as well as the number of rooms (or the surface area). At the end, we face different energy costs per energy mix composition and end use.

However, no information is provided on the energy price itself. We thus supplemented the PHEBUS database with information on the energy rate and the subscription cost for each type of energy (oil, gas, electricity and wood): the energy cost depends on the power required and the type of cost in 2011 and 2012. This information is available in the PEGASE database provided by the French Ministry of Energy.

Finally, for each household, it is possible to calculate a weighted energy cost depending on the energy mix and the structure of energy consumption. With a weighted energy cost, we have a specific rate of energy for each household. The formula is the following:

$$energy\ price_i = \sum_{j=1}^{n} \frac{volume\ in\ kwh_{ijt} \times energy\ price_{jt}}{total\ volume\ in\ kwh_{ij}}$$

where j represents the type of fuel, i the household and t the type of cost for a specific energy (electricity or gas).

Climate data for 2012

Our dataset also provided information on the department where each dwelling is located. This information was matched with 2012 meteorological data from Meteo France (annual heating degree days by *département*) in order to have a proxy for the real meteorological conditions of 2012. As theoretical energy consumption (EPC) integrates climate data from the past 30 years, using real heating degree days for 2012 is assumed to influence the gap between theoretical energy consumption and effective energy consumption.

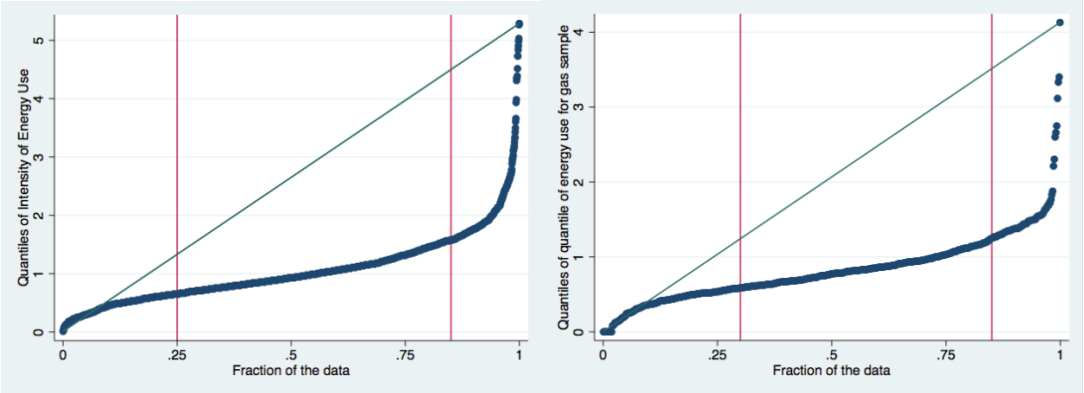
2) Descriptive statistics

The main descriptive statistics of the variables used in the model are summarized in Table 1 and in appendix B (Table 9). The final sample contains 1,853 observations after removing missing values. In the rest of this research, we also use a restricted sample composed of 517 dwellings with gas heat and gas-heated water.

In Figure 1, quantile plots are drawn for all observations and for the gas sample. According to Figure 1, the quantile plot for the whole sample has three different regions. The first includes a

horizontal line for zero IEU - we call such entities *digit preferences* (see Figure 1, gas sample on the right). The second region, with relatively high density, extends from just above zero up to about an IEU value of 2. Above it is a region with low and declining density. All the symbols are below the main diagonal: the distribution is skewed to the right. The maximum IEU is 5.29 and the average value is 1.05, while the median is equal to 0.93. Single outliers are also easily identified, for example the households with an IEU higher than 3. There are 120 households consuming more than twice their theoretical energy. For the gas sample, the median is equal to 0.77 and the average value is 0.83.

Figure 1: Distribution of the IEU



Data: PHEBUS 2012, authors' calculations

The descriptive statistics of household characteristics and dwelling attributes (see Table 1 of descriptive statistics by IEU quantiles) lead us to set the following assumption: Being in an "abnormal situation", meaning having either a very high IEU value (energy overconsumption) or a very low IEU value (energy under-consumption) could be linked to household socio-demographic characteristics, household preferences, economic and environmental context or home characteristics. For the future analysis, quantiles of IEU are selected according to the value of the IEU. We consider two extreme values. First, a low value of IEU (associated with under-consumption situations), around 0.5, which corresponds to quantile 0.2 of IEU for the global sample. Second, a high value of IEU (associated with over consumption situation), around 1.5, which corresponds to quantile 0.85 of IEU.

Table 1: Descriptive statistics (global sample and gas sample)

	Global sample						**Gas sample**			
	All observations		**20%***		**85%**		**30%****		**85%**	
	Mean	**Std, Dev**	**Mean**	**Std, Dev**	**Mean**	**Std, Dev**	**Mean**	**Std, Dev**	**Mean**	**Std, Dev**
Intensity of Energy Use	1.055	0.632	0.564	0.023	1.516	0.037	0.567	0.0151	1.323	0.0389
Average final energy consumption (kWh/m2/year) (based on bills)	168.282	95.496	129.428	56.310	191.692	85.567	166.170	45.111	215.828	70.615
Average EPC expressed in final energy (m2/CU)	265.007	134.075	309.968	137556	209.673	99.797	235.394	76.045	153.203	57.899
Average annual disposable income per household	40029	23920	38047	26233	43336	20461	38113	21387	45242	25031
Energy price in 2012	0.0942	0.0271	0.1012	0.0273	0.0923	0.0261	0.0831	0.0194	0.0795	0.0174
% of no comfort preference	0.272	0.445	0.295	0.458	0.191	0.395	0.385	0.496	0.000	0.000
% of low preference for comfort	0.212	0.409	0.189	0.394	0.157	0.366	0.077	0.272	0.308	0.471
% of medium preference for comfort	0.222	0.416	0.253	0.437	0.382	0.489	0.231	0.430	0.308	0.471
% of strong preference for comfort	0.294	0.456	0.263	0.443	0.270	0.446	0.308	0.471	0.385	0.496
% of comfort preference for heating	0.568	0.496	0.547	0.500	0.618	0.489	0.423	0.504	0.769	0.430
% of comfort preference for hot water	0.557	0.497	0.537	0.501	0.640	0.483	0.615	0.496	0.769	0.430
% of comfort preference for electricity	0.413	0.492	0.400	0.492	0.472	0.502	0.423	0.504	0.538	0.508
Mean heat temperature (°C)	19.93	1.49	19.83	1.56	20.22	1.43	19.75	1.63	20.10	1.23
Unit of consumption	1.69	0.54	1.55	0.51	1.89	0.53	1.65	0.66	1.95	0.59
Average age of the dwelling's reference person	56.19	15.13	58.51	15.36	51.34	14.79	54.08	16.04	52.92	16.57
Average number of appliances	16.24	14.06	13.94	5.14	16.45	5.47	13.00	6.39	15.88	5.81
Number of showers per week	1.06	3.69	0.76	1.62	1.11	2.39	1.50	2.30	1.96	3.54

Number of baths per week	13.11	9.69	11.25	12.71	17.20	10.04	12.58	11.25	15.42	9.97
Cold problem	0.161	0.367	0.179	0.385	0.101	0.303	0.231	0.430	0.077	0.272
Limit heating consumption	0.235	0.424	0.326	0.471	0.157	0.366	0.346	0.485	0.192	0.402
Fuel poor by the 10% definition	0.098	0.298	0.105	0.309	0.101	0.303	0.038	0.196	0.077	0.272
Monetary poor (60% median)	0.195	0.396	0.242	0.431	0.135	0.343	0.308	0.471	0.231	0.430
Renovation work	0.514	0.500	0.495	0.503	0.438	0.499	0.462	0.508	0.500	0.510
Never switch off the heating system	0.384	0.487	0.242	0.431	0.483	0.503	0.346	0.485	0.538	0.508
Adjust the heating system	0.870	0.336	0.884	0.322	0.876	0.331	0.923	0.272	0.923	0.272
Windows closed during heating	0.008	0.090	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Heating Degree Days	2496.06	383.007	2474.35	382.868	2492.73	401.848	2601.76	247.323	2398.93	394.970

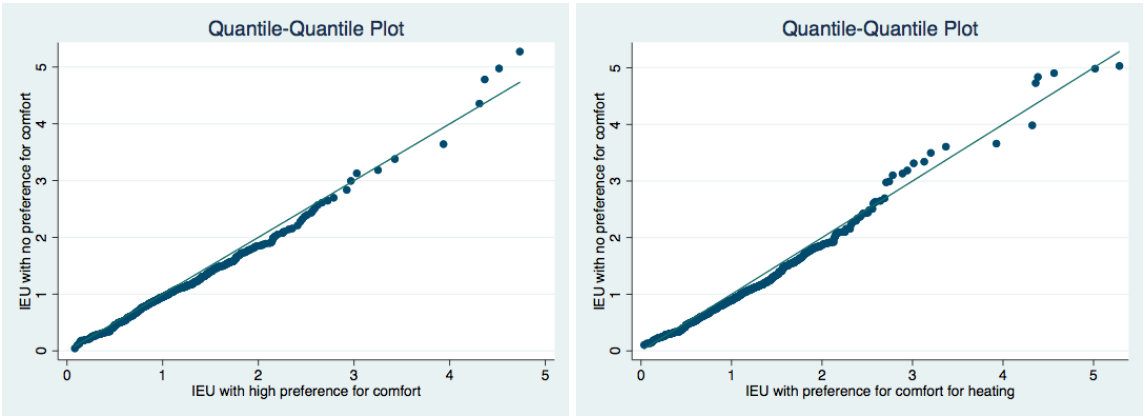
*Quantiles of IEU Source: authors' calculations, PHEBUS 2012 **the choice of 30% for gas is to ensure comparison of IEU values between samples.

Role of preferences for comfort over energy savings

According to Table 1, households with no preference for comfort represent 29.5 % of quantile 0.2 as opposed to only 19.1% for quantile 0.85. This difference is reinforced in the gas sample, with 38.5% in quantile 0.3 versus 0% in quantile 0.85 (see Table 10 in the appendix for the IEU value for the gas sample). Still in the gas sample, the share of households declaring a strong preference for comfort in heating represents 76.9% of the population that overconsumed but only 42.3% of households that under-consume. People who declare having preferences for comfort are overrepresented in households that overconsume.

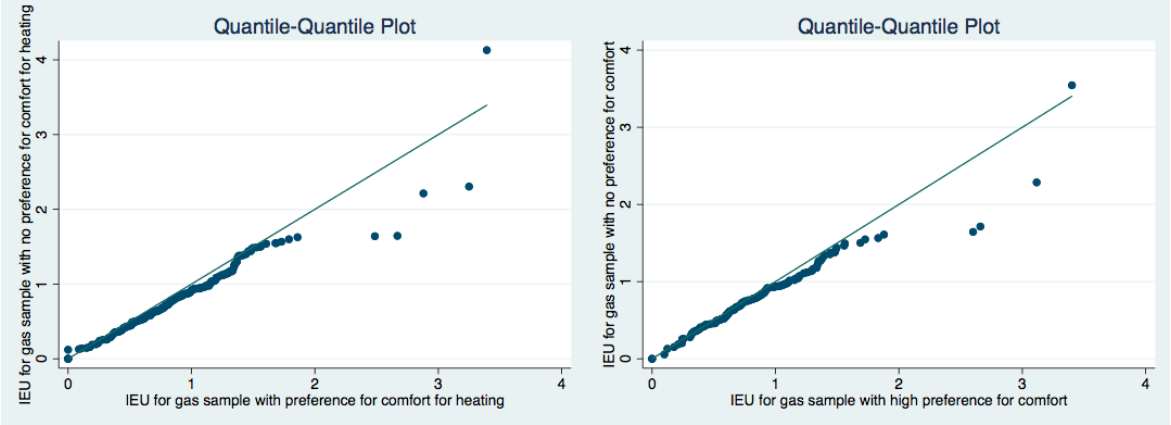
According to Figures 2a and 2b, we can also see that most data points are to the right of the main diagonal on both graphs. This means that the distribution values on the x-axis are usually higher than those on the y-axis. In our case, this means that households with strong preferences for comfort and preferences for comfort in heating have a higher IEU than households with no preference, in both samples. This confirms the descriptive statistics in Table 1 that show that preferences for comfort over economy are declared more often for high values of IEU (0.85 quantile) than for low values (0.20 quantile). Heating use makes up on average 61% of global energy consumption; its influence could thus be meaningful in impacting global energy consumption, which is confirmed with the gas sample.

Figure 2a: Quantile plot according to preferences for comfort (global sample)



Data: PHEBUS 2012, author calculations

Figure 2b: Quantile plot according to preferences for comfort (gas sample)



Data: PHEBUS 2012, authors' calculations

Energy price and revenue

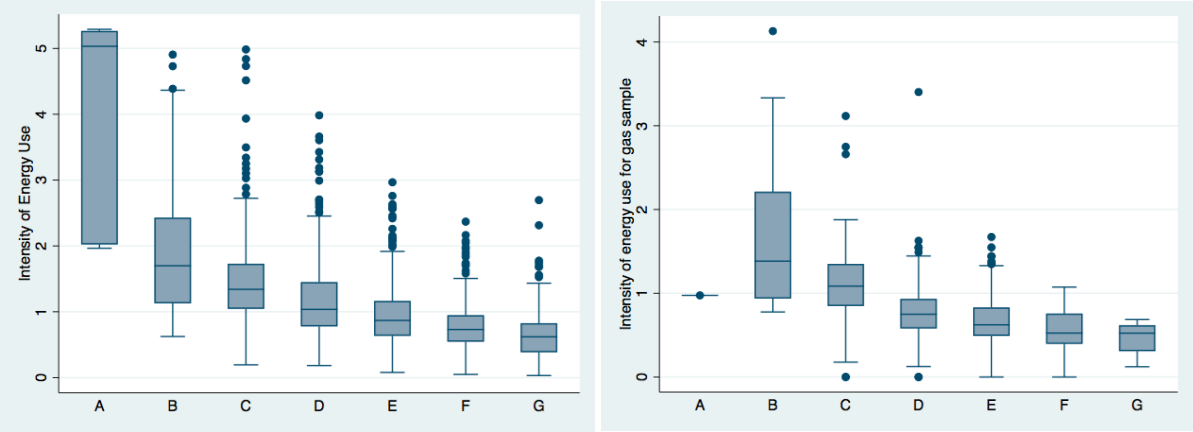
Higher energy price and lower revenue are found in the first quantiles of IEU. Energy price is 8.8% higher on average in the 0.20 quantile than in the 0.85 quantile. Revenue is 13.9% lower on average in the 0.20 quantile than in the 0.85 quantile.

Moreover, the percentage of households in monetary poverty also implies the potential role of financial resources in explaining under-consumption: the percentage of these households is much larger (two times higher) in the 2.0 IEU quantile than in the other quantile. These results lead to the hypothesis of significant effects of energy price (negative effect) and income elasticities (positive effect) on IEU, resulting in restriction behaviour relative to energy use.

Energy efficiency of the dwelling and IEU

Our analysis of PHEBUS data shows that intensity of energy use follows a visible trend linked to the energy-efficiency level of homes; similar results are found in Sunnikka-Blank and Galvin's research (2012). In order to investigate the characteristics of high IEU value, we compare values according to energy labels. For the less energy-efficient dwellings, energy is under-consumed, meaning that either the theoretical energy measure is over-assessed or households strictly restrict their energy consumption (Figure 3). The inverse trend is observable for very energy efficient-dwellings: energy is overconsumed in energy classes A and B due to what is usually called the rebound effect.

Figure 3: Intensity of energy use by energy class (EPC) for the global and gas samples

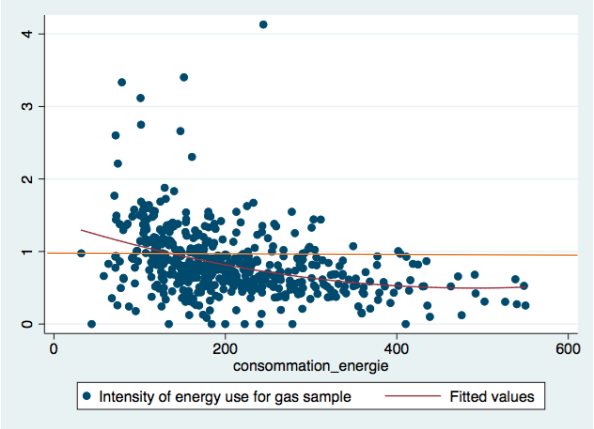


Global sample Gas sample

Data: PHEBUS 2012, authors' calculations

If we consider the dwellings with gas heat and gas-heated water, the relationship between theoretical energy consumption and IEU can be graphically modelled (Figure 4). We note that the link is statistically significant. There is a clear trend in the data: the more energy efficient the dwelling is, the higher the IEU. Under-consumption is noticeable for dwellings with a theoretical energy consumption over 200 kwh/m2 (Classes E-F-G).

Figure 4: Relationship between IEU (vertical axis) and EPC measure (expressed in final energy kwh/m^2) in the gas sample, 517 observations.



Note for the reader: Theoretical energy consumption on the abscissas axis, expressed in kWh/m2

In line with the literature, we thus assume that the trend observed in the global and gas samples could come in part from a "comfort effect" or from restriction behaviours regarding energy consumption (Sunikka-Blank and Galvin, 2012). This belief is strengthened by descriptive statistics in Table 2 that show that income and preferences for comfort seem to be linked with the energy efficiency of dwellings. Moreover, preferences are also linked to income (see Table 11 in the appendix). However, we are aware that errors in the theoretical measures are possible (for instance, theoretical energy consumption can be under-estimated in energy efficient dwellings, leading to a potential biais in the meaning of the IEU indicator).

Table 2: Individual preferences for comfort, behaviour and poverty by class

	Class A	**Class B**	**Class C**	**Class D**	**Class E**	**Class F**	**Class G**
Number of observations	5	39	260	526	554	261	208
Percentage of households preferring comfort over economy for:							
Heating	80%	64%	57%	58%	58%	51%	57%
Hot water	60%	67%	58%	58%	57%	52%	47%
Specific electricity	40%	38%	43%	44%	41%	41%	39%
Strong preference for comfort*	20%	31%	29%	31%	31%	27%	25%
Medium preference for comfort*	60%	28%	25%	24%	22%	18%	21%
Low preference for comfort*	0%	21%	21%	20%	21%	23%	24%
Limit heating consumption	0%	13%	22%	20%	23%	31%	27%
Monetary poor	0%	15%	12%	13%	18%	31%	37%
Report cold problem	0%	7.7%	10%	13.3%	15.3%	21.8%	27.4%
Fuel poor	20%	7.7%	3.8%	5.5%	10.3%	15.7%	19.7%
Income (st dv)	51067 (22293)	49733 (40628)	44872 (24804)	43337 (24990)	38685 (20553)	36462 (284804)	31578 (19507)

**This variable is compounded from PHEBUS data: strong preference for comfort means that the household declared that it prefers comfort over economy for all three energy uses: specific electricity, heating and hot water; medium preference means that this preference for comfort concerns two of the three energy uses; and finally, low preference means that the preference for comfort concerns only one energy use.*

Source: PHEBUS Survey 2012

4.Model

1) Quantile regressions

We perform a quantile regression analysis to understand the drivers of the energy performance gap; this method lets us tease out the effects of preferences on the entire distribution of the energy performance gap spectrum instead of focusing on the conditional average.

By using quantile regressions, we can specify the differentiated impacts of socioeconomic determinants on several energy consumption levels (under-consumption, normal consumption and overconsumption patterns), which are estimated by the *Intensity of Energy Use* (IEU) indicator. The quantile regression method is an extension of ordinary regression[90]. It was first introduced by Koenker and Bassett (1978) and generalizes the concept of the univariate quantile to a conditional quantile given one or more covariates. Thus, it is less restrictive than the OLS method because slope coefficients can vary across the chosen quantiles of the dependent variable and hence are not only mean estimations. This method makes it possible to detect whether explanatory determinants have the same effects for extreme values of the dependent variable (for example, for 5th, 25th and 75th quantiles) and to quantify these effects. In addition to giving robust coefficient estimations with respect to outliers, in our case, it is also useful to assess the variability of the main determinants of over- and under-consumption, behaviours represented by extreme values of our dependent variable *Intensity of energy use.* By doing so, we may detect differential impacts of revenue, energy price or individual data such as preferences on the level of consumption. As an example, the research of Kaza (2010) uses this method to estimate the impacts of numerous determinants on different quantiles of energy consumption in the US residential sector. It shows that the effects of neighbourhood density, housing size and housing type on the tails of the distribution are substantially different.

Any real valued random variable, Y, may be characterized by its distribution function as follows:

$$F_Y(y) = Prob\ (Y \leq y)$$

[90] Before choosing quantile regression, we ensure the absence of energy price endogeneity with the dependent variable. We introduce as an instrument the lag of energy prices in order to deal with the simultaneity problem. This instrument has already been used in previous studies to deal with the same problem (Risch and Salmon, 2017; Robert, 2015). We confirm the validity of our instruments and the absence of endogeneity.

For any θ in the interval (0,1), the quantile function $Q_Y(\theta)$ provides the θ-th (unconditional) quantile of Y. We have:

$$Q_Y(\theta) = F_Y^{-1}(\theta) = inf\{y: F_Y(y) \geq \theta\}, \theta \in (0,1)$$

We introduce y, the vector of *Intensity of energy use* data (in logarithmic form), x, a vector of all the regressors, β, the vector parameters to be estimated and u, a vector of residuals. In a classical linear regression model, we would have:

$$y_i = x_i'\beta + u_i\,, \quad i = 1, \dots, n$$

In the case of the linear regression, if we assume that the expected value of the error term given the regressors is 0, $(E(u_i|x_i) = 0)$, then the conditional mean of y_i with respect to x_i is

$$E(y_i|x_i) = x_i'\beta$$

The parameter vector β can be estimated by the method of least squares as follows:

$$\hat{\beta} = arg \min_{\beta \in R} \sum_i (y_i - x_i'\beta)^2$$

If we now consider the linear quantile regression, it can be written as follows:

$$y_i = x_i'\beta_\theta + u_{i,\theta}$$

Then the θ-th conditional quantile of $y_i$with respect to x_i is:

$$Q_\theta(y_i|x_i) = x_i'\,\beta_\theta,$$

This model is identical to the standard linear regression model, except that one replaces the conditional expectation $E(y_i|x_i)$ by a conditional quantile (Schulze 2004).

Let us consider $\rho_{\theta(u)} = u\big(\theta - I(u < 0)\big), 0 < \theta < 1$, also called the *check function*, and $I(A)$, the indicator function, $I(A) = 1$ if A is true and $I(A) = 0$ otherwise.
The quantile estimator minimizes the objective function over $\widehat{\beta_\theta}$ (Cameron and Trivadi, 2010) as follows:

$$\widehat{\beta_\theta} = arg\, min_{\beta_\theta \in R} \left[\sum_{i:yi \geq x_i'\beta}^{N} \theta|y_i - x_i'\beta_\theta| + \sum_{i:yi < x_i'\beta}^{N} (1-\theta)|y_i - x_i'\beta_\theta|\right]$$
$$= arg\, min_{\beta_\theta \in R} \sum_i \rho_\theta(y_i - x_i'\beta_\theta)$$

Thus, in the quantile regression, all observations above the estimated hyperplane given by $X\widehat{\beta_\theta}$ (the absolute difference between y_i and $x_i'\widehat{\beta_\theta}$) are weighted with θ and all observations below the estimated hyperplane are weighted with $(1-\theta)$ (Schulze 2004).
Consider that, for instance $\theta = 0.75$, then much more weight is placed on predictions for observations with $y_i \geq x_i'\beta_{0.75}$ than for observations with $y_i < x_i'\beta_{0.75}$. The special case of the conditional median (θ = 0.5) can be calculated as follows:

$$\widehat{\beta_{0.5}} = \ arg\ min_{\beta_{0.5} \in R} \sum_i |\, y_i - x_i'\beta_{0.5} \,|$$

Finally, asymptotic and bootstrapping methods are used to obtain the standard errors and confidence limits for coefficient estimates.

For our global model, we first use quantiles 0.2 and 0.85 to determine the specific effects of the determinants on extreme performance gaps. Quantile 0.2 represents an IEU equal to 0.56 and quantile 0.85 represents an IEU equal to 1.52. Quantile (0.2 0.85) also specifies that two equations are to be estimated, one for each quantile. For the gas sample, we use quantiles 0.3 and 0.85 (an IEU value of 0.57 and 1.32, respectively) in order to ensure a consistent comparison between the global sample and the gas sample.

Thus, quantile regression will allow us to determine the effects of individual preferences and energy prices on the intensity of energy use. The coefficient that will be obtained for each identified quantile of IEU tells us how the tails of intensity of energy use react differently to an increase in each variable of interest. While the price of energy should have a negative effect on the energy performance gap, we expect a positive impact for income and individual preferences for comfort.

The other explanatory variables used are the following: the number of heating degree days, the number of consumption units, the ability to adjust the heating system, the age of the reference person, the practice of not opening windows during the heating period and the practice of switching off the heating system when windows are open. We run several quantile regressions to test the effect of three related variables on IEU: strong preferences for comfort over economy (regression 2) and preferences for comfort over economy for heating use (regression 3) and heating temperature (regression 4). We also present our results compared to an OLS estimation (regression 1). Finally, robustness tests of parameters (especially when we introduce income and preferences separately) are presented in appendix C (Table 12).

2) Quantile treatment effects

When the objective is to assess the causal effect of a specific explanatory variable on the entire distribution of a variable of interest, the estimation of quantile treatment effects (QTEs) may be useful (D'Haultfoeuille and Givord, 2014). QTEs make it possible to evaluate the effect of a binary dummy variable T, which corresponds to the difference between the quantiles of the distribution in the population for the two states of the dummy. Here, we assume that each observation has two potential IEUs: Y_1 corresponds to the IEU the household can expect with the dummy in state 0 (for example, absence of strong preferences for comfort over economy) and Y_1, the IEU the household can expect with the dummy in state 1 (for example, having strong preferences for comfort over economy). Two distributions, F_{Y0} and F_{Y1}, are associated with these two potential IEUs. The τth "quantile treatment effect" is defined as the horizontal distance between the two distributions (Doksum, 1974).

$$\delta_q = q_\tau(Y_1) - q_\tau(Y_0)$$

This program uses a weighting strategy. The estimator proposed by Firpo (2007) is used in our case because unconditional QTEs under exogeneity are estimated.

In our research, we test the effect on the two extreme quantiles of IEU (0.2 and 0.85) of the following variables: preferences for comfort over economy (strong preferences and preferences for comfort in heating use, hot water use and specific electricity use), poverty, cold issue, restriction on heating consumption and fuel poverty. Quantile treatment effects are also run on the gas sample. Our results are presented in the following section.

5.Results

The general trend of our coefficient estimates (Regressions 2, 3 and 4) is consistent with our use of the quantile regression in understanding the drivers of the energy performance gap: several of our explanatory variables do have a differentiated effect varying across IEU quantiles (see Table 3).

Table 3: Results of quantile regressions on global sample

IEU is the dependant variable	OLS	Quantile regression							
		Regression 1		Regression 2		Regression 3		Regression 4	
		Q=0.2	Q=0.85	Q=0.2	Q=0.85	Q=0.2	Q=0.85	Q=0.2	Q=0.85
Energy price (log)	-0.104***	-0.0976***	-0.121***	-0.105***	-0.147***	-0.107***	-0.107***	-0.0956***	-0.140***
	(0.0209)	(0.0268)	(0.0375)	(0.0225)	(0.0367)	(0.0256)	(0.0365)	(0.0244)	(0.0335)
Income (log)	0.0744**	0.111**	0.106*	0.0878*	0.141**	0.0677	0.124**	0.0662	0.130***
	(0.0334)	(0.0485)	(0.0563)	(0.0475)	(0.0550)	(0.0526)	(0.0559)	(0.0456)	(0.0502)
Consumption unit (UC)	0.403*	0.485*	0.725*	0.436	1.016***	0.280	0.845**	0.291	0.967***
	(0.223)	(0.290)	(0.370)	(0.286)	(0.360)	(0.315)	(0.357)	(0.277)	(0.345)
age	-0.00179***	-0.00179***	-0.00212**	-0.00211***	-0.00209**	-0.00212***	-0.00186**	-0.00175***	-0.00172*
	(0.000434)	(0.000660)	(0.000860)	(0.000588)	(0.000832)	(0.000588)	(0.000862)	(0.000576)	(0.000934)
Heating degree days (log)	-0.200***	-0.107**	-0.324***	-0.104***	-0.298***	-0.113***	-0.306***	-0.118***	-0.324***
	(0.0366)	(0.0433)	(0.0693)	(0.0391)	(0.0674)	(0.0423)	(0.0648)	(0.0435)	(0.0694)
Never switch off the heating system	0.0459***	0.0487***	0.0589***	0.0368**	0.0420*	0.0383***	0.0402*	0.0506***	0.0602**
	(0.0131)	(0.0163)	(0.0227)	(0.0148)	(0.0234)	(0.0143)	(0.0225)	(0.0157)	(0.0238)
Possibility to adjust the heating system	0.0335*	0.0528*	0.00150	0.0535**	0.00846	0.0681**	0.00562	0.0565*	-7.07e-05
	(0.0196)	(0.0279)	(0.0326)	(0.0249)	(0.0352)	(0.0270)	(0.0345)	(0.0306)	(0.0308)
Windows closed during the heating period	-0.000703	-0.0675	0.0179	-0.115	0.0555	-0.0767	0.0107	-0.0606	0.0434
	(0.0816)	(0.118)	(0.156)	(0.120)	(0.150)	(0.114)	(0.150)	(0.109)	(0.186)
Strong preference for comfort				0.0450***	0.0695***				
				(0.0142)	(0.0253)				
Preference for comfort in heating						0.0418***	0.0483**		
						(0.0144)	(0.0217)		
Stated Heating temperature								0.0186***	0.0249***
								(0.00433)	(0.00619)
Interaction parameter (income and uc)	-0.0326	-0.0428	-0.0626*	-0.0373	-0.0895***	-0.0227	-0.0732**	-0.0240	-0.0852***
	(0.0210)	(0.0273)	(0.0352)	(0.0271)	(0.0340)	(0.0297)	(0.0339)	(0.0260)	(0.0323)
Constant	1.170**	-0.102	2.048***	0.0802	1.393**	0.341	1.705**	0.0793	1.223*
	(0.456)	(0.642)	(0.723)	(0.614)	(0.702)	(0.673)	(0.683)	(0.630)	(0.664)

Note: standard errors in parentheses *** p<0.01, ** p<0.05, ***p<0, 3000 replications

Table 4: Estimates for quantile treatment effects for global sample and gas sample

1) Global Sample (1,853 observations)	Q=0.2		Q=0.85	
	Coefficient	Bootstrap Std. Err.	Coefficient	Bootstrap Std. Err.
Strong preference for comfort	0.0320**	0.0141	0.0498**	0.0211
Comfort preference for heating	0.0421**	0.0169	0.0466**	0.0217
Comfort preference for hot water	0.0284*	0.0148	0.0185	0.0204
Comfort preference for electricity	0.0146*	2.0100	0.0521**	0.0202
Cold problem	-0.0512***	0.0242	-0.0580	0.0426
Limit heating consumption	-0.0397*	0.0144	-0.0298	0.0283
Fuel poor by the 10% definition	0.0249**	0.0195	-0.0073	0.0376
Monetary poor (60% median)	-0.0868*	0.0176	-0.0867	0.0256

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1, 3000 replications

2) Gas Sample (517 observations)	Q=0.3*		Q=0.85	
	Coefficient	Bootstrap Std. Err.	Coefficient	Bootstrap Std. Err.
Strong preference for comfort	0.0447653	0.0556478	0.1224759**	0.062161
Comfort preference for heating	0.1155424**	0.0537769	0.1233805*	0.0655496
Comfort preference for hot water	0.0648034	0.0617895	0.1277027**	0.0655822
Cold problem	-.006735	0.0785468	-0.1847566**	0.0851247
Limit heating consumption	-0.108445	0.0665022	-0.1276259	0.0809505
Fuel poor by the 10% definition	0.1248077	0.1408438	0.1395232	0.1123413
Monetary poor (60% median)	-0.1223761*	0.0664371	0.0125486	0.0912034

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1, 3000 replications

*the 0.3 quantile corresponds to a IEU of about 0.5 in the gas sample

Prices and income elasticities

Energy price elasticity is significant and negative for all the quantiles of IEU, which is consistent with previous findings in the energy economics literature. Extreme energy performance gaps (low and high IEU quantiles) are often explained by energy price elasticity (household reaction to a change in energy price). However, regressions show that energy price elasticity is slightly lower for the first quantiles of IEU (0.2) than for the 0.85 quantile, around

-0.11 and -0.15 respectively. Thus, energy price variability affects under-consumption less broadly than it does overconsumption situations.

Given this result, under-consumption seems to be associated with energy restriction behaviours. Indeed, the fact that households restrict their consumption of energy to the level needed to achieve only their basic needs (low IEU) is consistent with a lower sensitivity to changes in energy price. On the other hand, dwellings with overconsumption are likely to have more flexibility in their energy consumption, which can explain the greater energy price elasticity.

Income elasticities are in line with previous findings in the economics literature, i.e. between 0.06 and 0.14: energy is a normal good (Cayla, *et al.*, 2011; Labandeira, *et al.*, 2006; Nesbakken, 2001; Santamouris, *et al.*, 2007). However, coefficients vary according to IEU quantiles: households with a high IEU have a higher income elasticity, which could underscore an ability to increase their equipment rate (and their electricity consumption).

Monetary and fuel poverty

The poverty situation of the household explains up to 8.7% of the energy performance gap. Quantile treatment effects provide evidence that being poor (living below the poverty line) has a significant, negative effect on the lower quantile of IEU considered. This result is more pronounced in the gas sample: households restrict their heating consumption in monetary poverty (12.2% of the gap is explained by poverty in the gas sample case). In our descriptive statistics, we demonstrated that poor households are generally found in the lower value of IEU; thus, under-consumption is assumed to be strongly related to the limited economic resources of the household.

Otherwise, a link can be established with the findings of Meier, *et al.* (2013) who found that low-income households had lower energy price elasticities than high-income households. As we demonstrated in our descriptive statistics (Table 1), low-income households are more numerous in the lower quantile of IEU.

Finally, the role of poverty in explaining low IEU is even stronger if we remember the link between dwellings with poor energy efficiency (meaning high energy expenditures) and under-consumption situations (low IEU): as poor households face high energy expenditures because of the weak energy performance of their homes, we can assume that they are more likely to restrict their energy consumption. This is also in line with the effect of the variable called “limit heating consumption” (Tables 4 and 5), whose effect is significant and has a negative effect only on the first quantile of IEU considered, in both the global and gas samples.

Individual preferences and behaviour

The effects of individual preferences and behaviours are significant. Regressions show that the binary variable "strong preferences for comfort over economy" has a positive effect, growing with the quantiles of IEU. Preferring comfort over economy for all three energy uses (heating, hot water and specific electricity) leads to an increase by almost 5% of the IEU for the 0.85 quantile, meaning that individual preferences contribute 7% of the variability in the gap in overconsumption situations (versus 4.5% for 0.2 IEU quantiles). If we look at the effect of preferences for comfort in heating use for each quantile of IEU (regression 3), the values of the coefficients found are quite similar to those estimated in regression 2, which indicates that preferences for comfort in heating use are a prevalent driver in explaining the energy performance gap. This is consistent with the fact that 61% of the global energy consumption comes from residential heating needs. Preferences for comfort in specific electricity also contribute to explaining the gap for high IEU (Tables 4 a., quantile treatment effect for the global sample); we note that their effect on high IEU is greater than the one found for preferences for comfort in heating. Even though it only accounts for about 20% of energy consumption, a significant portion of high-energy consumption patterns can be explained by specific electricity consumption.

Our estimates show that individual preferences for comfort do have an impact in explaining the energy performance gap, but this impact seems limited (3 to 7%). However, this result has to be viewed cautiously, as the scopes of theoretical and real energy consumption considered in the IEU indicator are not equivalent: real energy consumption includes all types of energy consumption regardless of the energy uses, whereas theoretical energy consumption only includes consumption from heating and hot water energy uses. As a robustness check (table 4.b, gas sample), the results of the quantile treatment effect on the gas sample confirm that preferences for comfort in heating have a significant role in explaining the energy performance gap. Thus, up to 12% of the energy performance gap can be explained by individual preferences for heating.

Finally, never switching off the heating system has a significant positive effect on IEU; this effect is quite homogeneous over the different quantiles of IEU, unlike the possibility of adjusting the heating system, which has a positive effect only on the lower quantile of IEU.

Household characteristics and climate

Besides the roles of energy price and preferences in explaining the energy performance gap, our research highlights the role of several other salient drivers (see Tables 3). The number of consumption units has a significant positive effect on IEU; this effect is higher for the 0.85 quantile representative of overconsumption. The age of the reference person has a quite homogeneous negative effect over the different quantiles of IEU.

Finally, we note that the factor with the most impact on explaining the energy performance gap is heating degree days. The effect is significant and negative for all quantiles of IEU. However, the effect is much greater for the high quantiles of IEU. The significant impact of this climate variable could be the result of either a false assessment of the climate factors in developing the theoretical measure of energy consumption or an important behavioural adaptation of households to local climate change that is not considered in models: an increase in heating degree days (cold weather) leads to a decrease in IEU. Households with high IEU values can better adjust their consumption in severe winter (perhaps to avoid extra costs). Heating needs might thus be under-assessed for freezing temperatures.

6.Discussion and policy implications

To sum up the main results, we observe that the effect of heating or strong preferences for comfort is almost twice as large in the last quantile of IEU as it is in the first quantile of IEU; this confirms the more important role of preference for comfort in explaining the gap in overconsumption situations. This result is confirmed in regression 4 in Table 3, where we also note a growing trend in the effect of heating temperature on IEU quantiles: the indoor temperature, a proxy of comfort preferences, has more impact on high quantiles of IEU than it does on lower ones. On the other hand, energy under-consumption, i.e. low IEUs (Q=0.2), are partly explained by monetary and fuel poverty (Table 3 and 4).

In the current political context that is primarily focused on energy efficiency issues in the residential sector, the goal of this discussion is to use our main results to provide key elements of analysis to policymakers with this energy efficiency perspective. In that sense, we would point to Figure 3, which identifies a strong relationship between IEU and the energy class of each dwelling. The graph illustrates that overconsumption situations are more likely to be found in energy-efficient dwellings, whereas under-consumption situations are more frequent in dwellings with a very poor energy performance.

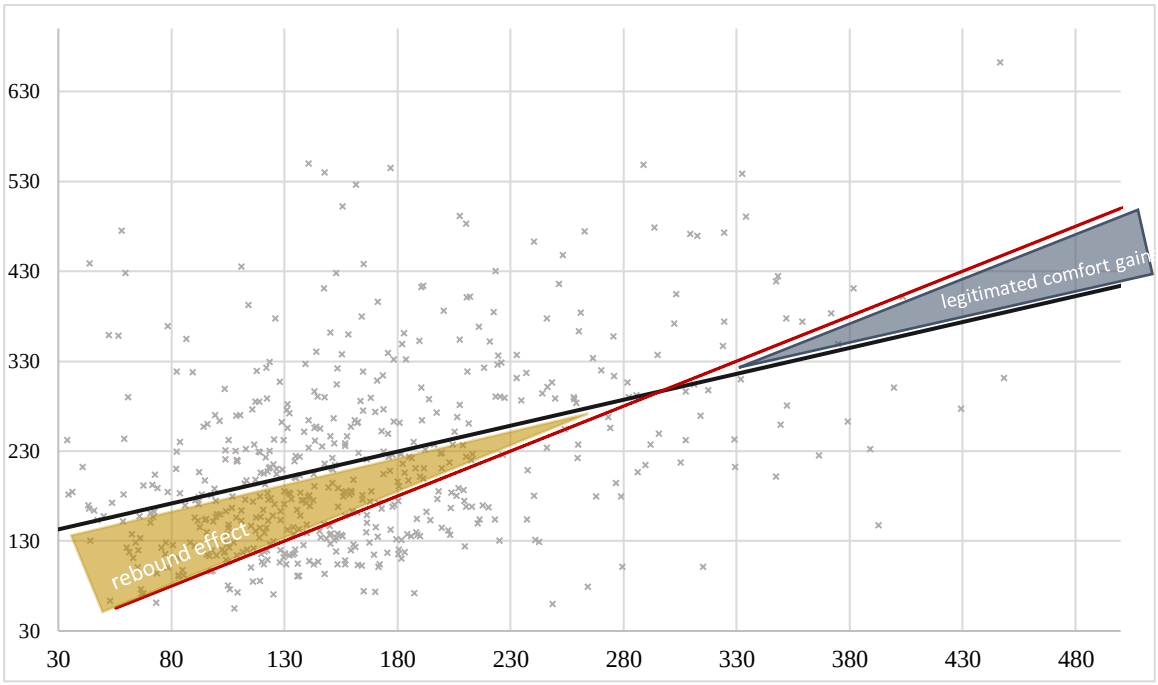
A new perspective in understanding the rebound effect in the residential sector

Our results can be linked to the issue of the rebound effect and provide key insights. The direct rebound effect reflects the potential increase in the demand for a service (here energy use) after an improvement in its efficiency (Freire-González, 2017; Greening et al., 2000). This effect is visible in our cross-sectional dataset (figure 5). Indeed, the real energy consumption does not decrease at the same rate as the theoretical energy consumption; it decreases more slowly. If we look at figure 5, our findings suggest that a 100 kWh/m2 decrease in theoretical energy consumption leads to a 42 kWh/m2 decrease in real energy consumption. More generally, a 100% improvement in home energy efficiency leads to a 58% reduction in real energy consumption, meaning that 43% of energy savings are "lost" (rebound effect): this could be partially justified by comfort improvement when energy service costs decrease.

If we consider the households in our database who report having increased heating after energy-efficiency work, a t-test demonstrates that they statistically overconsume (IEU equal to 1.24 for people declaring a direct rebound effect versus 1.0 for the others). They represent 6.3% of the households in the sample who have undertaken energy-efficiency renovations. This result underscores the fact that investment in energy efficiency have to be accompanied by moderation in energy consumption if energy goals are to be achieved.

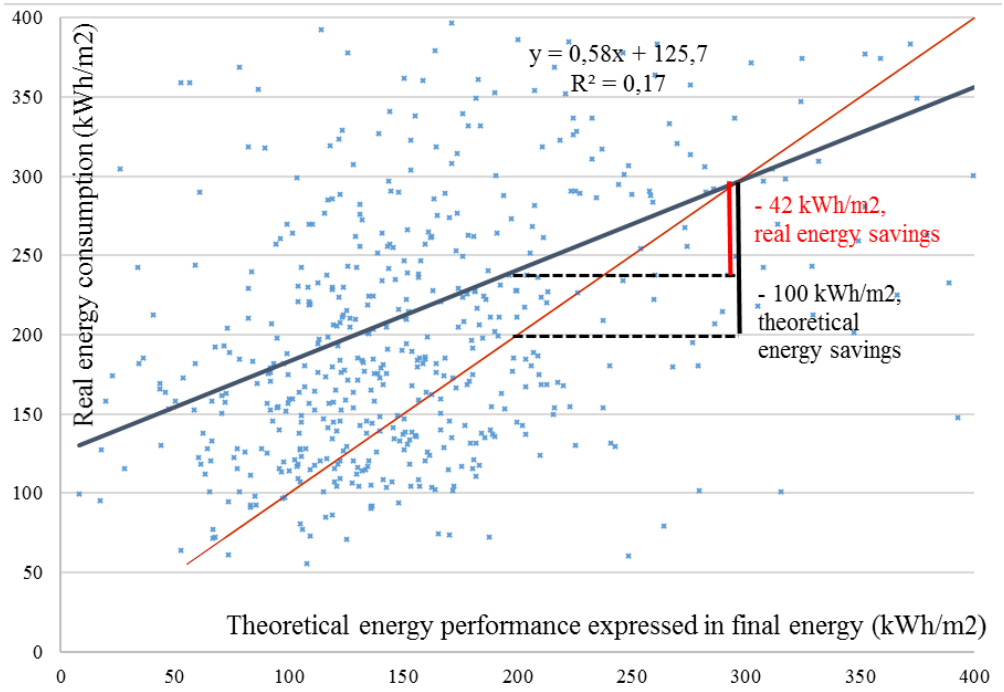
However, with regard to our results, the cross-sectional results suggest that the "rebound effect" does not have the same meaning for everybody. If we consider the households who live in a sub-standard situation in the first place, meaning a dwelling with very poor energy performance and an associated low IEU (the household severely restricts its energy consumption), an increase in energy efficiency will lead to a relaxation of the financial constraints related to energy consumption, which leads to a relative increase in its energy consumption (the rebound effect process). However, in this case, these households will increase their energy consumption in order to achieve or approach the "standard" or "legitimate" comfort level because they were previously limiting their energy consumption well below the norm (Nösperger, *et al.*, 2017). In this specific case, the rebound effect means households simply catching up with standard comfort standards; thus, here, the recommendation of energy consumption moderation is much less relevant.

Figure 5a: Real energy consumption vs theoretical energy consumption. y, real energy consumption and x, the theoretical energy consumption. Gas sample. Data: PHEBUS, 2012.



Note for the reader: The red curve stands for the bisector (theoretical energy consumption). If the gap between the two curves comes only from behavioural data, the "rebound effect" should be equal to (1-0.58)×100 =42%. However, here, it is probably less than 43% because other drivers also explain the energy performance gap. Data are cross-sectional.

Figure 5b: Measure of rebound effect with cross-sectional dataset (zoom of the previous figure)



Considerations on fuel poverty and restriction behaviours

Our research demonstrates that under-consumption of energy compared to the theoretical measure is partially explained by poverty and preferences for energy savings over comfort. This consumption pattern is also associated with low energy efficiency in dwellings. Thus, households that under-consume are likely to experience restriction behaviours regarding energy consumption mainly explained by a lack of financial resources to achieve their theoretical well-being standard.

In line with this result, we advise policymakers interested in the fuel poverty issue not to forget the people who restrict their energy consumption. The Grenelle II[91] law defines as fuel poor those people who face difficulties meeting their standard energy needs due to either their low income or their poor living and housing conditions. However, the classic fuel poverty indicator used in France does not identify households restricting their energy consumption as fuel poor; indeed, the measure is based on the ratio of real energy expenditures to income (how much money households are really spending on their consumption of energy relative to their revenue) and not on modelled energy needs. Thus, if a household restricts its energy consumption in comparison to what it should theoretically consume because of financial issues, by design, it will not be considered in the classical energy poverty indicators.

The IEU can also be estimated at national scale, which can give an interesting perspective to get the global picture of the welfare situation of the households of the French dwelling stock . Considering the mean energy performance gap for the gas-heated dwelling stock (6 million dwellings), we get a mean intensity of energy use of 0.74 (Table 5, sample weights[92]), meaning that in reality, the dwelling stock currently consumes 25% less than estimated by engineering calculations. This could be explained by the dwelling stock's constitution in 2012, when the half of the residential dwelling stock belonged to energy classes less than D and thus are more likely to "under-consume" energy. This result argues in favour of an existing welfare issue regarding thermal comfort for most French households. Future research needs to be done to identify how deep this issue really is.

[91] https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000022470434
[92] Representative of the French housing stock

Table 5 The Energy performance gap at national scale

Theoretical energy consumption, gas sample (EPC, kwh)	Real energy consumption (kwh)	IEU
1,21791E+11	90 974 714 580	0,75

7.Conclusion

This research provides a new proof of the significant role of individual characteristics in explaining energy consumption variability. Household income, energy price, the number of persons in the dwelling, the age of the reference person, the number of appliances, the number of heating degree days and the preferences for comfort over economy are found to be significant factors in explaining the energy performance gap in the French residential sector. In the specific gas sample, our research highlights that up to 12% of variability in the energy performance gap is explained by our variable for individual preferences for comfort.

More than just identifying a list of factors, our research highlights several phenomena that help understand energy consumption patterns in French homes. First, our research demonstrates that under-consumption of energy compared to the theoretical measure is partially explained by poverty issues and preferences for energy savings over comfort. Moreover, we provide evidence that overconsumption is associated with strong preferences for comfort as well with higher energy efficiency of dwellings. The identification and understanding of these energy consumption patterns are extremely relevant for energy policymaking.

Finally, we would like to stress that a significant share of the energy performance gap remains unexplained or misunderstood, underlying the fact that further research is needed to improve our understanding of extreme energy performance gaps.

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Appendix

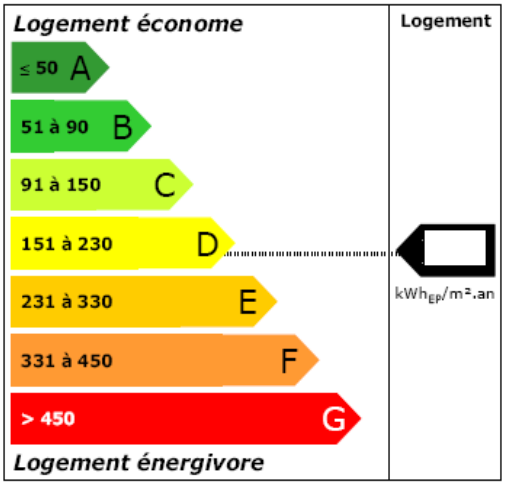
Energy class and EPC measure

The increase in comfort demand regarding energy use after an energy-efficiency improvement has been theoretically integrated into the EPC calculation thanks to a factor of intermittence[93] that can be defined as:

$$INT = \frac{I_0}{1 + 0.1\ (G - 1)}$$

where $G = \frac{ENV}{CORH}$ and $CORH = HSP/2{,}5$. ENV is a measurement of the heat losses in the dwelling. I_0 is tabulated data based on heating systems and building type. This INT factor increases with better insulation and thus implies an increase in theoretical energy consumption with the higher energy efficiency of the dwelling. Thanks to the descriptive analysis, we can assume that this factor of intermittence is potentially underestimated in terms of thermal efficiency's effect on energy consumption.

Figure 6: EPC energy classes



[93] This represents the variability of energy consumption due to day-occupancy duration and also includes a kind of rebound effect.

Descriptive statistics

Table 6: Stated preferences and behaviour

	Global sample		**Gas sample*** **	
	preference for…*		**preference for...**	
	Thermal comfort	**Energy-savings**	**Thermal comfort**	**Energy-savings**
Last winter, were you in the habit of regularly lowering the temperature or turning off the heat in the bedrooms …				
At daylight	0.283 **	0.345	0.271	0.354
At night	0 .465	0.517	0.521	0.611
When you open the window to ventilate a room, do you turn the heating of the room down or off?				
Always	0 .374	0.448	0.347	0.441
Most of the time	0.441	0.502	0.438	0.5109
Do you limit your heating consumption?				
Yes	0.090	0 .424	0.097	0.4323
	preference for...			
	Hot water comfort	**Energy savings**		
Number of showers (per cu)	7.137015	7.522		
	preference for...			
	Electricity comfort	**Energy savings**		
Number of appliances	17.08366	15.649		

*"When it comes to indoor heating, do you prefer …?". This question is asked after gathering energy-saving behaviours.

** The null hypothesis of equality of proportions cannot be rejected with a 90% confidence level. All the rest of the proportions are statistically different at the 90% confidence level or more.

***Only preferences for thermal comfort are studied

Table 7: Summary statistics of preferences

	Frequency	%	Frequency	%
No preference	504	27.20	146	28.21
Low preference	393	21.21	111	21.47
Medium preference	412	22.23	111	21.47
Strong preference	544	29.36	149	28.82
Total	1,853	100.00	517	100.00

Table 8: Preferences according to end uses

Whole sample				
	Preference for energy savings - hot water end use		Preference for comfort - hot water end use	
	Preference for energy savings - heating end use	Preference for comfort - heating end use	Preference for energy savings - heating end use	Preference for comfort - heating end use
Preference for energy savings - electricity end use	504	187	158	239
Preference for comfort - electricity end use	48	82	91	544

Gas sample				
	Preference for energy savings - hot water end use		Preference for comfort - hot water end use	
	Preference for energy savings - heating end use	Preference for comfort - heating end use	Preference for energy savings - heating end use	Preference for comfort - heating end use
Preference for energy savings - electricity end use	146	48	48	76
Preference for comfort - electricity end use	15	15	20	149

Table 9: Descriptive statistics

Variable	Obs	Mean	Std.Dev.	Min	Max
Real energy consumption (kwm/m2)	1,853	168.28	95.5	9.72	757.98
Theoretical energy consumption (kwm/m2)	1,853	265.01	134.08	22.52	994.59
Intensity of energy use	1,853	1.06	0.63	0.03	5.29
Intensity of energy use (gas sample)	517	0.83	0.47	0	4.13
Income	1,853	40029	23919	307	249406
Energy price 2012	1,853	0.09	0.03	0.01	0.38
No preference for comfort	1,853	0.27	0.45	0	1
Low preference for comfort	1,853	0.21	0.41	0	1
Medium preference for comfort	1,853	0.22	0.42	0	1
Strong preference for comfort	1,853	0.29	0.46	0	1
Preference for comfort in heating	1,853	0.57	0.5	0	1
Preference for comfort in hot water	1,853	0.56	0.5	0	1
Preference for comfort in electricity	1,853	0.41	0.49	0	1
Heating temperature	1,853	19.93	1.49	8	30
Number of consumption units	1,853	1.69	0.54	1	4.3
Age of reference person	1,853	56.19	15.13	13	98
Cold problem	1,853	0.16	0.37	0	1
Limit heating consumption	1,853	0.23	0.42	0	1
Fuel poor by the 10% definition	1,853	0.1	0.3	0	1
Monetary poor (60% median)	1,853	0.19	0.4	0	1
Renovation work	1,853	0.51	0.5	0	1
Never switch off the heating system	1,853	0.38	0.49	0	1
Adjust the heating system	1,853	0.87	0.34	0	1
Windows closed during heating	1,853	0.01	0.09	0	1
Heating Degree Days	1,853	2496.07	383.01	1285.6	3153.1

Table 10: Ventile of IEU (gas sample), Source: PHEBUS

	Mean	Std. Dev.	Min	Max
1	0.1180	0.0898	0.0000	0.2436
2	0.3181	0.0408	0.2548	0.3683
3	0.4098	0.0219	0.3710	0.4396
4	0.4761	0.0193	0.4442	0.5061
5	0.5219	0.0091	0.5074	0.5373
6	0.5674	0.0151	0.5380	0.5900
7	0.6097	0.0104	0.5901	0.6271
8	0.6476	0.0142	0.6271	0.6687
9	0.6894	0.0128	0.6723	0.7139
10	0.7408	0.0171	0.7153	0.7750
11	0.7952	0.0140	0.7763	0.8154
12	0.8342	0.0122	0.8172	0.8570
13	0.8780	0.0137	0.8575	0.9073
14	0.9296	0.0119	0.9079	0.9490
15	0.9861	0.0224	0.9497	1.0226
16	1.0769	0.0322	1.0289	1.1203
17	1.1787	0.0382	1.1231	1.2534
18	1.3236	0.0389	1.2618	1.3791
19	1.4568	0.0524	1.3804	1.5476
20	2.1234	0.7254	1.5481	4.1300

Table 11: Correlation table

	IEU	Income	No pref	Low pref	Medium pref	Strong pref	Pref heating	Pref HW	Pref elect	Temp (°C)
IEU	1.0000									
Income	0.0862	1.0000								
No pref	-0.0552	-0.1269	1.0000							
Low pref	-0.0514	-0.0392	-0.3171	1.0000						
Medium pref	0.0544	0.0807	-0.3268	-0.2774	1.0000					
Strong pref	0.0504	0.0855	-0.3940	-0.3345	-0.3447	1.0000				
Pref Heating	0.0675	0.1054	-0.7005	-0.0962	0.2282	0.5625	1.0000			
Pref HW	0.0567	0.1052	-0.6853	-0.1618	0.2627	0.5750	0.4323	1.0000		
Pref elect	0.0640	0.1288	-0.5125	-0.3063	0.0077	0.7688	0.4241	0.4611	1.0000	
Temp (°C)	0.1217	0.0304	-0.1819	-0.0168	0.0454	0.1514	0.2420	0.1110	0.1273	1.0000

D. Regressions

Table 12: Robustness tests

	(1)		(2)		(3)		(4)	
VARIABLES	Q=0.2	Q=0.85	Q=0.2	Q=0.85	Q=0.2	Q=0.85	Q=0.2	Q=0.85
Energy price (log)	-0.0976***	-0.121***	-0.0905***	-0.0993***	-0.0950***	-0.121***	-0.0967***	-0.151***
	(0.0268)	(0.0375)	(0.0233)	(0.0350)	(0.0260)	(0.0368)	(0.0220)	(0.0368)
Income (log)	0.111**	0.106*			0.106**	0.109**		
	(0.0485)	(0.0563)			(0.0496)	(0.0551)		
Uc (consumption unit)	0.485*	0.725*			0.470	0.759**	0.0582***	0.0758***
	(0.290)	(0.370)			(0.294)	(0.366)	(0.0180)	(0.0212)
Age	-0.00179***	-0.00212**			-0.00177***	-0.00211**	-0.00169***	-0.00181**
	(0.000660)	(0.000860)			(0.000655)	(0.000847)	(0.000582)	(0.000786)
Heating degree days(log)	-0.107**	-0.324***			-0.109**	-0.322***	-0.110***	-0.286***
	(0.0433)	(0.0693)			(0.0445)	(0.0671)	(0.0385)	(0.0690)
Never switch off the heating system	0.0487***	0.0589***			0.0490***	0.0587***	0.0295*	0.0458*
	(0.0163)	(0.0227)			(0.0161)	(0.0225)	(0.0157)	(0.0249)
Possibility to adjust the heating system	0.0528*	0.00150			0.0503*	0.00196	0.0560**	0.0134
	(0.0279)	(0.0326)			(0.0277)	(0.0343)	(0.0237)	(0.0365)
Windows closed during heating	-0.0675	0.0179			-0.0652	0.0179	-0.0721	0.0125
	(0.118)	(0.156)			(0.120)	(0.162)	(0.122)	(0.162)
Strong preference for comfort							0.0440***	0.0445*
							(0.0142)	(0.0244)
Interaction parameter between income and uc	-0.0373	-0.0895***			-0.0412	-0.0657*		
	(0.0276)	(0.0331)			(0.0277)	(0.0347)		
Constant	0.0802	1.393**	0.253***	0.705***	-0.0366	1.999***	1.027***	2.735***
	(0.615)	(0.705)	(0.0575)	(0.0830)	(0.657)	(0.691)	(0.299)	(0.552)

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Conclusion et transition vers le chapitre 4

Les conclusions issues de ce troisième article confirment les résultats obtenus précédemment. Les préférences individuelles, les contraintes économiques des ménages et la performance énergétique du logement sont bien des éléments clés de la compréhension des comportements énergétiques dans le secteur résidentiel. La combinaison de ces facteurs permet d'expliquer une partie significative des « écarts à la norme » en termes de consommation énergétique (12% par exemple pour les préférences individuelles).

Les résultats montrent que la pauvreté serait un facteur explicatif des situations de sous-consommation énergétique, cela est particulièrement le cas pour les ménages habitant dans les logements de faible performance énergétique. Au contraire, des préférences individuelles pour les conforts élevés expliqueraient une partie significative des écarts de consommation énergétique dans le sens de la surconsommation, notamment dans les logements de meilleure performance énergétique.

Ces éléments d'éclairage à destination des décideurs publics fait émerger des enjeux de justice sociale et énergétique liés à la question de la transition énergétique des bâtiments, notamment par rapport à l'utilisation d'outils de politique publiques incitatifs comme la fiscalité écologique : cela pourrait aggraver la précarité énergétique si des dispositifs compensatoires ne sont pas mis en place.

Finalement, nos travaux suggèrent aussi l'existence d'un effet rebond, visible à partir de nos données en coupe (enquête Phebus, 2012). Mis en relation avec les résultats de l'analyse quantile, cet effet rebond serait justifiable par un gain de confort légitime pour les ménages habitant initialement dans les logements les moins performants d'un point de vue de l'efficacité énergétique. Bien qu'il soit légitime, l'effet rebond direct réduit cependant le potentiel d'économie d'énergie attendu par la mise en place des solutions d'efficacité énergétique. Estimer sa magnitude est nécessaire, notamment pour mieux appréhender les économies d'énergies qui peuvent être effectivement atteintes par la massification des mesures d'amélioration de l'efficacité énergétique, ce qui peut apporter un éclairage important pour les futures stratégies d'efficacité énergétique dans le résidentiel.

Cela fera l'objet du quatrième chapitre de la présente thèse.

Chapitre 4

Direct rebound effect of residential gas demand: Empirical evidence from France using an autoregressive distributed lag approach to cointegration*

*Cet article a été écrit en collaboration avec Fateh Belaïd et Davide Roubaud. Il a été publié dans Energy Policy en 2018[94].

Abstract

Energy policymakers are increasingly concerned about energy efficiency improvements, as such improvements are considered to be a key strategy in reducing energy demand in the residential sector. However, energy efficiency investments may not yield the expected energy-savings due to the rebound effect concept, which leads to lower savings than expected when energy-efficiency increases. Using the standard OLS regression and autoregressive distributed lag cointegration (ARDL) approach, this paper provides estimates of the magnitude of the rebound effect for residential gas consumption in France. Using 1983–2015 annual time-series data, the methodology is based on estimates of the gas demand elasticity with respect to service price. The empirical findings indicate that the variables used in the model are cointegrated and suggest the presence of an obvious rebound effect in residential gas use. More specifically, estimates of the direct rebound effect in residential gas demand are approximately 60% in the short-run and approximately 64% in the long-run. Our findings reject the hypothesis of a backfire effect regarding residential gas use in France and hence suggest incorporating carbon taxation, energy efficiency and alternative energy in the formulation of an energy-saving policy to facilitate the transition towards a low-carbon economy in France.

Keywords: Rebound effect; Energy efficiency; Residential gas demand; Jevons Paradox

[94] Belaïd, Fateh & Bakaloglou, Salomé & Roubaud, David, 2018. "**Direct rebound effect of residential gas demand: Empirical evidence from France**," Energy Policy, Elsevier, vol. 115(C), pages 23-31.

1.Introduction

In the context of the 2015 Paris agreement, 195 countries have committed to limit global warming to no more than 2 degrees above pre-industrials levels. To do so, contracting parties have presented their national contribution and committed to review it every five years, with each new contribution including a progression in comparison to the previous one. The French government committed to reduce its greenhouse gas emissions by 40% by 2030 and by 75% by 2050 compared to the 1990 level[95]. To achieve these goals, France has undertaken to increase to 32% the contribution of renewable energies to its final energy consumption by 2030 and to reduce energy consumption by 50% by 2050.

Strategic orientations and roadmaps have been defined by sector to implement a low-carbon transition process between 2015 and 2028. Relative to its important potential for greenhouses gas (GhG) emissions reduction and energy savings, the greatest effort is required by the building sector, with a goal to reduce its GhG emissions by 54%. Improving dwelling energy efficiency is one of the core strategies for reducing energy consumption and its related carbon emissions. Improving the energy efficiency of the housing stock has long been considered an effective strategy to reduce residential energy demand and achieve sustainability policy goals. Nevertheless, an increase in housing energy efficiency does not necessarily translate into an equal decrease, in absolute terms, in energy demand as energy efficiency savings can be undermined by changes in consumer attitude and behaviour, i.e., the rebound effect.

The rebound effect depicts an attitudinal and a behavioural response to an improvement in energy efficiency. Therefore, the scope of the savings depends on the efficiency-induced attitudinal and behavioural effects. Although the rebound effect concept has fairly old origins that date back to the seminal works of Jevons, the rebound effect phenomenon has been gaining in popularity since the early 1980s, when it was rediscovered in both policy and academic areas (Jevons, 1865). In fact, the positive causal relationship between energy efficiency and energy demand was identified by Jevons (Jevons, 1865) after having been literally overlooked for more than a century.

Major findings from recent years have produced evidence of the existence of a rebound effect regarding energy consumption in the residential sector (Berkhout et al., 2000; Greening et al.,

[95] The energy transition law for green growth, published in the official journal of August 2015.

2000; Khazzoom 1980; Thomas and Azevedo, 2013), indicating that improving the energy efficiency of the dwelling has behavioural side effects that can drastically reduce its benefits. Indeed, the rebound effect reflects the propensity of households to increase their comfort, that is, energy demand, when home energy efficiency is improved. Today, the existence of the rebound effect in the residential sector is well known, but its magnitude is still a major focus of economics research. In a great majority of the cases, the rebound effect can induce a loss of more than 30% of the energy savings achievable with an energy efficiency investment. Therefore, as the energy road map strongly focuses on the energy efficiency improvement of the existing dwellings stock, to be aware of the magnitude of the potential non-achieved energy savings, it seems of critical significance to measure the extent of the rebound effect.

In this paper, we focus on the rebound effect regarding gas consumption in the residential sector. Gas is the second most used energy for individual energy uses (see Fig. 3) and accounts for more than 30% of the national energy consumption. In France, gas is consumed primarily for heating and cooking needs, and thus, because of the important share of energy consumption dedicated to heating, we assume that gas consumption is a good proxy for heating energy consumption. Accordingly, this paper focuses on the measurement of the magnitude of the rebound effect for this particular energy use. More precisely, we focus on the challenge of measuring the magnitude of the direct rebound effect, which is the additional gas use attributable to the increased energy service demand when the implicit price of gas declines due to energy efficiency improvement, whereas the indirect rebound effect is the increase in gas use following a change in the demand of other services due to improved energy efficiency.

The main hypothesis of this study is that household attitude and behaviour are among many factors that limit expected energy-savings from energy efficiency investment in what is known as the rebound effect. By embarking on this path, this study contributes to the existing literature on the rebound effect phenomenon in several ways.

First, this study examines the magnitude of the direct rebound effect with respect to gas demand in France. To the best of our knowledge, empirical research on this rebound effect in France is rather limited due to the lack of information and availability of data on residential energy use.

Second, using the ARDL co-integration approach, which has a distinct advantage compared with other co-integration approaches (e.g., Engle and Granger, 1987; Johansen and Juselius, 1990), this research provides estimates of the magnitude of the residential gas rebound effect both over the short and the long run. One distinguishing advantage of the ARDL testing

approach is its ability to estimate the long-run economic relationship irrespective of whether the explanatory variables are I(0) or I(1).

Third, based on the recent advances in time series econometrics this study investigates the backfire hypothesis, both in the short run and in the long run. The findings refute the backfire hypothesis in both the short-run and long-run, which implies that improvement in energy efficiency helps to reduce residential gas demand in France.

Finally, from a policy-making perspective, this study answers the question of what type of strategy (e.g., refurbishing existing dwellings, providing assistance to poor households, providing additional information and data on household lifestyles and behaviours, incorporating housing policy into residential energy policy, etc.) affects residential energy efficiency schemes.

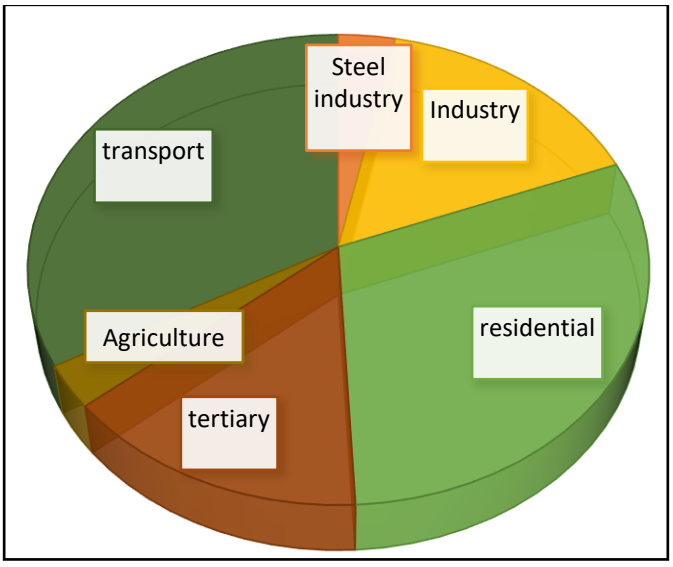
This paper is organized as follows. Section 2 provides a brief overview of the French residential energy efficiency policy. Section 3 reviews the literature and presents the theoretical background. Section 4 describes the data and the modelling procedure. Section 5 presents our empirical results and discusses their implications. Section 6 then concludes and provides some possible policy implications of our main findings.

2. Overview of the French residential energy-efficiency scheme and domestic energy demand

In France, the residential dwelling stock is composed of approximately 33.5 million housing units (French household survey, 2013)[96]. This stock is responsible for 30% of the global French energy demand (45 Mtoe in 2015) and for 20% of the greenhouse gas emissions emitted in 2014 (CGDD, 2015).

[96] French household survey conducted by the National Institute for Statistics and Economic Studies (INSEE, 2013).

Figure 1 Share of each sector in the total final energy consumption of France in 2015. Source: Bilan energetique de la France-2015, Statistique développement durable



Because of the huge energy-savings and GhG emissions reduction potential, the residential sector has been designated a major target for energy transition. The Energy Transition for Green Growth law (2015) specified the road map for the residential sector as follows: (i) by 2025, all private residential buildings consuming more than 330 kWh/m².year must have been thermally renovated; (ii) by 2050, the dwelling stock must be renovated with respect to the BBC standards or related rules. As it appears in the roadmap today, the improvement of the energy efficiency of the residential sector is the focus. To achieve its goals, the main French energy policies are concerned with the improvement of the energy efficiency of the residential dwelling stock with a focus on the improvement of the thermal characteristics of former and new homes to decrease heating energy consumption. The policies are twofold: (i) implement thermal regulation (RT 1974, 1982, 1988, 2005, 2012[97]) that sets energy performance thresholds for new and existing dwellings (when retrofitting), and (ii) institute financial incentives to foster thermal retrofits with the objective to execute 500 000 thermal retrofits per year.

As a result, energy efficiency technologies aiming to reduce heating needs have spread, and final energy consumption for space heating has declined by 10% since 1990[98]. However, the diffusion of energy efficiency equipment for thermal improvement faces two major barriers: (i) A low demand, principally because high investments are required. In 2014, only 288 000

[97] http://www.developpement-durable.gouv.fr/Chapitre-I-La-RT-existant-par.html
[98] Odyssee, climatic correction, France.

dwellings of the 26 million constituting the residential stock were renovated efficiently or very efficiently with respect to energy performance (OPEN, 2016). (ii) A less than expected effectiveness as the energy savings realized after the energy efficiency improvements are not as great as theoretically expected. This less than expected performance may be explained by the bad quality of energy retrofits, errors in measuring energy efficiency, and behavioural impacts of dwelling occupants (Galvin and Sunnika-Blank, 2012), the latter of which is the focus of this paper.

Today, heating energy use is the major driver of domestic energy consumption, accounting for more than 60% of the final energy consumption of a French household (see Fig. 1). Even if this particular cause of energy consumption has decreased in absolute terms (see Fig. 2) due to the implementation of thermal retrofits, regulations and economic circumstances, the resulting decrease is less important than expected. Thus, there is a need to understand the weight of behavioural issues in explaining the inefficient share of energy efficiency for heating consumption. To do so, we focus on gas consumption because it is in second position (see Fig. 3) in terms of sources of energy used for domestic purposes and constitutes a good proxy to approach heating energy consumption and the rebound effect, which we consider in our analysis.

Figure 2. Share of each energy use and evolution of residential energy consumptions (Twh, normal climate). Source: CEREN

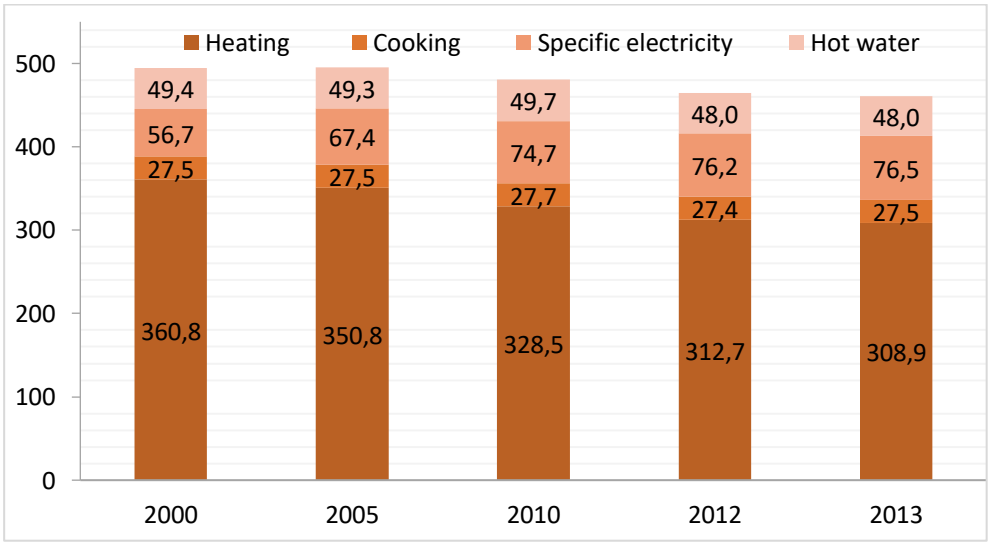
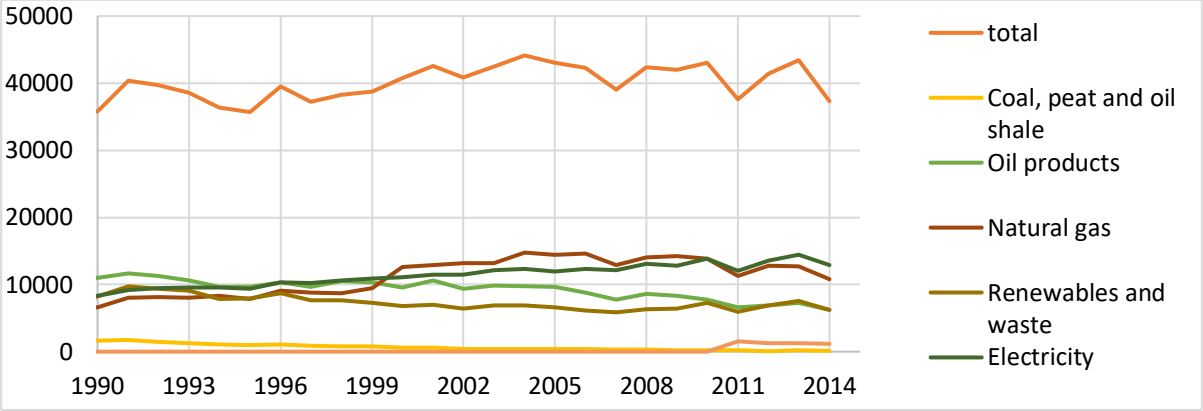


Figure 3. Trajectories of energy consumptions (residential sector by energy source) for France (ktoe). Source: International Energy Agency



Finally, in the global context as introduced herein, understanding the drivers of national residential energy demand is a major factor, as such understanding will contribute to identifying certain elements necessary to support and anticipate future energy trajectories in the framework of the Paris Agreement. Specifically, by choosing to quantify the share of the residential energy demand with respect to the rebound effect, we offer French policies new elements to design, more precisely, future energy commitments and build efficient public policies.

3. Literature review of methodological approaches, definitions and estimations of rebound effect

3.1 Defining the rebound effect

According to the perimeter we consider, the economic literature identifies three types of rebound effects, namely, direct rebound effect, indirect rebound effect and economy-wide effect (Freire-González, 2017; Greening et al., 2000; Thomas and Azevedo, 2013). Moreover, the reduction in the cost of an energy service due to an energy efficiency improvement could have three possible effects:

(1) The potential increase in the demand of this service

(2) The potential increase in the demand of other goods and services

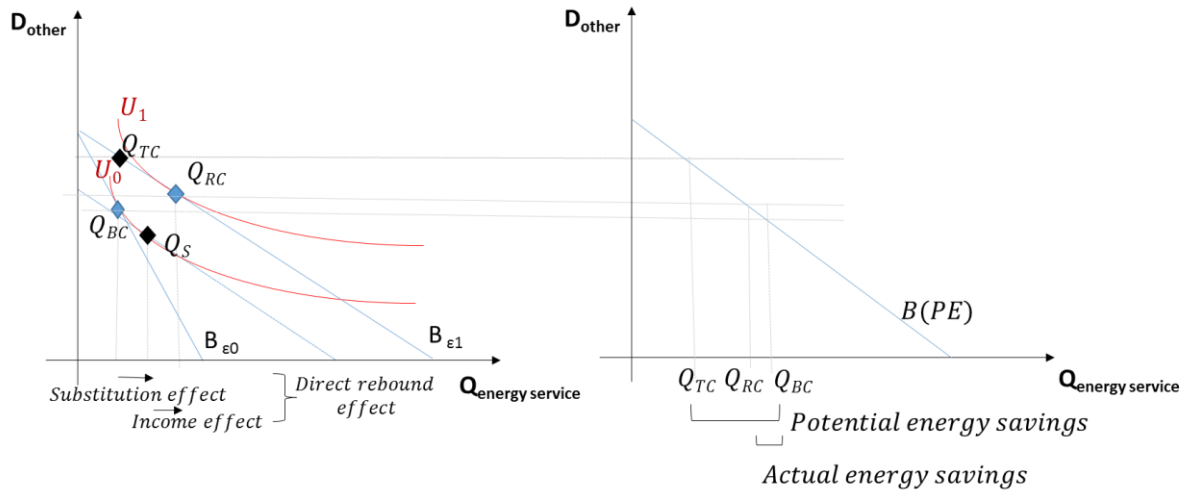
(3) The rebalancing of the economic system through price and quantities

Because of its significant impact on efficiency and the efficiency assessment of the sectorial public policies, the measurement of the direct rebound effect is highly relevant in this research. The direct rebound effect refers to the loss of energy efficiency due to behavioural changes after energy efficiency improvements. Due to technical progress, less energy is necessary for the same energy service, which first leads to a fall or decrease in the energy

service cost per unit of service provided and then induces an increase in energy consumption (Berkhout et al., 2000; Sorrell and Dimitropoulos, 2008). This effect is usually explained by the fact that households choose to re-allocate energy cost savings into comfort improvements, e.g., by increasing indoor temperature or heating duration. The rebound effect mechanism reflects the classic reaction to a price change. That is, first, a substitution effect occurs that corresponds to a re-allocation effect at constant utility. Then, as the energy service becomes cheaper, the bundle of goods consumed by the household is adjusted, thus leading to an increase in energy goods at the expense of other goods. Hence, an income effect occurs because the consumer does not spend as much money as before on the energy good, and therefore, the consumer's purchase power increases, which allows the consumer to allocate the savings to an increased demand for the energy good and thereby achieve a higher utility.

For the same level of heating service demand Q_{BC}, less energy is needed when using more energy-efficient equipment ($\varepsilon_1 > \varepsilon_0$). Households adjust their utility level and, as a result, increase their energy service demand(Q_{BC} becomes Q_{RC}). A rebound effect of x% corresponds to the share of theoretical energy savings ($Q_{RC} - Q_{BC}$) lost because of the adjusted increase in the heating service demand after the energy efficiency improvement, $x = \frac{(Q_{RC} - Q_{BC})}{(Q_{TC} - Q_{BC})} \times 100$. If the rebound effect exceeds 100%, i.e., when the share of actual energy savings lost because of the rebound effect is greater than the share of potential energy savings, it is referred to as the backfire effect (Khazzoom 1980; Sorrell and Dimitropoulos 2008; Thomas and Azevedo 2013).

Figure 4. Direct rebound effect mechanism as inspired by (Thomas and Azevedo, 2013)



where
D_{other} denotes demand for other goods;
$Q_{energy\ service}$ denotes demand for energy service, with BC as a baseline case, RC as a rebound case, TC as a theoretical case, and S as a substitution effect case;

B Budget constraint
U Utility level, with $\varepsilon 0$ low energy efficient equipment and $\varepsilon 1$ high energy efficient equipment;
P_E Energy price;

3.2. Review on methods and measurements

For decades, empirical research has attempted to capture the measure of the rebound effect through a large panel of methodologies. In their literature review, Sorrell and Dimitropoulos (2008) distinguish two main approaches. The first, named the *quasi-experimental approach*, relies on a comparison of energy consumption before/after energy retrofit and strongly depends on the availability of precise data and control variables. The other is the *econometric approach*, which includes a cross-sectional analysis, time series and panel data. With this approach, economists assess energy efficiency elasticity, in other words, the way energy service demand reacts to energy efficient improvement. However, this specific approach is rarely used because of the lack of data, including a variable representative of the energy efficiency level of the equipment. The other option, however, is the estimation of the energy service cost elasticity. This methodological approach, which is detailed in this paper, is the most widely used in the literature.

3.2.1. Focus on the direct rebound effect and energy price relationship

Assessing the rebound effect through energy service elasticity has been the focus of recent works in this field. To do so, some authors have directly assessed the energy price elasticity based on the two following assumptions (Freire-González, 2017): (1) consumers react in a similar way to an efficiency improvement and a reduction in energy price; (2) energy efficiency is not affected by energy prices (Berkhout et al., 2000; Binswanger 2001; Khazzoom, 1980). Because Khazzooms's concept of the rebound effect (Khazzoom, 1980) associates energy service with a single commodity, he found that the efficiency elasticity of the demand for energy equals the negative of the price elasticity for demand for the energy service minus one.

$$\eta_{\varepsilon}(e) = -\eta_P(v) - 1$$

where P is the price of the energy service, $\mathrm{P} = \frac{\mathrm{P_E}}{\varepsilon}$, $\mathrm{P_E}$ is the energy price and ε is the energy efficiency of the equipment.

The rebound effect and energy price are then closely related such that a high energy price elasticity implies a high rebound effect.

However, with this approach, the rebound effect tends to be overestimated (Thomas and Azevedo, 2013). By doing so, energy price elasticities are assumed to be the same for rising

and falling prices (Haas and Biermayr, 2000); however, this is not a realistic scenario. Energy demand comes from space heating demand, which depends on both energy use and efficiency. Then, when the energy price increases, the household has the possibility to invest in irreversible energy efficient equipment, such as better insulation and efficient heating systems, to reduce its service demand and save costs. Simultaneously, because of the important decrease in the heating service cost, the household may increase its thermal comfort to a certain extent. However, if the energy price decreases, technologies will not be removed, and only the reversible share of energy efficiency can then be adjusted by households and be increased. This constitutes a reversible efficiency elasticity or rebound effect. In our method, we include this non-symmetry of energy prices effect by using a price decomposition method developed by Gately (Dargay and Gately, 1995) and used by other scholars (Haas and Biermayr, 2000; Wang et al., 2014) who introduced the imperfect price–reversibility approach based on the following three-way decomposition of the logarithm of the energy price. As such, the price cut elasticity provides an estimation of the magnitude of the rebound effect.

$$P_t = P_1 + P_{max,t} + P_{cut,t} + P_{rec,t}$$

where $P_{1.}$ = log of price in starting year t=1

$P_{\max}$ is the cumulative increase in the log of the maximum historical price; $p_{max,t} = max\{p_0, p_1, \dots, p_t\}$

P_{cut} represents the cumulative decrease in the log price. When the energy price decreases, only the reversible share of energy efficiency is captured. This price cut elasticity is interpreted as the rebound effect.

P_{rec} represents the cumulative sub-maximum increase in the log price

3.2.2. Example of the direct rebound effect estimations in the literature

Rebound effect estimations vary across methodologies, countries, energy use, etc. In their 2008 review, Sorrell and Dimitropoulos (2008) found rebound effects varying from 10 to 58% for the short-run rebound effect for heating use and from 1.4 to 60% for the long-run rebound effect for heating use. Moreover, scholars have shed light on the extent to which the rebound effect varies across countries and regions (Thomas and Azevedo, 2013; Wang et al., 2014). The direct rebound effect can also vary according to the energy service being considered. For example, heating and cooling energy consumptions are more likely than baseline end-uses

to be of concern when examining rebound effects (Thomas and Azevedo, 2013). A precise review of recent works on rebound effect estimations is provided in the Table 1. Its systematic high values suggest that the public policies are of critical importance.

Table 1 Recent works on the assessment of the rebound effect in the residential sector.

Author	Country	Perimeter	Method	Estimated rebound effect
(Zhang and Peng, 2016)	China	Electricity consumption	Energy price elasticity, time series (panel regression) 2000-2013	71.5%
(Galvin, 2015)	Germany	Space heating consumption	Cross-section method	30%
(Wang et al., 2014)	China	Electricity consumption	Energy price elasticity with price decomposition, time series (panel regression) (1996-2010)	Short term: 72% Long term: 74%
(Thomas and Azevedo, 2013)	USA	Space heating/ electric end-uses	Review of US research; diverse approaches	1-15%
(Freire-González, 2011)	Catalonia	Electricity consumption	Energy price elasticity, time series 1999-2006	Short term: 36% Long-term: 49%
(Guertin et al., 2003)	USA	Space heating consumption	Cross-section method (OLS)	29–47% in the long term
(Haas and Biermayr, 2000)	Austria,	Space heating and electricity consumption	Energy price elasticity with price decomposition, time series (1972-1995) Cross-section method	Between 20 and 30%

4. Data

To assess the French rebound effect for the residential sector, this research uses time series for the period 1983-2014. The drivers of energy consumption include energy price, income per inhabitant, population density and, to capture the climate impact, heating degree days. Data of annual energy prices are obtained from the Pegase database[99] available on the website of the French ministry of Environment, Energy and Sea. Annual gas consumptions for

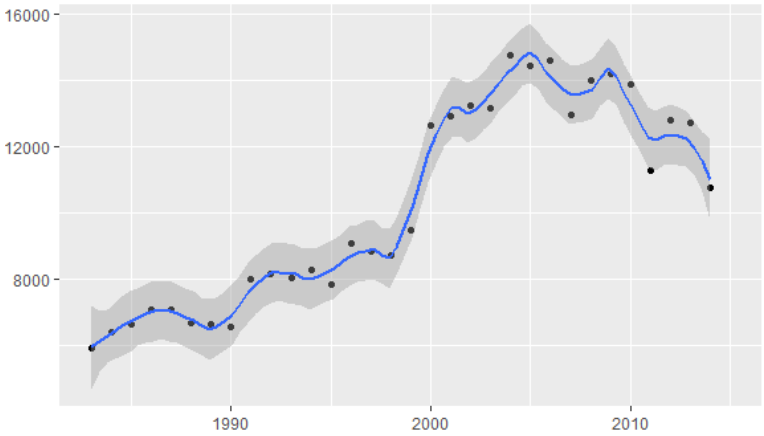
[99] Pégase (Pétrole, Électricité, Gaz et Autres Statistiques de l'Énergie) http://www.statistiques.developpement-durable.gouv.fr/donnees-ligne/r/pegase.html

the residential sector are accessible from the International Energy Agency[100] website. Socio-demographic data are obtained from the World Bank website[101], and climate data are obtained from the European Environment Agency website[102].

The evolution of gas prices indicates an increasing global trend since the end of the 1990s. The existence of intermediate trends (price falls and recoveries) justifies the relevance of using the price decomposition method previously discussed in this paper. As energy price increases induce energy efficiency investments and energy savings behaviours, we assume that the response to the local falls in the energy price that follow the increases allows us to observe only the reversible response of energy consumption, i.e., the rebound effect.

We find a similar global trend over time for energy consumption and the variable income per capita. More specifically, first, there is a slow increase between 1983 and 2000, which then accelerates until 2007, i.e., the beginning of the economic crisis, and finally, we observe a slight decrease over the period 2007-2014. The variable heating degree day constitutes a proxy for the number of days in the year that require the use of heating energy. This variable exhibits a decreasing trend over the period of our study. Finally, the density of the population increases continuously at the same rate over the period 1983-2014.

Figure 5. Evolution of gas consumption (ktoe). Source: IEA



[100] Source: IEA ©OECD/IEA 2016 (http://www.iea.org/t&c/termsandconditions/)
[101] http://databank.banquemondiale.org/data
[102] http://www.eea.europa.eu/data and-maps/data/external/european-degree-day-climatologies-and -

Figure 6a Evolution of gas price and price decomposition (in log) for the period 1983-2014 (euros/100 kWh)

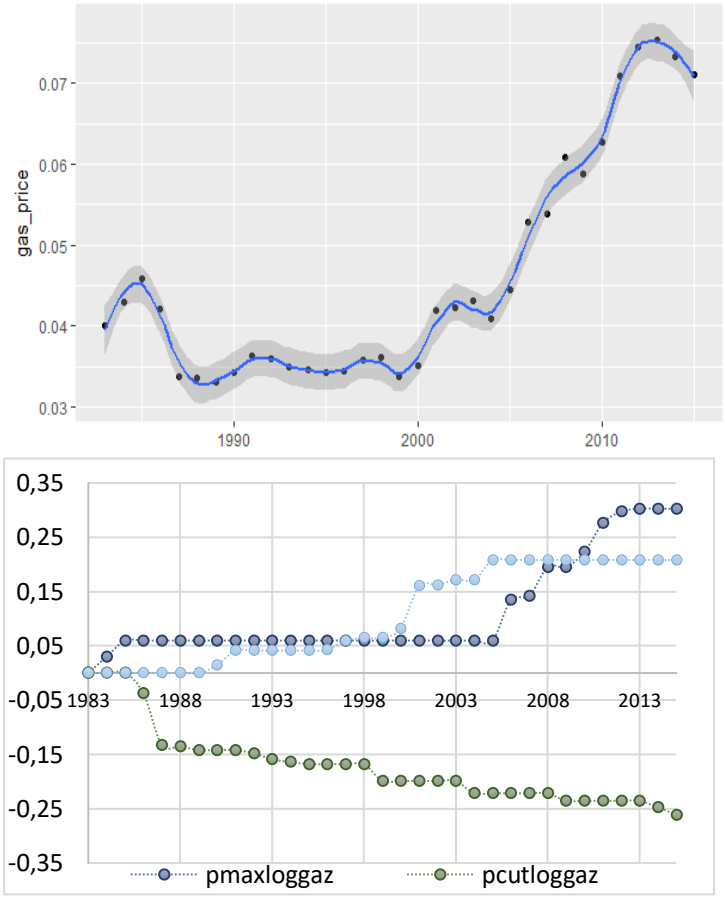
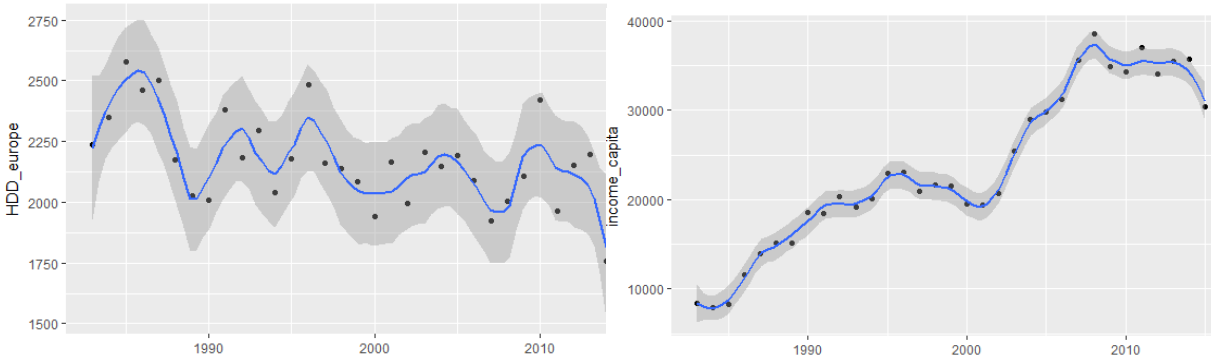
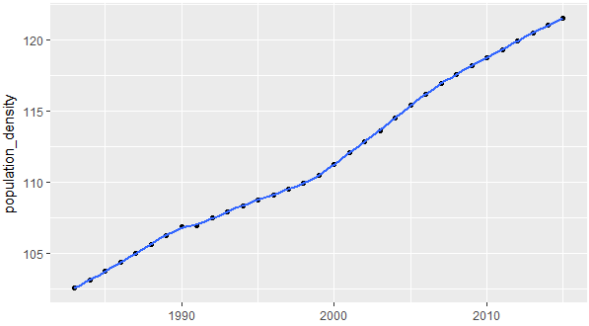


Figure 6b. Evolution of other variables. HDD: heating degree days, income per capita and population density.





5. Modelling approach

Based on data availability and on previous studies of received economic theory, our model is specified on a standard double-log linear functional form as follows:

$$\mathrm{GAS}_t = \beta_0 + \beta_1 \mathrm{GDP}_t + \beta_2 P_t^{rec} + \beta_3 P_t^{cut} + \beta_4 P_t^{max} + \beta_5 \mathrm{POP}_t + \beta_6 \mathrm{HDD}_t + \varepsilon_t \quad (1)$$

In Eq. (1), GAS, GDP, P^{rec}, P^{cut}, P^{max}, POP and HDD are, respectively, in natural logarithms, residential gas consumption, per capita real income, price recoveries, price cuts, historical maximum price, population growth and heating degree days in year t. The white noise term, ε_t, is assumed to be normally distributed. The coefficients β_1, β_2, β_3, β_4, β_5 and β_6 are, respectively, the elasticities of gas consumption with respect to GDP, P^{rec}, P^{cut}, P^{max}, POP and HDD.

To examine the presence of a long-run relationship in model (1) using ordinary least squares, we use the ARDL bounds approach based on the following specification:

$$\begin{aligned}\Delta\, GAS_t = \alpha_0 &+ \sum_{i=1}^{n-1} \alpha_{1i}\, \Delta\, \mathrm{GAS}_{t-i} + \sum_{i=1}^{n-1} \alpha_{2i}\, \Delta\, \mathrm{GDP}_{t-i} \\ &+ \sum_{i=1}^{n-1} \alpha_{3i} \Delta\, P_{t-1}^{rec} + \sum_{i=1}^{n-1} \alpha_{4i}\, \Delta\, P_{t-1}^{cut} + \sum_{i=1}^{n-1} \alpha_{5i}\, \Delta\, P_{t-1}^{max} \\ &+ \sum_{i=1}^{n-1} \alpha_{6i}\, \Delta\, POP_{t-1} + \sum_{i=1}^{n-1} \alpha_{7i}\, \Delta\, HDD_{t-1} + \beta_1 \mathrm{GAS}_{t-1} + \beta_2 \mathrm{GDP}_{t-1} + \beta_3 P_{t-1}^{rec} \\ &+ \beta_4 P_{t-1}^{cut} + \beta_5 P_{t-1}^{max} + \beta_6 \mathrm{POP}_{t-1} + \beta_7 \mathrm{HDD}_{t-1} + \varepsilon_t \quad (2)\end{aligned}$$

where α_0 denotes the deterministic drift component and Δ denotes the first difference operator of the respective variable. The existence of a cointegration relationship among GAS, GDP, P^{rec}, P^{cut}, P^{max}, POP and HDD in the long-run is verified via the non-standard F-test developed by Pesaran et al. (2001) and further modified by Narayan (2005) for a small series. Therefore, we test the null hypothesis of no cointegration $H_0: \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = \beta_7$, whereas the alternative hypothesis is $H_1: \beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq \beta_6 \neq \beta_7$

If we accept the alternative hypothesis of cointegration in model (2), we estimate the unrestricted error-correction model following the procedure in Pesaran (2001):

$$\Delta\, GAS_t = \alpha_0 + \sum_{i=1}^{n-1} \alpha_1\, \Delta\, \mathrm{GAS}_{t-i} + \sum_{i=1}^{n-1} \alpha_2\, \Delta\, \mathrm{GDP}_{t-i} + \sum_{i=1}^{n-1} \alpha_3 \Delta\, P_{t-1}^{rec} + \sum_{i=1}^{n-1} \alpha_4\, \Delta\, P_{t-1}^{cut} + \sum_{i=1}^{n-1} \alpha_5\, \Delta\, P_{t-1}^{max} + \sum_{i=1}^{n-1} \alpha_6\, \Delta\, POP_{t-1} + \sum_{i=1}^{n-1} \alpha_7\, \Delta\, HDD_{t-1} + \vartheta Z_{t-1} + vt \quad (3)$$

where Z_{t-1} denotes the error correction term, which represents the long-run equilibrium speed of adjustment after the shock in the short-term and ϑ is the speed of adjustment parameter. In addition, we conducted diagnostic tests to assess the goodness of fit of the model, including functional form, non-normality, heteroscedasticity and serial correlation. Finally, to assess the stability of model (3), we ran the CUSUM (cumulative sum of regression residuals) and the CUSUMQ (cumulative sum of squares of regression residuals) tests (Brown et al., 1975, Pesaran, 2001).

6. Results and discussion

6.1. Stationarity test

To determine which cointegration test is most appropriate, we examined the stochastic properties of our series, i.e., stationarity and unit-roots. The ARDL bounds approach can be used irrespective of whether the variables are I (0) or I (1) or whether the variables are fractionally integrated. Therefore, to determine the order of integration of our variables, we used two unit root tests, namely, the Philips Perron PP test and the Dickey-Fuller ADF test.

Results presented in Table 2 indicate the stationarity of POP and HDD and the non-stationarity of GAS, GDP, P^{rec}, P^{cut}, and P^{max} at various levels. However, all variables are stationary at the first difference. Therefore, the results confirm that the order of integration of our series is a mixture of I(0) and I(0), thus validating the implementation of the ARDL bounds testing approach to examine the existence of cointegration among the variables used in the model.

Table 2 Unit root test results.

Method	GAS	GDP	PMAX	PREC	PCUT	POP	HDD
ADF							
Level	-0.958	-1.411	-0.620	-1.720	-2.410	-3.898	-4.795
	(0.9495)	(0.8576)	(0.9779)	(0.7420)	(0.3741)	(0.0122)**	(0.0005)***
First difference	-6.144	-4.751	-4.943	-6.073	-4.412	-7.205	-8.004
	(0.0000)***	(0.0006)***	(0.0003)***	(0.0000)***	(0.0021)***	(0.0000)***	(0.0000)***
PP							
Level	-0.727	-1.390	-0.882	-2.367	-2.367	-3.864	-4.725
	(0.9713)	(0.8639)	(0.9580)	(0.3974)	(0.3974)	(0.0136)**	(0.0006)***
First difference	-6.277	-4.729	-4.948	-6.073	-4.318	-8.252	-9.067
	(0.0000)***	(0.0006)***	(0.0003)***	(0.0000)***	(0.0029)***	(0.0000)***	(0.0000)***

Note: Entries in parenthesis indicate the p-values; ***, **, and * indicate that the test is significant at the 1%, 5% and 10% levels, respectively.

6.2. Cointegration test

We examined the long-run relationship of model (1) using the Pesaran's ARDL bounds testing procedure. The results are displayed in Table 3. The results reported in Table 3 indicate that when GAS is employed as the dependent variable, the estimated F-statistic is higher than the critical value at the 1% level. However, we reject the null hypothesis of no-cointegration at the 1% level of significance. This confirms the existence of a unique cointegration vector in model (1).

Table 3 Bounds of F-test for cointegration.

Dependent variable		**Function**		**F- test statistic**	
GAS		GAS (GDP, P^{rec}, P^{cut}, P^{max}, POP, HDD)		4.318***	
Asymptotic critical value					
1%		5%		10%	
I (0)	I(1)	I (0)	I(1)	I (0)	I(1)
2.66	4.05	2.04	3.24	1.75	2.87

Note: ***, **, and * indicate that the test is significant at the 1%, 5% and 10% levels, respectively.

6.3. Parameter stability

To avoid bias related to the unstable parameters, we performed a Pesaran and Pesaran (1997) test to test for the presence of short-run and long-run parameter stability. Therefore, we performed the CUSUM (cumulative sum) and CUSUMQ (cumulative sum of squares) tests (Brown et al., 1975, Pesaran, 2001). The results of the COSUM and COSUMQ stability tests

are displayed in Figs. 7 and 8. These figures indicate that the plots of the CUSMQ and the CUSUM are within the critical boundaries of the 5% level, thus confirming the stability of the ARDL model parameters.

Figure 7. Plot of the cumulative sum of the squares of recursive residuals

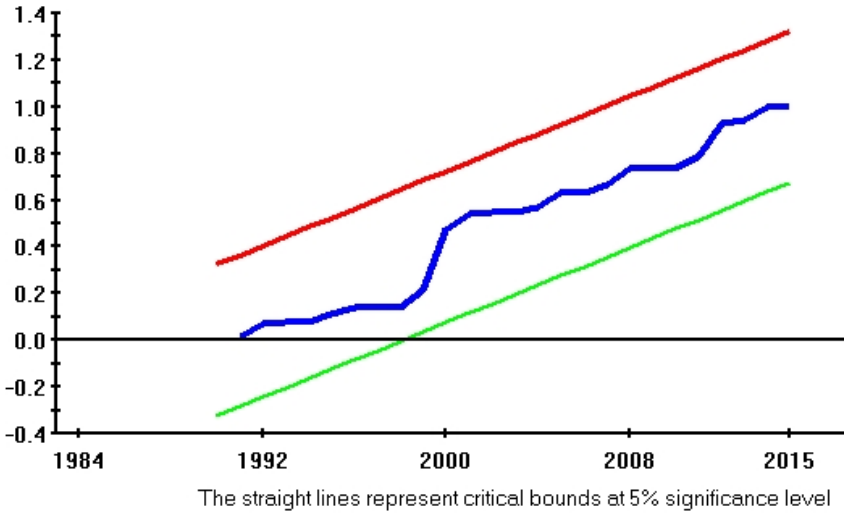
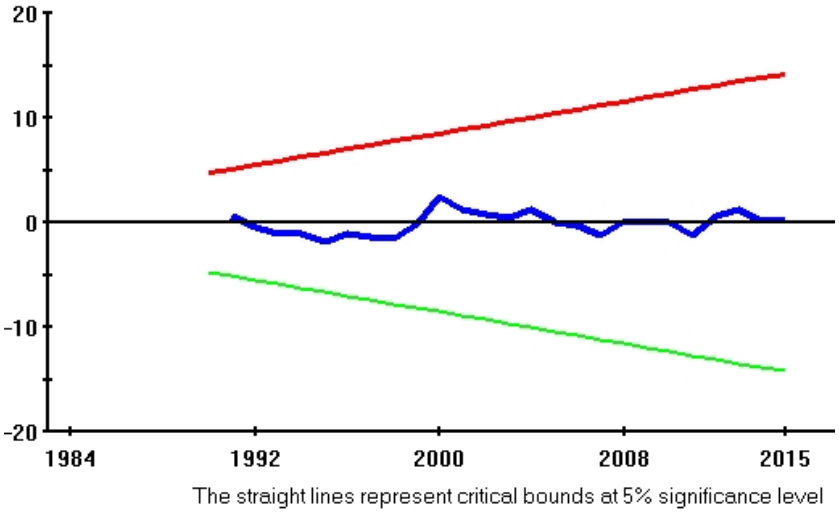


Fig. 8. Plot of the cumulative sum of the recursive residuals



6.4. ARDL long-run results

Having confirmed the existence of a long-run relationship between the variables used in model (1), the next stage is to examine the long-run marginal impact of GDP, P^{rec}, P^{cut}, P^{max}, POP and HDD on the demand for gas.

Table 4 presents the ARDL long-run results and their diagnostic tests. The findings support that premise that a price fall has a negative and significant effect on residential gas consumption in the long run in France, meaning that the demand for domestic gas will increase as the gas price falls. If there occurs a decrease of 1% in the domestic gas price, it will cause an increase of approximately 0.64% in gas demand. This suggests that the direct rebound effect of residential energy consumption is approximately 64% in the long run.

Table 4 The long-run ARDL cointegration model (1, 0, 0, 0, 0, 0, 0).

Variable	Coefficient	Std. Error	t-Statistic
LGDP	-0.141	0.131	-1.07
GPMAX	-0.633***	0.107	-5.92
GPREC	1.383***	0.146	9.47
GPCUT	-0.637*	0.328	-1.94
LPOP	1.464***	0.375	3.90
LHDD	0.426**	0.204	2.09

*** p<0.01, ** p<0.05, * p<0.1

6.5. ARDL short-run results

Table 5 presents the ARDL short-run results and their diagnostic tests. The short-run estimates support that, similar to the long-run, price cuts have a negative and significant effect on residential gas demand. The finding further discloses that if there is a decrease of 1% in the price cut, gas consumption will increase by 0.6% in the short run. This implies that the direct rebound effect of residential gas consumption is approximately 60% in the short run.

Table 5 The short-run ARDL error-correction model (1, 0, 0, 0, 0, 0, 0).

Std. Error	t-Statistics	Std. Error	t-Statistic
Δ GDP	-0.131	0.117	-1.12
Δ GPMAX	-0.592***	0.156	-3.79
Δ GPREC	1.293***	0.332	3.89
Δ GPCUT	-0.596*	0.292	-2.04
Δ LPOP	1.368**	0.505	2.71
Δ LHDD	0.399**	0.183	2.18
ECT (−1)	-0.935***	0.228	-4.10

*** p<0.01, ** p<0.05, * p<0.1

Finally, the error correction coefficient (speed of adjustment) exhibits a statistically significant negative value of 0.93, thus supporting the presence of the long-run relationship

among the variables used in this study, i.e., significant at the 1% significance level. The coefficient value of -0.93 indicates that deviations (disequilibrium) for gas demand in the short-term were corrected by 93% per year towards the long-run equilibrium.

Our analysis confirms the existence of a direct rebound effect for residential gas consumption in France. Thus, the evidence indicates that more than 60% of the energy savings potential of energy-efficient technologies could be lost because of the ex-post behavioural adjustments of households. Moreover, we refute the possibility of a backfire rebound effect for heating consumption because even with the integration of behavioural issues, increasing the energy efficiency of the housing stock regarding thermal characteristics induces a reduction in energy consumption on a national scale. Our results range between those found for other countries. For example, using the same method of energy price decomposition, Wang et al. (2014) find that the rebound effect for electricity consumption in China is approximately 72% for the short term and 74% for the long term, and in Europe, Haas and Biermayr (2000) estimated that the rebound effect for space heating and electricity consumption in Austria is approximately 30%.

The existence of this substantial rebound effect for the housing sector suggests the importance of considering behaviours when conducting prospective simulations of the effects of energy retrofit policies on real energy consumption. The predictive power of engineering models with respect to the final energy consumption of the dwelling stock must be examined against the behavioural weight when explaining energy consumption. Finally, we confirm the hypothesis of the non-symmetry of price rise and drop elasticities.

7. Conclusions and policy implications

This article is the first study to implement the ARDL approach to empirically examine the magnitude of the rebound effect in residential gas demand during the period 1983 to 2015 in France. The empirical findings suggest that the short-run direct rebound effect is approximately 60%, and the log-run rebound effect is approximately 63%. Nevertheless, our results refute the backfire hypothesis for both the short-run and long-run and, hence, imply that improvements in energy efficiency reduce residential gas demands in France.

From the energy-saving policy perspective, the evidence of a partial rebound effect suggests that policies intended to improve energy efficiency are not as effective as policymakers

had expected them to be. Indeed, the results indicate that only 40% of the potential energy savings predicted by technical and engineering models is realized and that the lost share is being absorbed for comfort needs and welfare improvements. Hence, rebound effects should be anticipated appropriately by those who determine public policies and set energy goals.

At the dwelling level, energy efficiency improvements dedicated to decreasing domestic energy use are twofold. Specifically, they are to improve envelope insulation and increase the efficiency of the heating system. While in both cases, the implementation of these measures is costly for the household, we have determined that benefits in terms of energy savings could be drastically reduced by the rebound effect, thus implying that energy efficiency investment profitability is questionable at the individual level. We join here the vast literature on the energy efficiency gap and question the profitability of such investments and the reasons why people do not invest more in energy efficiency.

As a result of this simple multi-scale analysis, we face a gap between the expectations of national goals and public policies with respect to reducing energy consumption and increasing individual economic interests in investing in energy efficiency improvements to their homes. Solutions such as the increase in subsidies to reduce implementation costs or the promotion of individual and common co-benefits for energy retrofits, i.e., thermal, acoustic gains and environmental contributions, could be a way to reach more potential investors.

The most important contribution of this paper is to measure the magnitude of the direct rebound effect of household gas demand, both in the short run and in the long run. We suggest that certain behaviours, habits and lifestyles are drivers for the reduction of residential energy demand and its negative environmental effects. Furthermore, the findings provide a new outlook for further studies. Therefore, examining new surveys with more comprehensive data on household lifestyles and energy use behaviours may help to specify the nature of the rebound effect in more detail. In addition, richer sources of information can aid in the development of a comprehensive framework of the salient drivers shaping household energy-savings attitudes and behaviours. The ongoing literature on household energy demand acknowledges the importance of household lifestyles and behaviours in shaping domestic energy consumption patterns (Belaïd, 2016; Belaïd and Garcia, 2015; Lévy and Belaïd, 2017; Sardianou, 2007). However, informing households about the importance of improving their housing energy efficiency and promoting energy-savings behaviours is vital to achieving optimum outcomes in terms of energy-savings and related carbon emissions reductions.

The findings advance the existing direct rebound effect for residential gas demand by linking gas demand with energy price, housing energy efficiency, and occupant attributes and

behaviours. This implies a policy shift from technically oriented efficiency programmes and towards a mixture of renovation and behavioural changes.

Nevertheless, this research does not aim to be exhaustive in policy implications terms, but rather to provide some information on different ways to reduce residential energy demand, e.g., incorporation of the occupant attitude and behaviour in developing refurbishment strategies. Indeed, these results would provide policy makers valuable information on the role of occupant behavioural and attitudinal factors in shaping residential gas demand patterns.

Although the procedures used provide consistent results, for the most part, and even though the data used in this research are representative of the residential demand for gas in France, interpretations of the results must be regarded with caution, especially given that the results and conclusions depend on the quality of the database. Due the nature of behavioural uncertainty and complexity, empirical estimations without behavioural information may introduce errors into the model creating a bias that may undermine the accuracy of the results. Hence, more comprehensive data regarding behavioural and socio-economic factors related to domestic energy use would help to untangle the effects of household attributes and dwelling options when designing domestic energy demand patterns.

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Conclusion Générale

Dans les prochaines années, la transition énergétique rapide et de grande ampleur est attendue du secteur du bâtiment et notamment, du secteur résidentiel. Des obligations de résultat et de moyens ont été fixées par la réglementation française (directives européennes, LTECV) pour faciliter cette transition. Aujourd'hui, bien que les leviers pour accélérer la transition soient connus (i.e, massifier la rénovation énergétique et adopter des comportements plus sobres en énergie), la consommation énergétique peine à décroître dans le secteur résidentiel. Les raisons peuvent être d'origine multiples et leurs mises en évidence requièrent l'aide de la recherche empirique.

Notamment, nous avons identifié un réel besoin de caractériser plus précisément les schémas de la décision énergétique dans le secteur résidentiel français tant pour améliorer la compréhension de la situation énergétique actuelle que pour suggérer des pistes d'action adaptées en faveur de la réduction de la consommation énergétique du secteur à destination des décideurs publics.

Ce travail doctoral a été l'occasion d'investiguer avant tout les barrières de marché à la réduction des consommations énergétiques du secteur résidentiel, notamment le rôle de l'incertitude sur les bénéfices de la rénovation et le rôle de l'hétérogénéité individuelle.

Tout d'abord, sur le sujet des barrières au déploiement de la rénovation énergétique côté ménages, les contributions empiriques sont rares. Notamment, la perception effective des ménages de l'incertitude sur les bénéfices portée par les investissements en efficacité énergétique est encore peu étudiée. Il y avait donc un réel enjeu à clarifier la réalité de l'importance de cette barrière. D'autre part, contrairement au secteur tertiaire où le rôle de l'hétérogénéité des comportements individuels pour expliquer la consommation énergétique est limité, les facteurs individuels (préférences individuelles, connaissances et perception du contexte, convictions, contraintes économiques, etc.) sont identifiés comme déterminants importants de la consommation énergétique ainsi que de la prise de décision relative à l'investissement en efficacité énergétique dans le secteur résidentiel. La réduction efficace des consommations énergétiques du secteur résidentiel passe donc par leur meilleure compréhension. Les relations entre caractéristiques techniques du logement, consommation énergétique et caractéristiques socio-économiques des ménages sont étroites, complexes et peuvent conditionner la réduction des consommations énergétiques et l'efficacité des outils de

politique publique mis en œuvre. Si le rôle et les interactions de ces facteurs ne sont pas proprement identifiés et intégrés, la marge de manœuvre de réduction de la consommation énergétique résidentielle pourrait être mésestimée et les politiques publiques d'efficacité énergétique mises en place pourraient s'avérer, *in fine,* non-adaptées et inefficaces.
Ainsi, en s'insérant dans la littérature sur le *paradoxe énergétique*, l'objectif de cette thèse était d'apporter des éléments d'éclairage empiriques sur les comportements énergétiques dans le secteur résidentiel français dans l'optique de comprendre certaines des barrières de marché limitant la réduction de la consommation énergétique. Notamment, les travaux ont voulu comprendre (i) certains des freins à l'investissement en efficacité énergétique dans le logement individuel, avec un focus sur le rôle de l'incertitude dans la prise de décision des ménages et le passage à l'acte, (ii) comment se constituait la décision de consommation d'énergie à l'échelle du logement et le rôle des préférences individuelles, (iii) mieux considérer et quantifier les écarts entre efficacité énergétique et consommation énergétique réelle, en statique, et finalement,(iv) tester l'hypothèse de l'existence d'un effet rebond pour le chauffage dans le secteur résidentiel français.

Cette thèse à dominante empirique rassemble quatre chapitres adressant les différents points mentionnés ci-dessus. Ces travaux de recherche se caractérisent par des approches méthodologiques fondées sur les contributions empiriques les plus récentes, l'utilisation de données innovantes ainsi que par l'originalité des questions de recherche posées.

Les principales contributions des chapitres sont résumées en premier lieu puis nous revenons en seconde partie sur les principaux éléments d'éclairage pour les politiques publiques tirés de ces papiers.

I.Synthèse générale

Les travaux démontrent que les décisions énergétiques (consommation énergétique et efficacité énergétique) dans le secteur résidentiel sont issues de processus décisionnels complexes, pré déterminées notamment par les caractéristiques technico –et socio-économiques, les préférences et les perceptions individuelles (qui peuvent refléter la réalité, comme c'est le cas ici pour la perception de l'incertitude sur les bénéfices de la rénovation). La compréhension des comportements énergétiques individuels est donc un élément majeur pour comprendre les tendances énergétiques actuelles et identifier les leviers d'action pour réduire la consommation énergétique. En effet, ne pas les prendre en compte peut amener à mésestimer les marges de

manœuvres et les effets des politiques publiques en faveur de la réduction des consommations énergétiques.

Les travaux de thèse ont ainsi permis d'identifier des obstacles à la baisse des consommations énergétiques résidentielles suivants (non exhaustif): (1) le premier chapitre montre que le risque et l'incertitude sur certains paramètres de la rénovation énergétique est effectivement perçu par les ménages et peut être un frein à l'investissement, l'importance de ce frein dépend de certaines caractéristiques individuelles comme l'aversion au risque; (2) le second chapitre suggère que la consommation énergétique est positivement influencée par des préférences individuelles des ménages pour le confort mais qu'elle est aussi conditionnée par les caractéristiques socio-économiques des ménages, qui peuvent jouer à un double niveau (directement et indirectement, via les caractéristiques du logement) ; (3) le troisième chapitre met en évidence que la sobriété énergétique peut être la conséquence de la pauvreté des ménages (il s'agit de restriction) et qu'une forte intensité d'utilisation de l'énergie est associée à des préférences pour le confort élevées, souvent dans les logements performants ; (4) le dernier chapitre confirme la présence d'un effet rebond pour le chauffage dans le secteur résidentiel français mais démontre aussi que les économies d'énergie induites par la mise en place de solutions d'efficacité énergétique restent intéressantes.

Cependant, ces obstacles ne sont pas insurmontables. De fait, dans certains cas, notamment l'effet rebond, l'obstacle identifié n'est pas forcément « mauvais » dans l'optique normative puisqu'il est en partie représentatif d'un rattrapage de confort qui peut être considéré « légitime». La meilleure connaissance des comportements énergétiques des ménages français permise par les conclusions de ces travaux de recherche est déjà une opportunité pour les décideurs publics d'agir de façon plus renseignée en faveur de l'élaboration d'outils de politiques publiques adaptés à la réduction des consommations énergétiques sectorielles, tout en intégrant d'autres critères (comme les critères sociaux) : soutien financier aux ménages au revenu faible pour la rénovation énergétique ou la maîtrise des consommations énergétiques, mise en place d'outils innovants de type garantie pour accélérer la rénovation énergétique, outils informationnels pour changer les comportements énergétiques des plus aisés, accompagnement des marchés, etc.

II.Principales contributions de la thèse chapitre par chapitre et perspectives

Pour répondre à la problématique soulevée, les travaux de recherche réalisés mobilisent différentes sources de données, cadres d'analyse et modèles économétriques. Ces travaux apportent des éléments d'intérêt pour la recherche empirique future sur le sujet ainsi que des éléments d'éclairage pour aider la prise de décision publique dans le secteur résidentiel.

Le premier travail de thèse met en lumière la sensibilité de la réaction des ménages à l'incertitude contextuelle lors de la décision de rénovation énergétique. Pour ce faire, la méthodologie du « discrete choice experiment » (ou expérience de choix discret en français) a été mobilisée auprès de 3000 propriétaires occupants français au cours d'une enquête unique financée par le CSTB. Les résultats du papier constituent une contribution originale à la littérature sur le paradoxe énergétique en suggérant que l'incertitude sur les bénéfices de la rénovation énergétique et/ou le contexte peut être un frein à l'investissement significatif chez les ménages français. Notamment, l'absence de certitude sur la qualité finale des travaux de rénovation et le flou autour du coût futur de leur énergie de chauffage seraient des obstacles au passage à l'acte. Le rôle de frein de ces facteurs est systématique mais leur importance relative dépend des ménages : il existerait de l'hétérogénéité dans les préférences des ménages, dépendant, entre autres, de leur aversion au risque et de leur connaissance du contexte. L'exercice de simulation mené dans le cadre de cet article suggère que de nouveaux outils comme la garantie décennale pour la rénovation énergétique, comme présentée dans le choice experiment, pourrait faire augmenter le taux de rénovation énergétique jusqu'à 15- 20%. Ce chapitre ouvre la discussion sur la nécessité de réduire l'asymétrie d'information sur la qualité des travaux de rénovation énergétique, sur les modalités de mise sur le marché de schémas d'assurance visant la réduction des incertitudes sur les gains de la rénovation et l'accompagnement par les pouvoirs publics des contrats prix fixes de l'énergie.

Le chapitre 2 apporte un éclairage unique sur les différents processus de choix qui interviennent in fine dans la décision de consommation d'énergie des ménages du secteur résidentiel français. Ce travail montre notamment que le choix du logement et de ses caractéristiques énergétiques est dépendant des facteurs socio-économiques et des préférences individuelles des ménages ; ces interactions doivent être prises en compte dans les futurs travaux de recherche pour ne pas biaiser les estimations réalisées dans les travaux empiriques. Ces mêmes facteurs expliquent aussi directement la consommation d'énergie toutes choses égales par ailleurs. Les résultats démontrent le rôle essentiel du revenu et de la contrainte économique comme frein (pour les

ménages à revenu faible) ou moteur (ménages à revenus élevés) directs et indirects (via le choix du logement) de la consommation énergétique pour le secteur résidentiel français. Les résultats suggèrent le rôle significatif des préférences pour le confort pour expliquer la consommation énergétique importante des ménages les plus aisés, ces ménages vivraient de surcroît dans les logements les plus performants d'un point de vue énergétique. Par opposition, il existerait une double peine énergétique pour les ménages les plus modestes : (1) habiter dans les logements les moins performants et (2) restreindre leur consommation d'énergie pour des raisons économiques.

Le travail de recherche présenté dans le chapitre trois propose un autre éclairage en se focalisant sur les déterminants des écarts à la norme entre consommation d'énergie théorique du logement prédites par le Diagnostic de Performance Energétique (DPE) et la consommation finale réelle. Il en ressort que les préférences individuelles pour le confort, relatives à certains usages énergétiques, les facteurs économiques (prix de l'énergie, revenu des ménages), les facteurs environnementaux (climat réel) expliquent ces écarts. Notamment, les résultats mettent en évidence que 12% de l'écart correspondant aux situations de surconsommation peut être expliqué par des préférences élevées pour le confort. Par ailleurs, l'écart correspondant aux situations de sous-consommation s'explique en partie par des contraintes économiques au niveau du ménage. Finalement, ce travail de recherche suggère un lien significatif entre écart de consommation énergétique et niveau d'efficacité énergétique du logement : notamment, il est mis en évidence qu'il existerait un effet rebond légitime ou « de rattrapage ». Une partie des économies d'énergie attendues suite à l'amélioration de la performance énergétique du logement serait alors perdue à cause d'une augmentation de la demande énergétique suite à la rénovation. Cependant, cette augmentation de la demande s'expliquerait en grande partie par un relâchement de la contrainte financière des ménages sur la consommation énergétique suite à la diminution du coût du service énergétique et ce, pour rattraper un niveau de confort « légitime ».Dans ce contexte, la rénovation énergétique du parc conduirait à la fois à une réduction de la consommation énergétique significative (mais moins forte qu'attendue à cause de l'effet rebond) et à l'amélioration du bien-être thermique des ménages français qui se traduit par l'atteinte d'un niveau « légitime » de consommation énergétique. Ainsi, les enjeux de la transition énergétique ne doivent pas être dissociés de ceux de « justice sociale ».

Dans le dernier chapitre, nous avons cherché à estimer la magnitude de l'effet rebond direct relatif à l'usage chauffage dans le secteur résidentiel français. L'effet rebond direct est un phénomène comportemental reconnu existant pour différents usages énergétiques ; Il découle

d'une réaction économique offre/demande fondamentale : suite à la baisse du coût d'un bien ou un service, la demande pour ce bien ou service est susceptible d'augmenter. Pour l'usage chauffage, cet effet rebond est justifié par un rattrapage de confort thermique, légitime ou accessoire (cf les résultats du papier précédent). Nous estimons que l'effet rebond direct pour l'usage chauffage est de 60% à court terme et de 64% à long terme. Du point de vue des décideurs publics, cet effet rebond significatif peut être interprété selon deux perspectives : (1) les économies d'énergie attendues par la massification de la rénovation des enveloppes des logements ou des systèmes de chauffage seraient de moitié moins importante que prévu, même si toujours positives. Nous suggérons que cet effet soit intégré dans les futures trajectoires énergétiques anticipées au niveau national et les modèles ingénieurs pour plus de réalité. (2) Compte tenu des résultats précédents, il y aurait pour une grande partie des ménages un vrai gain de bien-être thermique qui résulterait de la rénovation massive du parc de logements (cf papier précédent). Les gains non-énergétiques issus de la rénovation énergétique sont donc aussi à prendre en considération dans le contexte français.

Quelques pistes pour la recherche future

Dans l'optique de la massification de la rénovation énergétique du parc résidentiel français et dans la continuité des travaux académiques, il serait intéressant de creuser la question de l'effet rebond, qui constitue, comme on l'a vu, une limite majeure à la réduction de la consommation énergétique dans le secteur résidentiel. Ainsi, il pourrait être envisagé d'estimer la variabilité de l'effet rebond sur l'usage chauffage selon les caractéristiques individuelles types des ménages et des logements (caractéristiques économiques du ménage comme le revenu, performance énergétique initiale du logement) afin de mieux anticiper les effets des politiques publiques d'efficacité énergétique.

Cette thèse se focalisant majoritairement sur les enjeux de consommation énergétique relatifs à l'usage de chauffage ; il pourrait être intéressant de développer des approches similaires pour les autres usages : par exemple, en étudiant les déterminants de la consommation d'énergie ou l'existence d'un effet rebond pour la consommation d'électricité spécifique qui représente une part croissante de la consommation d'énergie finale.

Finalement, l'approfondissement des barrières à la rénovation énergétique est d'un intérêt majeur pour la recherche et les politiques publiques. Il pourrait être intéressant d'aller plus loin dans la compréhension du rôle de l'incertitude contextuelle sur la décision de rénovation, notamment, en approfondissant le rôle de l'hétérogénéité des ménages pour expliquer la perception de l'incertitude ou la préférence pour le status quo dans la continuité du travail déjà

réalisé et/ou en testant le rôle de l'incertitude des politiques énergétiques (revirement sur la taxe carbone, incertitude sur l'augmentation ou la baisse des subventions à la rénovation énergétique dans les années futures, etc.).

III.Éléments d'éclairage pour les décideurs publics : obstacle à la baisse des consommations énergétiques et leviers d'action.

En termes d'éclairage pour la décision publique, les travaux présentés dans cette thèse mettent en évidence quelques points d'intérêt discutés dans la présente section.

Tout d'abord, l'ensemble de ces résultats fait ressortir le besoin d'intégrer les caractéristiques et dynamiques individuelles (l'hétérogénéité des agents et des comportements) dans les modèles de consommation d'énergie résidentielle de type « ingénieur » utilisés comme support à la décision publique pour représenter plus réalistement les marges d'action pour les politiques publiques. Disposer d'une cartographie du parc résidentiel intégrant à la fois des informations techniques sur les bâtiments, des données socio-économiques sur les ménages occupants ces logements et des schémas de comportements énergétiques « types » (élasticité- prix de l'énergie différenciée selon le niveau de revenu, effet rebond) est indispensable pour créer des modèles réalistes de prédiction de la consommation énergétique et pour tester l'effet des politiques publiques futures.

Par ailleurs, en cohérence avec les observations faites sur les liens entre revenu et comportement énergétique, il ressort que la mise en place d'incitation à la réduction des consommations énergétiques par des instruments économiques requiert qu'une attention particulière soit portée au niveau de revenu des ménages, à leur bien-être et à leur capacité à assumer les choix politiques énergétiques. Les travaux confirment par exemple que l'utilisation d'instruments de politiques publiques agira effectivement sur la consommation énergétique des ménages mais avec pour risque de voire accroître les inégalités déjà présentes. En effet, les ménages à faible revenu seraient impactés significativement par des instruments économiques incitatifs de type taxe sur les énergies : ces ménages sont plus susceptibles d'habiter dans des logements peu performants donc énergivores dans lesquels les sources d'énergie sont plus chères. Dans ces logements, les ménages n'atteignent pas encore un seuil de confort thermique « légitime ». Pour ces ménages, l'addition d'une contrainte économique supplémentaire pourrait aggraver leur situation sans déclencher l'investissement en efficacité énergétique par manque de ressource. Ainsi, différencier les cibles des outils de politique publique selon les revenus ou mettre en

place des outils ou aides financières complémentaires pour réduire certains effets distributifs est de mise, tout en faisant attention aux effets de distorsion (Combet et al., 2010).
Actuellement, les chèques énergie mis en place en 2018 ont cette vocation mais pourraient être étendus en montant et en nombre d'émissions (actuellement, il concerne 4 millions de bénéficiaires aux revenus modestes pour 150 euros par an en moyenne). Sur ce dernier point, comme précisé antérieurement, nos travaux suggèrent que ce sont les ménages aux plus faibles revenus qui sont susceptibles d'habiter dans la part du parc résidentiel la moins performante du point de vue énergétique. On peut donc supposer que le besoin de financement nécessaire pour la rénovation énergétique de ces logements serait difficilement couvert par la capacité de financement disponible chez ces ménages. Dans ce contexte, les aides publiques à la rénovation énergétique devraient être plus largement conditionnées selon les ressources des individus[103]. Cette conclusion est d'autant plus intéressante que nos résultats démontrent que les ménages les plus aisés auraient tendance à surconsommer de l'énergie pour des raisons de confort individuel une fois la rénovation énergétique mise en œuvre, rendant inefficaces les aides financières dont ils peuvent bénéficier au regard des gains énergétiques réalisés.

Outre les ressources financières, nos travaux suggèrent que les ménages auraient aussi besoin de plus grande certitude sur les gains de la rénovation énergétique pour faciliter le passage à l'acte. La variabilité du prix de l'énergie dans le futur et les aléas relatifs à la qualité des travaux de rénovation énergétique réalisés peuvent rendre incertains les économies (d'énergie) réalisées suite aux travaux. Plus largement, l'incertitude sur l'environnement futur et les conditions externes est un frein significatif au passage à l'acte quand on parle d'investissements rentabilisés sur du long terme comme le sont les investissements en efficacité énergétique.
Ainsi, dans le cas de la rénovation énergétique du parc résidentiel français, la combinaison de faibles ressources économiques chez une grande partie des ménages concernés d'une part, et de l'incertitude sur le rendement des opérations de rénovation énergétique d'autre part constituent un frein renforcé au passage à l'acte et justifie la mobilisation de nouveaux outils ou de mesures plus ciblées par les politiques publiques. Combiner des mesures de réduction du coût des travaux ou de financement alternatif et le déploiement de systèmes d'assurances sur certains paramètres de la rénovation énergétique peut être un duo intéressant pour augmenter le taux de rénovation énergétique.

[103] Comme le sont actuellement les aides financières délivrées par l'ANAH

Les décideurs publics auraient donc une réflexion à conduire sur les modalités de mise en œuvre de schémas d'assurance couvrant l'incertitude sur les paramètres identifiés (prix de l'énergie, qualité des travaux). Concernant les contrats prix fixes de l'énergie, ceux-ci sont déjà proposés par le marché (pour une durée maximale de 3 ans) ; leur développement pourrait faire l'objet d'un accompagnement par les pouvoirs publics. Concernant la qualité des travaux énergétiques, outre le modèle de la garantie décennale qui pourrait être appliqué à la rénovation énergétique, l'exemple pourrait être pris du secteur tertiaire où depuis quelques années en France se développent les contrats de performance énergétique. Il s'agit de partenariats au cours duquel le maitre d'ouvrage et l'opérateur s'entendent sur un objectif d'efficacité énergétique. Si l'objectif n'est pas atteint, un système de pénalité peut être appliqué pour l'opérateur. Dans ce cadre, la mesure de la performance énergétique atteinte est une mesure de la consommation énergétique in situ à laquelle on compare une mesure de consommation énergétique avant-travaux, corrigé des variations climatiques. De leur côté, les maitres d'ouvrage s'engagent contractuellement à respecter une certaine température de chauffage dans leurs bâtiments après travaux afin de coller aux prédictions de consommation énergétique établies dans le contrat. Jusqu'à présent ce système a été appliqué à des bâtiments tertiaires (des lycées par exemple) donc peu soumis à l'influence comportementale des occupants sur la consommation énergétique finale. La généralisation de ce type de contrat à l'échelle du logement individuelle pourrait rassurer les ménages tout en débloquant potentiellement de nouveaux (ou encore peu courants) modèles de financement de type tiers financement, dans lesquels le coût des travaux de rénovation énergétique est pris en charge par un organisme tiers qui remboursera ses frais et intérêts sur les économies d'énergie effectivement réalisées suite à la mise en œuvre des solutions d'efficacité énergétique. Avec un tel modèle de financement, les ménages à revenu modeste pourraient faire financer leurs travaux de rénovation énergétique facilement tout en étant rassuré sur les bénéfices atteints grâce à leur mise en œuvre. Cependant, certaines questions se posent quant à la faisabilité de déploiement de tels modèles dans le secteur résidentiel. En effet, nos travaux ont pu montrer que l'effet rebond direct pouvait réduire significativement les économies d'énergie obtenues par le déploiement de mesures d'amélioration de la performance énergétique. Si ce paramètre est intégré dans les nouveaux contrats, la durée de contractualisation entre tiers financeur et ménage pourraient s'en trouver rallongée pour intégrer le fait que les bénéfices énergétiques soient moins importants. L'incertitude autour des gains réels découlant des changements comportementaux et la durée de contractualisation longue pourraient constituer une limite au système ; les ménages pouvant être susceptible de ne pas être très enclins à s'engager sur la durée. La faisabilité de ce genre de

mécanisme combiné garantie-tiers financeur pourrait faire l'objet d'une analyse plus aboutie. Si celle-ci est limitée, l'aide au développement d'une mesure intrinsèque de la performance énergétique pourrait constituer un moyen de limiter l'asymétrie d'information autour de la qualité des opérations de rénovation pour les ménages souhaitant investir dans la rénovation énergétique.

Finalement, une autre possibilité d'action pour les décideurs publics seraient de cibler la réduction des consommations énergétiques des ménages les plus aisés et vivant dans les logements énergétiques les plus performants. Ceux-ci démontreraient en effet des comportements de surconsommation énergétique s'expliquant par des préférences significatives pour le confort. Dans de telles situations, des outils informatifs comme les nudges[104] ou les smart meters pourraient être déployés. En informant les ménages sur les excès de consommation énergétique réalisés (par le biais d'une information autonome pour les smart-meters ou forcée et comparative pour les nudges), les deux systèmes pourraient avoir un effet positid sur la réduction de la consommation énergétique individuelle (Ouyang and Hokao, 2009; Wilhite and Ling, 1995). Concernant l'utilisation accrue de smart meters qui donneraient aux ménages un feedback en temps réel sur leur consommation énergétique, la littérature a montré qu'elle pouvait induire des gains énergétiques significatifs après adaptation des comportements individuels (Brounen et al., 2012; Di Cosmo et al., 2014; Jessoe and Rapson, 2012). Plus largement, la littérature a pu montrer que les incitations comportementales pouvaient être dans certains cas aussi efficaces relativement aux économies d'énergie réalisées que les améliorations de l'efficacité énergétique. Ainsi, même si les effets de ces incitations comportementales ne s'inscrivent pas forcément dans le long terme (c'est notamment ce qui peut être reproché aux outils de type nudges ou de type « campagne d'information », voir (Allcott and Rogers, 2014), elles ne doivent pas être négligées et pourraient être complémentaires à la massification des mesures d'efficacité énergétique. La persistance dans le temps des effets des traitements comportementaux peut être atteinte après un certain nombre de répétition du traitement ; la dynamique de persistance doit être alors exploitée pour améliorer le rapport coût efficacité des mesures d'amélioration de l'efficacité énergétique.

[104] Le nudge, ou « coup de coude », est une technique pour inciter une population cible à changer leurs comportements « sans leur interdire aucune option ou modifier de manière significative leurs motivations économiques » (en pratique mise en œuvre souvent via de l'information ciblée, comparative). Elle a été définie par Richard Thaler et Cass Sunstein dans leur livre Nudge : Améliorer les décisions concernant la santé, la richesse et le bonheur (2008).

Pour conclure, il semble indispensable de souligner le rôle important de l'analyse économique pour le design des politiques publiques dans le domaine de l'efficacité énergétique ou de la consommation énergétique, mais aussi de façon plus générale. En effet, la compréhension des comportements ex-ante, l'identification adéquate des populations cibles des politiques publiques et l'évaluation de leurs effets sont fortement dépendantes de la caractérisation des individus et de leurs comportements. Notamment, nos travaux montrent l'importance de l'existence et de la provision de données, fiables, rigoureuses (sur le plan technique et socio-économique), si possible représentatives des populations d'intérêt et bien sûr, accessibles librement aux chercheurs.

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