ED 396 : Ecole doctorale
Economie, organisations, société

UMR 7235 - Economix

Clément BONNET

L'innovation dans les technologies de l'énergie bas-carbone :

analyses théoriques et évaluations empiriques

Thèse présentée et soutenue publiquement le 14 décembre 2016
en vue de l'obtention du doctorat de Sciences économiques
de l'Université Paris Ouest Nanterre La Défense

sous la direction de M./Mme Jean-Marc BAUDRY

Jury :

Rapporteur:	Monsieur Julien PENIN	Professeur des Universités, Université de Strasbourg
Rapporteur:	Monsieur Gaétan DE RASSENFOSSE	Professeur assistant, École polytechnique fédérale de Lausanne
Membre du jury:	Monsieur Pierre-André JOUVET	Professeur des Universités, Université Paris Nanterre
Membre du jury:	Monsieur Pierre MOHNEN	Professeur des Universités, Université de Maastricht

Université Paris Nanterre
École doctorale Économie, Organisations, Société
Laboratoire EconomiX - CNRS (UMR 7235)

Thèse

pour l'obtention du grade de

Docteur és sciences économiques

présentée et soutenue publiquement par

Clément Bonnet

14 décembre 2016

L'innovation dans les technologies de l'énergie bas-carbone: analyses théoriques et évaluations empiriques

Jury

Directeur de thèse : Monsieur Marc Baudry
Professeur des Universités, Université Paris Nanterre

Rapporteurs : Monsieur Julien Penin
Professeur des Universités, Université de Strasbourg

Monsieur Gaétan de Rassenfosse
Professeur assistant, École polytechnique fédérale de Lausanne

Suffragants : Monsieur Pierre-André Jouvet
Professeur des Universités, Université Paris Nanterre

Monsieur Pierre Mohnen
Professeur des Universités, Université de Maastricht

Ni l'Université Paris Ouest, ni la Chaire Économie du Climat, n'entendent donner aucune approbation ni improbation au contenu de cette thèse. L'auteur en demeure le seul reponsable.

À Guillaume.

Remerciements

Mes premiers remerciements vont à mon directeur de thèse Marc Baudry. Durant ces trois ans, il a encadré ma thèse avec une habilité remarquable, me faisant bénéficier de sa connaissance du sujet et encourageant chacune de mes initiatives. La rareté ne fait pas seule la valeur, puisque son infaillible disponibilité n'aura pas empêché à nos nombreux échanges d'être des moments qui m'ont été particulièrement précieux. Je lui suis redevable d'avoir appris de sa rigueur scientifique et de sa pédagogie exemplaire, et je lui exprime ici mes plus sincères remerciements.

Je tiens également à exprimer toute ma gratitude à Messieurs Julien Penin, Gaétan de Rassenfosse, Pierre-André Jouvet et Pierre Mohnen pour me faire l'honneur de constituer le jury de cette thèse.

Christian de Perthuis et Pierre-André Jouvet m'ont offert la chance de réaliser cette thèse au sein de la Chaire Economie du Climat et je leur exprime ma profonde reconnaissance. La Chaire m'a fait bénéficier d'un environnement intellectuel stimulant et d'un cadre de travail idéal pour mener ces recherches. Je souhaite également remercier Preety Nadarasapillay qui a brillamment administré cette structure durant ces années.

Je souhaite remercier les membres du laboratoire EconomiX, et tout particulièrement sa directrice Valérie Mignon, son directeur adjoint Jean-Pierre Allegret, son secrétaire général Fréderic Hammerer et le directeur de l'axe DDEE Alain Ayong le Kama. La première raison à ces remerciements est bien sûr de m'avoir accueilli en tant que doctorant et de me permettre ainsi de profiter des enseignements des excellents chercheurs qui font vivre ce laboratoire. La seconde raison est de m'avoir donné l'opportunité d'enseigner à l'Université Paris Ouest et d'avoir pu ainsi tenter de rendre à cette institution ne serait-ce qu'une part infime de tout ce qu'elle m'a offert.

Ces remerciements ne seraient pas complets sans ceux adressés à l'ensemble de mes collègues de la Chaire Economie du Climat avec qui j'ai partagé cette belle aventure. J'ai une pensée particulière pour Jill, Yvain et Jérémy qui, comme moi, offraient ces derniers mois le spectacle si égayant d'un doctorant en fin de thèse, et qui par leur détermination ont contribué à renforcer la mienne. J'ai également eu beaucoup de plaisir, et me réjouis de continuer à l'avoir ces prochains mois, à partager une partie de leur temps avec les membres du laboratoire EconomiX. Je tiens à les remercier pour leur accueil chaleureux. J'ai plus particulièrement une dette plus important qu'ils ne le pensent envers Stellio et Leslie du bureau 313.H qui ont si souvent su répondre à mes nombreuses incompréhensions.

En même temps que cette thèse débutait, je faisais la rencontre de deux personnes qui deviendront rapidement des amis proches. Ces années passées auront été l'occasion de découvrir Simon et Victor, qui ont su me passionner pour leurs sujets de recherches, sans jamais oublier de faire la part belle dans nos débats à certains fondamentaux de la vie tels que le malt et l'aviation. Si cette thèse n'a pas été le désert de solitude tant annoncé, c'est en grande partie grâce à eux et je leur en suis profondément redevable. J'attends avec impatience les occasions de mettre en œuvre les projets que nous avons imaginés durant tout ce temps.

Ces dernières années, des individus qui n'avaient rien demandé à personne ont dû subir mes interrogations rébarbatives sur la science économique. Les pauvres ne pouvaient pas faire autrement : ils sont mes amis les plus proches et ma famille. Ces remerciements ne sont qu'une occasion parmi d'autres, quoique plus solennelle qu'à l'habitude, de leur exprimer une fois encore tout l'amour que je leur porte.

Merci à Alexia, Charlotte, Christophe, Emilie, Louis et Mickael d'avoir su me préserver de fusionner avec ma chaise de bureau en me donnant sans cesse l'envie de les voir. Merci également à Charlie pour, entre autre, m'avoir accompagné dans le défouloir qu'était la boxe; jamais punching-ball n'aura eu de répondant aussi apaisant. Je ne peux oublier de remercier Clément Bizet, dont la détermination ne cesse de m'inspirer depuis notre rencontre à la B.U. de Nanterre.

Un nombre encore plus restreint de personnes méritent une place particulière dans ces remerciements. Ils m'ont vu grandir et me donner la prétention de devenir docteur. Aussi étrange que ce soit, ils m'ont pris au sérieux et m'en ont même cru capable. Merci à Antony, à mon frère Tanguy et à mes sœurs Alice et Lucie. Enfin, merci aux 'auteurs de l'auteur' pour m'avoir encouragé durant toute cette thèse et pour une infinité d'autres choses.

Résumé

L'innovation dans les technologies de l'énergie bas-carbone est entravée, d'une part, par les externalités sur l'environnement et, d'autre part, par les externalités de connaissance. Ces défaillances de marché nécessitent d'être corrigées par l'intervention des pouvoirs publics. L'objectif de cette thèse est d'établir les conditions d'un soutien efficace à l'innovation dans les technologies de l'énergie bas-carbone. Le travail de recherche mène des analyses théoriques sur le traitement de ces défaillances de marché en conjonction avec des évaluations empiriques des politiques de soutien à l'innovation dans ces technologies mises en place jusqu'à présent. Cette thèse se structure en cinq chapitres. Le Chapitre 1 interroge la nécessité de mettre en place des politiques spécifiquement dédiées à l'innovation dans les technologies de l'énergie bas-carbone, en opposition à un soutien à l'innovation de la part des pouvoirs publics ne discriminant pas ces technologies des autres. La revue des instruments économiques mis en place jusqu'à présent est ensuite proposée et indique la prédominance du soutien à l'innovation dans ces technologies par la demande, plutôt que par l'offre. Le Chapitre 2 resserre l'analyse sur les instruments de soutien par la demande. Un modèle micro-fondé de diffusion est utilisé en vue de mener une analyse contrefactuelle évaluant les effets de ces instruments sur la diffusion de la technologie éolienne dans six pays européens. Le Chapitre 3 développe une méthode économétrique de mesure de la connaissance produite dans les technologies de l'énergie bas-carbone. L'utilisation d'un modèle à facteur latent commun permet d'estimer un indice de qualité des inventions brevetées entre 1980 et 2010, dans quinze types de technologies et dans six pays innovateurs. Le Chapitre 4 revisite la question du design optimal du système de brevet quand il s'adresse à une invention de procédé dont la rémunération dépend des politiques de tarification des externalités sur l'environnement. Le Chapitre 5 résume nos résultats et en déduit les principaux messages.

Mots-clés: approvisionnement énergétique, technologies bas-carbone, double externalité,

politiques d'innovation, brevet, diffusion

Innovation in low-carbon energy technologies: theoretical analyses and empirical assessments

Abstract

Innovation in low-carbon energy technologies (LCETs) is impeded by externalities on the environment on the one hand, and on knowledge on the other hand. These market failures need to be addressed through public policies. The purpose of this thesis is to investigate the conditions for effectiveness of policies aiming at supporting innovation in LCETs. It does so by having recourse to theoretical analyses in conjunction with empirical assessments. The thesis is structured into five chapters. Chapter 1 questions the need to implement innovation policies specifically dedicated to LCETs — as opposed to neutral innovation policies that do not discriminate between these technologies and other technologies. A review of the economic instruments that have been implemented is proposed and indicates the predominance of a demand-pull approach — over a supply-push approach — to support innovation in LCETs. Chapter 2 evaluates the effects of demand-pull support instruments by conducting a counterfactual analysis to determine the extent to which the diffusion of wind power in six European countries is imputable to these instruments. Chapter 3 develops an econometrical method aiming at providing a robust measure of the produced knowledge that pertains to LCETs. A common latent factor model is used to estimate the quality of inventions that have been patented by six countries between 1980 and 2010 in fifteen low-carbon energy technologies. Chapter 4 revisits the question of the optimal design of a patent system when specifically dedicated to a process invention, whose reward depends on the pricing of environmental externalities. Chapter 5 summarizes our results and articulates key issues and messages.

Keywords: energy supply, low-carbon technologies, double externality, innovation policies, patent, diffusion

Contents

List of Figures

List of Tables

Introduction

Everything that can be invented has been invented.

Charles H. Duell, 1899

Ces mots, du commissaire américain aux brevets adressés au président des États-Unis d'Amérique William McKinley en 1899[1], nous autorisent à un certain optimisme. Que Mr. Duell, travaillant au plus proche des secteurs de l'innovation, n'ait pu imaginer que de nouveaux paradigmes technologiques contribueraient à transformer les sociétés humaines tout au long du 20ème siècle[2] est révélateur de la formidable capacité des systèmes sociaux à sans cesse se renouveler en proposant de nouvelles solutions technologiques aux problèmes qu'ils rencontrent. Pour autant, l'histoire économique nous interdit de faire vœu de patience en considérant la technologie comme une manne providentielle. Les nouvelles technologies, et les modifications des sociétés qu'elles participent à alimenter, sont endogènes au système économique. Schumpeter avait distingué l'invention de l'innovation, cette dernière étant la réussite dans la mise en œuvre au sein de l'appareil productif d'une idée nouvelle, définie comme l'invention (Schumpeter, 1943, (190)). Il s'ensuit naturellement que les déterminants de l'innovation sont économiques. Schumpeter avait ainsi proposé une théorie économique du changement technique dont l'un des principaux apports peut être résumé comme ceci : les conditions économiques poussent les individus à mettre en œuvre de nouvelles combinaisons productives, qui participent en retour à modifier les conditions économiques qui appelleront les innovations futures. La société n'est donc pas déterminée par la technologie, mais toutes deux co-évoluent ensemble.

L'histoire économique des révolutions industrielles est sur ce point riche en enseignements. Avant 1750, la croissance du Produit Intérieur Brut (PIB) réel par tête dans les pays

[1]Rapporté dans Cerf et Navasky, 1994,(176).

[2]Citons par exemple l'avion (1903), la télévision (1926), le code-barres (1949), le micro-processeur (1971) et le World Wide Web (1989).

les plus développés sur le plan économique était virtuellement inexistante (Gordon, 2012, (56)). D'après Mokyr, l'entrée dans la phase de croissance des révolutions industrielles se fait grâce à la transition entre deux modes d'utilisation de la connaissance à des fins productives. Le premier est l'utilisation d'une connaissance empirique, désorganisée et construite autour de consensus tacites. Le second est l'usage d'une connaissance technique fondée sur la compréhension des sciences à des fins d'amélioration des modes de production; la mobilisation d'une base épistémique pour motifs économiques étant la première forme de Recherche & Développement (Mokyr, 2010, (187)). Au cœur des transformations de nos sociétés que chaque révolution industrielle a suscité se trouve le couple énergie-technologie. En effet, il est difficile de distinguer les apports respectifs de l'énergie et de la technologie à la croissance tant elles sont liées. L'histoire du changement technique est celle de l'invention et de l'innovation réalisées en vue de proposer de nouvelles sources d'énergie, de nouveaux moyens de contrôle de son utilisation et de nouveaux matériaux synthétiques avec lesquels travailler (Metcalfe, 2008, (186)).

Les interactions entre innovation et énergie sont illustrées par l'exemple de la machine à vapeur qui a constitué, avec la mécanisation de l'industrie textile, l'une des innovations majeures ayant amorcé la première révolution industrielle (1750-1830). Dans son livre 'The Coal Question', Jevons rapporte la volonté du gouvernement anglais de trouver une nouvelle méthode de pompage de l'eau dans les mines de charbon pour permettre des forages plus profonds (Jevons, 1866, (184)). La première application que trouvera la machine à vapeur est de répondre à ce besoin. Par voie de conséquence, le succès économique de cette nouvelle technique d'extraction, en diminuant le coût du charbon, participera à multiplier les applications faites de la machine à vapeur, devenues rentables grâce à un charbon bon-marché et à des gains d'apprentissage provenants de ses premières applications. La technologie s'est diffusé ensuite aux chemins de fer et aux bateaux à vapeur. De même, l'exploitation des chemins de fers a mené à l'usage de l'électricité et de l'acier (Caron, 1983, (25)). Et le développement de la voiture s'est fait de concert avec l'utilisation du pétrole puisque le moteur à combustion interne viendra résoudre les contraintes opérationnelles des premières formes d'automobiles dont la voiture à gaz (Isaac de Rivaz en 1807) et la voiture électrique (Camille Faure en 1881 et parallèlement Gustave Trouvé en 1881).

Innovation et énergie ont contribué à améliorer les standards de vie de manière phénoménale en comparaison des progrès acquis avant le 18ème siècle. Avec un siècle et demi de retard, les progrès scientifiques révéleront l'un des coûts ignorés de cette croissance : celui du changement climatique.

L'influence des activités humaines sur le réchauffement climatique

Publié en 1972, le rapport 'The limits To Growth' commandé par le Club de Rome et réalisé par une équipe de chercheurs du Massachussetts Institute of Technology propose une modélisation prospective de l'évolution de cinq tendances : industrialisation accélérée, croissance de population rapide, malnutrition, épuisement des ressources non renouvelables et environnement détérioré. Ses conclusions interpellent la communauté internationale sur les limites écologiques de la croissance économique dans un monde à ressources finies. Quelques années plus tard, le risque du réchauffement climatique est pointé à nouveau par le GIEC (Groupe d'experts Intergouvernemental sur l'Evolution du Climat), un corps international d'environ 2000 chercheurs mandaté par les gouvernements pour synthétiser les études sur le changement climatique ayant fait l'objet d'une évaluation par les pairs. Le premier rapport de synthèse parait en 1990 et confirme l'influence des activités humaines sur le réchauffement climatique observé, tout en prédisant un réchauffement moyen de la température du globe d'environ 3 $^\circ$ C par rapport au niveau préindustriel à horizon 2100; ce dans un scénario où aucune mesure de réduction des émissions de gaz à effet de serre (GES) ne serait prise. Les conséquences prédites sont désastreuses puisqu'elles impliquent, entre autres, une augmentation du niveau de la mer de 65 cm à horizon 2100, une réduction massive de la biodiversité, une diminution des ressources en eau et en biomasse disponibles et une prolifération des maladies.

En réponse à cette alerte, la communauté internationale se rassemble en 1992 durant le Sommet de la Terre qui réunit 196 États. Ce sommet reconnaît la nécessité de prendre des mesures pour limiter le réchauffement climatique et met en place la Convention Cadre des Nations Unies sur les Changements Climatiques (UNFCC). Cette dernière pose les fondements de la négociation climatique telle qu'elle s'amorce avec la première Conférence des Parties (COP) qui a lieu en 1995 à Berlin. Sans faire état des ratés et des succès de la négociation climatique qui se poursuit depuis plus de vingt ans, nous pouvons affirmer que sa plus grande réussite visible a été de faire prendre aux pays des engagements chiffrés de réduction de leurs émissions de GES. Le 12 décembre 2015 à Paris et sur la base de leurs contributions nationales à l'effort global de réduction des émissions de GES, les 196 pays de l'UNFCC prennent l'engagement de réduire leurs émissions de manière à contenir le réchauffement moyen de l'atmosphère entre 1,5 $^\circ$ C et 2 $^\circ$ C d'ici à 2100. En parallèle à la négociation climatique, le niveau des émissions de GES en 2012 augmentera de 42,07% par rapport à son niveau de 1990 et le GIEC, intégrant les données nouvelles et renforçant son expertise, reverra à la hausse ses prévisions sur l'évolution de la température moyenne du globe.

Le défi technologique d'une énergie bas-carbone

L'International Energy Agency (IEA) estime qu'en 2010, 68% de l'ensemble des émissions de GES d'origine anthropique proviennent de l'utilisation de l'énergie (IEA, 2015, (216)). Le reste des émissions se réparti entre les procédés industriels (7%), l'agriculture (11%) et des sources additionnelles d'émissions telles que l'usage de solvant ou le traitement des déchets (9%). Une décomposition par secteur permet de souligner le poids de la production d'énergie en elle-même. Le secteur de l'approvisionnement en énergie convertit une part de l'énergie primaire totale disponible sous forme d'énergie fossile (pétrole, gaz naturel, charbon), d'énergie fissile (uranium) ou d'énergie renouvelable (éolien, hydro, géothermie, solaire, bioénergie) en différentes formes secondaires d'énergies (e.g. électricité, essence, gasoil, hydrogène) et d'énergies finales telles que le transport ou la chaleur. En 2010, ce secteur représentent 34,6% des émissions de GES d'origine anthropique (IPCC, 2014, (220)). Les secteurs dits consommateurs, qui produisent des biens et des services en utilisant de l'énergie finale, se répartissent le reste des émissions : le transport (14%), le bâtiment (6,4%), l'industrie (21%) et l'agriculture et la forêt (24%).

En raison de son poids dans les émissions totales et de la place de plus en plus importante qu'il est appelé à prendre dans l'économie mondiale[3], l'un des chantiers de la lutte contre le réchauffement climatique est la décarbonation du secteur d'approvisionnement en énergie. Plus particulièrement, l'activité de génération d'électricité bas-carbone de ce secteur offre une opportunité de réduction rapide des émissions de GES, en comparaison des secteurs du bâtiment, de l'industrie et du transport (IPCC, 2014, (219)). En vue de stabiliser les émissions de GES à des niveaux suffisamment faibles pour limiter le réchauffement climatique à 2° C à horizon 2100, le GIEC estime que la part d'électricité bas-carbone dans la quantité totale d'électricité générée doit passer d'environ 30% en 2010 à 80% en 2050.

Les options technologiques bas-carbone connues du secteur de l'approvisionnement en énergie sont les technologies des énergies renouvelables (TERs), de l'énergie nucléaire, du Captage et du Stockage du Carbone (CCS) et de l'efficacité énergétique dans la transmission et la distribution de l'énergie qui ne visent pas, en soi, à décarboner la production mais à la réduire. Ces options technologiques présentent des degrés de maturité[4] très différents. Tandis que le nucléaire est une technologie mature qui, après avoir connu une période faste,

[3]Les scénarios de projection de la tendance actuelle du Cinquième rapport du GIEC anticipent un doublement, voir un triplement, des émissions directes de CO_2 du secteur de l'approvisionnement en l'énergie en 2050, en comparaison des niveaux d'émissions de 2014 (IPCC, 2014, (220)).

[4]Le développement d'une technologie traverse plusieurs étapes, de la recherche basique à la diffusion en passant par la recherche appliquée, la démonstration, la pré-commercialisation et la commercialisation. Le degré de maturité croît quand la technologie se rapproche de sa diffusion.

se heurte désormais à de nouvelles limites en termes de coûts et de sécurité[5], les technologies du CCS ne présentent que de trop rares exemples opérationnels pour générer l'expérience nécessaire à leurs déploiements à grande échelle (IEA, 2013, (213)). Ainsi ce sont les TERs qui font l'objet de la plus grande attention de la part des pouvoirs publics. La Commission Européenne a par exemple choisi d'ajouter aux objectifs de réduction des émissions de GES un objectif de déploiement des TERs. En 2014, l'objectif que fixe la Commission est que 27% de la consommation brute d'énergie finale en 2030 soit d'origine renouvelable, contre 16% alors. Cette transition énergétique implique une transformation profonde du secteur de l'énergie reposant, entre autres, sur l'innovation bas-carbone définie comme la mise en œuvre de méthodes de production et l'introduction de produits nouveaux orientés vers la réduction des émissions de GES. L'analyse économique identifie deux défaillances de marché que les pouvoirs publics peuvent corriger pour encourager l'innovation bas-carbone. Nous les détaillons ci-dessous avant de revenir sur l'histoire particulière des politiques de soutien aux TERs qui les dote d'une certaine inertie dans leurs modalités de conception dont nous esquissons les contours.

L'innovation bas-carbone entravée par une double externalité

L'analyse économique distingue deux défaillances de marché qui entravent l'innovation bas-carbone. C'est l'idée de double externalité (Rennings, 2000, (145) ; Jaffe et al., 2005, (78)). D'une part, les activités émettrices de GES génèrent des dommages environnementaux qui ne sont pas pris en compte par les agents économiques. Ces coûts environnementaux sont externalisés dans le sens où ils seront subis par les générations futures. Pour pallier à cette défaillance de marché les pouvoirs publics peuvent intervenir en mettant en place, par exemple, des systèmes de taxe ou des marchés de permis d'émissions visant à faire porter aux agents responsables des décisions de production/consommation polluantes les coûts externalisés. Cette idée suit le principe du pollueur-payeur, qui consiste à corriger le prix des marchandises de l'emploi de ressources naturelles non-tarifiées (Godard, 2004, (55)). D'autre part, la littérature économique identifie des défaillances de marché sur la création de connaissance qui freinent le phénomène d'innovation. Il en résulte qu'un marché dérégulé induit un sous-investissement dans la création de connaissance par rapport à son niveau socialement optimal[6]. Pour réduire le coût social des défaillances de marché sur la connaissance, les pouvoirs publics peuvent intervenir à différents stades de la chaîne du changement technique en vue de promouvoir sa création et sa diffusion. C'est par exemple

[5]Pour une analyse de l'augmentation des coûts du nucléaire, voir Grubler, 2010, (64).

[6]La situation socialement optimale est celle où le prix de la connaissance est nul, puisqu'égal à son coût de reproduction. Autrement dit, c'est la situation dans laquelle la connaissance est la plus largement diffusée dans la société (Arrow, 1962, (172)).

le rôle des subventions à la recherche fondamentale, aux projets démonstrateurs et à la diffusion d'une innovation.

La décarbonation du secteur de l'énergie repose sur ces deux types d'intervention. Une politique ambitieuse de tarification des émissions de GES permet : (1) de révéler des options technologiques déjà existantes dont la rentabilité est entravée par l'absence d'un signal prix rémunérant leurs avantages environnementaux ; (2) de contribuer à réorienter les investissements des agents vers des technologies bas-carbone. En parallèle, les pouvoirs publics peuvent renforcer le deuxième effet via des politiques de soutien à l'innovation.

L'histoire des politiques de soutien à l'innovation dans les TERs : entre volonté d'indépendance énergétique et lutte contre le réchauffement climatique

La double externalité et ses implications en termes de politiques publiques s'appliquent tout particulièrement au problème climatique. Pour autant, ce n'est pas la prise de conscience des enjeux climatiques qui a initié le soutien à l'innovation dans les TERs tel qu'il a été implémenté, mais la volonté d'indépendance énergétique des États ; le réchauffement climatique viendra par la suite renforcer l'attention qu'accorderont les pouvoirs publics aux TERs.

Le premier choc pétrolier de 1973 agit comme un catalyseur du soutien aux énergies renouvelables. Certains pays ambitionnent alors de créer des industries nationales et pour cela mettent en place dès les années soixante-dix des programmes de R&D destinés aux secteurs des TERs. C'est le cas de l'Allemagne, du Danemark, des USA et des Pays-Bas (Lewis et Wiser, 2007, (107)). Ces politiques de soutien s'inscrivent dans une démarche dite *supply-push* en renforçant les compétences de R&D du secteur. Elles sont très tôt complétées par des politiques de soutien par la demande, dites *demand-pull*, visant à stimuler le déploiement de la technologie[7]. Par exemple, la Californie implémente en 1980 un système de tarif garanti (FIT) pour l'électricité d'origine renouvelable. Ainsi 16000 turbines éoliennes sont installées durant la décennie pour une puissance cumulée de 1700 MW (Kaldellis et Zafirakis, 2011, (84)). Si l'arrivée du président Ronald Reagan freine cette dynamique, d'autres pays continueront sur leurs lancées. L'Allemagne par exemple, qui dès 1974 avait commencé à soutenir la création d'un tissu industriel dans la technologie éolienne, renforce son soutien après deux évènements majeurs : l'accident de Tchernobyl qui lui fait prendre le chemin de l'abandon du nucléaire et l'arrêt des subventions publiques à l'utilisation du

[7]Le principe des politiques demand-pull est de garantir aux producteurs d'énergies renouvelables un paiement au-dessus du prix de marché pendant une durée prédéfinie en vue d'assurer la rentabilité de leurs investissements.

charbon, déclarées illégales par la Commission Européenne. Plusieurs programmes soutiennent l'industrie allemande des renouvelables comme le programme 100MW/250MW qui amorce la diffusion de la technologie éolienne et offre ainsi un marché aux équipementiers nationaux[8].

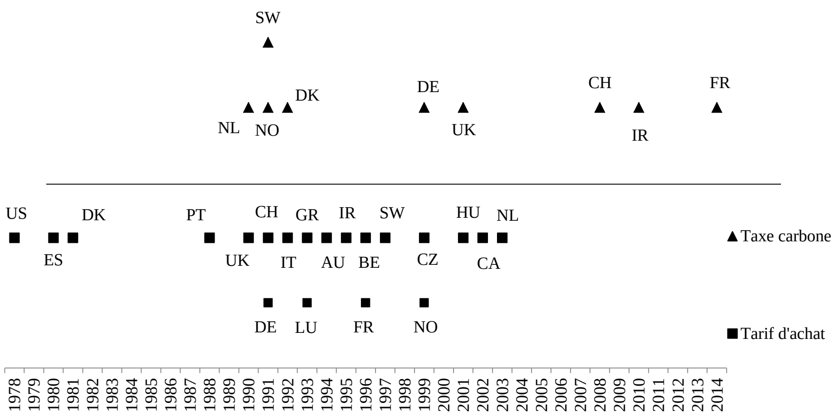

Figure 1: Années d'introduction des tarifs d'achat à l'électricité renouvelable et des taxes carbone pour 20 pays de l'OCDE[9].

Les préoccupations environnementales ont amplifié la volonté des États de développer les énergies renouvelables. Face aux difficultés de mettre en place une taxe carbone risquant d'entraver la compétitivité des secteurs économiques énergivores (Fischer et Newell, 2009, (50)), le soutien demand-pull à l'innovation s'est vu *de facto* attribuer la tâche supplémentaire de réduire les émissions de GES. Comme le montre la Figure 1, l'introduction d'une taxe carbone, quand elle a lieu, se fait généralement après la mise en place des tarifs d'achat[10]. Les rares exceptions parmi les pays représentés sur la Figure 1 sont la Norvège, les Pays-Bas et la Suède. Encore maintenant, la Commission Européenne reconnait que la faiblesse du prix carbone peut être compensée par un soutien demand-pull plus avantageux aux énergies renouvelables (Commission Européenne, 2014, (203)). Or, ces politiques de soutien sont de plus en plus critiquées pour, d'une part, le coût croissant qu'elles font porter à la collectivité sans pouvoir remplacer efficacement une taxe carbone et, d'autre part, l'ampleur du soutien demand-pull à l'innovation en comparaison de celui supply-push. De fait, ce déséquilibre questionne l'efficacité du soutien à l'innovation dans les TERs (Zachmann et al., 2014, (193); Albrecht et al., 2015, (3)).

[8]Deux tiers des éoliennes construites dans le cadre de ce programme sont de conception allemande (Laird et Stefes, 2009, (95)).
[9]Noms des pays au format ISO 3166-1 Alpha-2.
[10]Les informations produites sur la figure proviennent de l'IEA (2004, (210)).

Questions de recherche

Dans l'optique d'une transition vers l'introduction d'une taxation du carbone incitative, la question de recherche de cette thèse est d'établir les conditions d'un soutien efficace à l'innovation dans les technologies de l'énergie bas-carbone. Pour y répondre, l'analyse est divisée en deux parties. La partie empirique propose l'évaluation des politiques de soutien mises en place jusqu'à présent pour en déduire plusieurs implications en termes de politiques publiques. La seconde partie pose les bases théoriques de l'interaction entre les deux types de défaillances de marché qui entrave l'innovation bas-carbone et les étudie dans le cadre d'une politique de propriété intellectuelle, en l'occurrence de brevet.

Structure de la thèse et résumé des chapitres

Cette thèse se compose de cinq chapitres. Les chapitres 2, 3 et 4 sont des articles de recherche dans lesquels sont développées des analyses pouvant être considérées indépendamment les unes des autres. Le Chapitre 1 rappelle le contexte dans lequel s'inscrivent ces trois chapitres et définit plusieurs notions qui constituent le liant des trois articles de recherche. Le Chapitre 5 propose une analyse globale de leurs résultats principaux.

Le Chapitre 1 contextualise à la fois sur le plan théorique et sur le plan empirique les questions de recherches abordées. Son point de départ est l'identification de quatre modèles théoriques qui visent à guider l'intervention publique dans son soutien à l'innovation dans les technologies de l'énergie renouvelable (TERs). Ces modèles diffèrent par leur traitement de la double externalité. Le premier est nommé par Nordhaus le 'price fundamentalism' et plaide en faveur d'un traitement séparé des deux externalités. Ainsi le rôle du prix du carbone est fondamental puisqu'il donne un signal de marché aux dommages environnementaux. En parallèle, une politique de soutien à l'innovation doit être mise en place à destination des nouvelles technologies sans discriminer les technologies bas-carbone des autres types de technologies. Ce modèle repose sur deux hypothèses centrales : (1) l'absence de contraintes imposées aux pouvoirs publics sur la mise en place de la politique environnementale, impliquant la possibilité d'une politique de tarification du carbone de premier rang ; (2) l'impossibilité pour le régulateur de distinguer les conséquences sociales d'une innovation selon son secteur d'application, impliquant qu'il considère les secteurs comme identiques sur le plan technologique. Le second modèle, plus pragmatique, relâche la première hypothèse et déduit qu'une internalisation imparfaite des dommages environnementaux doit être compensée par une politique de soutien à l'innovation plus avantageuse aux technologies environnementales. Le troisième modèle, plus optimiste quant aux informations accessibles au régulateur, relâche la seconde hypothèse et explore les possibilités qu'offre la prise en compte des particularités sectorielles des TERs dans la mise en place de politiques de soutien à l'innovation dédiées spécifiquement à ces technologies. Le quatrième modèle explore une piste de recherche en questionnant l'influence de l'interaction entre le caractère partiellement appropriable de la connaissance et l'internalisation des dommages environnementaux sur les politiques de soutien à l'innovation environnementale. Les deuxième et troisième modèles constituent les bases théoriques des politiques de soutien à l'innovation dans les TERs telles qu'elles ont été mises en place. Leurs principales limites sont donc détaillées. Finalement, une revue des instruments économiques dont dispose le régulateur est proposée et met en exergue la prédominance du soutien par la demande dans les politiques de soutien à l'innovation aux TERs (approche dite demand-pull), aux dépens d'un soutien par l'offre (approche dite supply-push).

Le Chapitre 2 est un article de recherche évaluant l'effet des instruments de soutien demand-pull sur la diffusion de la technologie éolienne[11]. Pour mener cet exercice d'évaluation, l'analyse est construite en deux temps. Dans un premier temps, les diffusions observées de la technologie éolienne dans six pays européens sont répliquées. A cet effet, un modèle micro-fondé de diffusion est construit pour intégrer: (1) l'influence des politiques demand-pull sur la rentabilité des projets éoliens ; (2) les effets des apprentissages nationaux et européen qui ont contribué à faire décroitre le coût de la technologie avec l'expérience accumulée dans sa fabrication; c'est l'hypothèse de learning-by-doing ; (3) des facteurs exogènes ayant joué sur la rentabilité des projets éoliens (e.g. prix des métaux, conditions météorologiques). Dans un second temps, plusieurs scénarios sont simulés en vue de conduire une analyse contrefactuelle. Sont testés les effets des suppressions unilatérales des politiques demand-pull par chacun des six pays de l'échantillon; à savoir l'Allemagne, le Danemark, l'Espagne, la France, l'Italie et le Portugal. Est également testé l'effet sur les diffusions de l'éolien dans ces pays d'une suppression commune de leurs politiques demand-pull. Plusieurs conclusions sont tirées de l'analyse de ces scénarios. Premièrement, les politiques demand-pull ont fortement contribué à accroitre la diffusion de l'éolien, puisque supprimer le soutien demand-pull dans un pays aurait réduit de 32% à 95% les capacités éoliennes cumulées installées en 2012, selon le pays. Deuxièmement, l'Espagne, l'Allemagne et le Danemark ont bénéficié d'un avantage de first-mover lié à l'antériorité de la diffusion de la technologie éolienne dans leurs parcs électriques. En comparaison des trois autres pays, cet avantage se traduit par une diffusion de la technologie nettement moins dépendante, d'une part, de la politique nationale et, d'autre part, des politiques étrangères. La diffusion de l'éolien dans ces pays

[11] Article actuellement en seconde relecture dans le journal Energy Policy.

est dite partiellement auto-entretenue. Ces deux constats impliquent que différer la mise en place d'un soutien demand-pull dans l'espérance de profiter de l'apprentissage stimulé par les politiques étrangères s'avère préjudiciable à la diffusion de la technologie éolienne.

Le Chapitre 3 est un article de recherche[12] dont le but est de mesurer la connaissance accumulée par sept pays dans quinze technologies de l'énergie bas-carbone entre 1980 et 2010. Pour mesurer la création de connaissance, et non ses tentatives, les données de brevets sont privilégiées aux données de dépenses de R&D. De nombreux travaux démontrent le risque lié à la distribution fortement asymétrique de la qualité des inventions brevetées d'utiliser un simple compte de brevets pour mesurer la connaissance. Pour pallier à ce risque, un modèle à facteur latent commun est estimé. Pour chaque invention, il permet d'expliquer simultanément les valeurs prises par les différentes métriques d'un brevet par la qualité de l'invention protégée, celle-ci étant non observée mais estimée comme facteur latent commun. Le choix des métriques se fonde sur une vaste littérature empirique qui démontre les liens entre la qualité d'une invention et les métriques d'un document de brevet. En l'occurrence, celles inclues dans la modélisation proposée sont la largeur du scope technologique d'une invention, le nombre de brevets la protégeant, le nombre de citations faites à d'autres inventions et le nombre de citations reçues par l'invention. L'estimation d'un indice de qualité est corrigée des effets d'office, de cohorte et de technologie pour autoriser la comparaison de la qualité des inventions inclues dans notre base de données. Le stock de connaissance accumulée dans 15 technologies de l'énergie bas-carbone est calculé en pondérant le compte des inventions par leurs indices de qualité. D'importants effets de substitution sont constatés: les technologies de l'énergie nucléaire, géothermique et solaire thermique sont progressivement délaissées et remplacées par de nouvelles technologies, aux premiers rangs desquelles celles de l'énergie solaire photovoltaïque, de l'énergie éolienne et du stockage d'énergie. Ces substitutions s'expliquent, d'une part, par le nombre d'inventions et, d'autre part, par l'évolution de la qualité moyenne de ces inventions. La qualité moyenne des inventions dans les technologies les plus anciennes stagne dans le temps, voir diminue. Au contraire, de nouvelles technologies disposent d'un stock de connaissance croissant et se bâtissent sur des inventions qui, en moyenne, gagnent en qualité au fil du temps. L'analyse de l'évolution temporelle de la distribution de la qualité des inventions brevetées dans le nucléaire et l'éolien suggère que dans le premier cas, le potentiel pour des inventions de haute qualité s'est épuisé au fil du temps, tandis que l'inverse est observé dans le second cas. Des analyses complémentaires des avantages technologiques des pays étudiés sont finalement proposées.

Le Chapitre 4 est un article[13] qui revisite l'arbitrage auquel fait face le régulateur quand il

[12] Publié en tant que document de travail EconomiX.

[13] Publié en tant que document de travail EconomiX.

met en place un système de brevet destiné aux technologies environnementales. Ce travail propose une formalisation du quatrième modèle présenté dans le Chapitre 1 en explorant l'interaction entre l'appropriation de la connaissance et la tarification d'une externalité environnementale. Un système de brevet concède l'appropriation partielle d'une invention par son inventeur en vue de garantir une rente incitative qui stimule les investissements en R&D. L'arbitrage auquel fait face le régulateur est le suivant : d'une part il promeut la création de connaissance pour ses effets positifs sur le bien-être social, d'autre part il garantit à l'inventeur une rente incitative mais socialement coûteuse durant la durée du brevet puisque ce dernier prive temporairement la société d'un usage libre de la connaissance protégée. À cet arbitrage s'ajoute une dimension supplémentaire à l'ensemble de choix du régulateur qui est celle de la tarification des dommages environnementaux. Il est démontré dans un premier temps que la politique optimale de brevet interagit avec la taxation environnementale imposée à l'inventeur. Deux cas de figure surviennent. Le premier est celui d'une tarification environnementale qui annihile la perte sèche de bien-être social résultant du pouvoir de marché concédé par le système de brevet. Le second cas de figure est celui où la perte sèche demeure, mais peut être réduite via une taxation environnementale plus favorable à l'inventeur que celle de premier rang. Finalement, deux applications sont proposées pour illustrer les deux cas de figure évoqués.

Le Chapitre 5 croise les résultats des articles de recherche inclus dans cette thèse pour en déduire ses principaux messages.

Chapter 1

Overview of economic instruments for the support of innovation in renewable energy technologies

1.1 Introduction

From government authorities to the energy sector's stakeholders, renewable energy has been widely acknowledged as a key component of the energy transition. In 2014, the European Commission has set a reduction target of 40% of the European Union greenhouse gas (GHG) emissions by 2030 compared to the 1990 levels. To achieve this, an additional objective is that renewable energy represents 27% of the gross final energy consumption by 2030, against 16% in 2014 in the EU-28. Such an increase is conditional upon major technological advances in Renewable Energy Technologies (RETs). So far, several barriers hinder their large-scale deployment. One of them is the higher cost of electricity generated from renewable sources compared to conventional technologies when the impact on the environment from burning fossil fuels is excluded from the retained definition of the 'cost' of electricity. In Europe, the Levelised Cost Of Electricity[1] (LCOE) from coal ranged from 46.3 to 81.6 €/MWh and from 55.52 to 80.76 €/MWh for gas while wind and solar LCOE ranged from 58.15 to 99.18 €/MWh and from 194.9 to 319.55 €/MWh, respectively (IEA, 2010,(211)). There is a room for optimism as the cost of RETs have experienced a

[1] The Levelised Cost of Electricity corresponds to the unit cost of electricity (MWh) over the economic lifetime of a power plant. It assumes that all production costs are certain. All the given values are computed at a 5% discount rate and expressed in 2008 €.

significant decrease over the last decades. For instance, the turnkey cost[2] of wind power projects in Denmark have been roughly divided by two between 1985 and 2013 and the productivity of wind power plants has been substantially improved (IEAWIND Annual Report 2013, (212)). With the aim of stimulating innovation, many countries have implemented technology policies dedicated to RETs. Providing for an efficient support to RETs is an intricate question for public authorities because there are several market failures and barriers that hamper innovation related to RETs, among which environment and knowledge externalities. First, market prices do not reflect the environmental damage from burning fossil energies. Second, innovation suffers from underinvestment because: (1) newly created knowledge cannot be perfectly appropriated by innovators and (2) agents do not take into account the positive spillovers from knowledge that increase the overall social welfare.

The chapter is organized as follows. The first section presents the rationales for a public support for RETs. It starts by defining the two externalities at the core of the environmental innovation in order to identify four policy blueprints to support RETs. Emphasis is given on the need for dedicated support policies toward innovation in these technological fields. The two main approaches, demand-pull and supply-push, are then analyzed before detailing several pitfalls of support policies drawn from past experience. From the first section we deduce three efficiency criteria to guide policy support. The second section reviews the policy options provided by demand-pull instruments and outlines the importance of their designs. Particular attention is paid to the potential of each instrument to maintain an incentive to innovate and to favor the integration of renewable energies to the electricity market. The third section investigates the role of supply-push policies and proposes several ways of fostering innovation in RETs sectors.

[2] Turnkey cost includes all the costs and expenditures paid by a generator before the power plant is operational.

1.2 The role of innovation policies in the energy transition

1.2.1 Environmental innovation policies and the double externality

1.2.1.1 The double externality

The fundamentals of economics teach us that environmental innovation is hampered by two market failures. On the one hand, polluting economic activities generate negative externalities on the environment. These externalities arise from the fact that a part, if not the totality, of the environmental cost from pollution is borne by agents who do not take the decision to produce or consume the polluting good. In the absence of corrective mechanisms, private decisions are made regardless of their environmental consequences and the amount of polluting good that is produced and consumed is higher than its socially optimal level. On the other hand new knowledge, on which innovation relies, creates positive externalities. As a public good knowledge has indeed two properties: non-rivalry and non-excludability. Non-rivalry means that consuming knowledge does not reduce the available quantity for other agents, while non-excludability implies that in the absence of policy intervention it is too costly to fully prevent someone from consuming knowledge. As a result when an agent makes a discovery that embodies new knowledge, other agents will benefit from positive knowledge externalities. However, from the public good's properties arises a knowledge dilemma. Since agents expect to benefit from positive knowledge externalities, they tend to reduce their efforts towards knowledge creation. Simultaneously, the zero cost of knowledge reproduction[3] involves that the optimal price for knowledge is also zero; in other words society benefits from the largest knowledge diffusion. The problem however is that profit-making companies, when engaging research activities for commercial purposes, expect a positive price. In a free market economy this dilemma generates underinvestment in R&D activities, compared to its socially optimal level (Arrow, 1962, (172), p. 619).

1.2.1.2 Public policies aiming at correcting externalities

Environmental and innovation policies intend to correct the two externalities detailed above. The purpose of these policies is to influence private behaviors by making agents internalizing a part, if not the totality, of the social consequences of their actions.

[3]Reproduction cost are considered to be null when transmission cost are excluded.

Environmental policies, through price or quantity instruments for instance, endeavour to regulate the polluting economic activity. The principle of an environmental policy is well illustrated by a first-best pricing policy of the negative externalities. It aims at internalizing the damage on the environment by equalizing the marginal private production cost of a polluting good with its marginal social production cost; the latter including environmental damages. Therefore, private decisions are made on the basis of the social cost of polluting activities.

Innovation policies seek to increase the private rate of return on innovation in order to foster knowledge creation (Martin and Scott, 2000, (117)). To capture the idea of knowledge dilemma it is helpful to distinguish between two dimensions of an innovation. First, it has a social rate of return which expresses its influence on the social welfare (taking into account knowledge spillovers). Second, it has a private rate of return, expected by the inventor, which guides fund allocation in the case of profit-making inventions. By supporting innovation the regulator brings closer these two rates of return. To increase the private rate of return of an innovation, the policy maker has two intrinsically linked alternatives:

- To strengthen an innovation's appropriability in order to increase the profit of the inventor. This is the role of Intellectual Property Rights (IPR).
- To increase an innovation's private rate of return for a given level of appropriability, by lowering the cost of R&D or by increasing the revenue from selling the innovation.

Based on this, a policy maker is aware: (1) that two externalities hinder environmental innovation; (2) that policy intervention aims at influencing private behaviors with respect to their social consequences; (3) that policy intervention can rely on several instruments. The remaining missing information is about the design of environmental and innovation policies.

1.2.1.3 The double externality problem: does environmental innovation deserve dedicated policies?

The design of environmental and innovation policies can be apprehended through four policy blueprints discussed in the next subsection. Before detailing these policy blueprints it is helpful to clarify some concepts.

If one considers that the two externalities detailed above do not interact with each other, an *environmentally neutral policy* can be implemented to support environmental innovation.

This is the idea defended by the first policy blueprint we present in 1.2.2.1. An environmentally neutral policy is defined as an innovation policy that does not discriminate between the supported technologies on the basis of their environmental features.

Dropping the assumption that the two externalities operate independently of one another, we define a *double externality problem* as the interaction between these. It prevents the policy maker from addressing separately each market failures and, to this extent, requires an innovation policy support dedicated to environmental technologies. Hence, we define a *dedicated innovation policy* as a policy that targets solely the creation of new knowledge related to environmental technologies.

The three last policy blueprints we present assume the existence of a double externality problem. Each of them however considers a different form of the double externality problem. First, environmental externalities, if underpriced, can deter the creation of new knowledge; it is discussed in 1.2.2.2. Second, the imperfect correction of knowledge externalities due to the heterogeneity of new technologies and the additional barriers to RETs makes environmental pricing alone insufficient to efficiently redirect investments toward RETs; this premise is investigated in 1.2.2.3 and advocates for an innovation policy support dedicated to RETs, being a subset of environmental technologies. Finally, a third version of the double externality problem states that even with a first-best environmental policy and a technological homogeneity, the imperfect appropriability of new knowledge implies a dedicated support to environmental technologies. Despite the strong implications it would have on environmental policy design, a rigorous demonstration remains to be made; as explained in 1.2.2.4.

1.2.2 A taxonomy of policy blueprints for environmental innovation

1.2.2.1 Addressing separately the two externalities to support environmental innovation

A first approach to foster environmental innovation, called by Nordhaus *price fundamentalism* (Nordhaus, 2011, (130)), starts from the basic assumption that the two externalities do not interact with each other. It states that environmental innovation should be promoted by combining the first-best environmental policy with an environmentally neutral innovation policy.

The concept of price fundamentalism can be illustrated by considering two kinds of innovation: an environmental innovation and a regular innovation. The former reduces, *ceteris paribus*, the negative externalities on the environment while the latter allows the innovative firms to raise an additional profit by, for instance, reducing the production cost of a good. If the environmental externality is perfectly corrected, an agent commercializing an environmental innovation sees its private rate of return increases due to the internalization of environmental externalities. Considering two competing innovations, an environmental one and a regular one, with equal social rates of return the perfect correction of the environmental externality combined with an environmentally neutral innovation policy is sufficient to foster environmental innovation.

Based on this policy blueprint, there are no rationales for innovation policies dedicated to environmental technologies. As Nordhaus acknowledges however, price fundamentalism may be too simplistic and his work details several qualifications to this approach. They add to a broader set of arguments against price fundamentalism. These critics argue that there is a double externality problem requiring the implementation of dedicated innovation policies. Although the double externality problem is discussed by several authors, it lacks from a taxonomy that clearly identifies the factors assumed to be responsible for it. We try to fill this gap by distinguishing three forms of the double externality problems.

1.2.2.2 Weak double externality problem from underpricing

A first critic made to price fundamentalism considers that given the low chances to see a first-best environmental policy being implemented, environmental technologies should receive an additional support compared to regular technologies. We call this argument the weak double externality problem from underpricing. The term weak underlines the difference with the strong double externality problem[4] defined in 1.2.2.4.

Considering the fields of RETs, the actual pricing of GHG emissions in the energy sector induces a rate of investment lower than the socially optimal level. The experience accumulated over the two last decades on international agreements suggests that a perfect pricing of GHG emissions is unlikely to occur soon enough to avoid the massive cost of climate change. Obviously, the little political appeal of an emission pricing scheme negatively impacting the activity in energy-intensive sectors reduces the probability to see such an agreement appears in the short term (Fischer and Newell, 2008, (50)). Hence, the optimal strategy in a

[4]The reader should not be confused by the obvious similarity of the terminology we use with the weak and the strong double dividends (Goulder, 1995, (57)). This similarity with his work is strictly limited to the words we have borrowed to Goulder.

second-best world where environmental externalities are not perfectly corrected is to implement support instruments dedicated to low-carbon innovation in addition to environmental policies (Jaffe et al., 2005, (78)). Besides, due to the important role technology has in international negotiations, dedicated policies would be an opportunity to strengthen the agreements between countries (Carraro and Siniscalco, 1994, (26)).

In certain cases, this policy blueprint has been already adopted. For instance, the role that policy support to RETs can endorse when environmental externalities are underpriced is acknowledged by the European Commission. Indeed, the *Guidelines on state aids for environmental protection and energy 2014-2020* are a prime example of a policy relying on the weak double externality problem from underpricing. They underline that the current instruments of environmental policies, being the carbon market and the national carbon taxes, do not fully internalize, yet, the environmental damages from carbon emissions. To this extent, they consider that renewable energy support can address a 'residual market failure on the environment' (European Commission, 2014, (203), p.24). Nonetheless, providing an additional support to RETs can be counterproductive as it can reduce in turn the efficiency of environmental policies, as discussed in subsection 1.2.4.

1.2.2.3 Weak double externality problem from technological heterogeneity

A second rationale for implementing innovation policies dedicated to RETs is the heterogeneity of the supported technologies. In this case, the scope is reduced to RETs only and does not encompass every environmental technologies. To take into account the differences among the technologies she promotes, the regulator must fine tune innovation policies to their peculiarities. We call this argument the weak double externality problem from technological heterogeneity. It has two causes: the difference in terms of adoption externalities and the specific barriers to the deployment of RETs. While the latter is specific to the technologies examined here, the former is not and is common to every new technology. It remains nonetheless a rationale for innovation policies dedicated to RETs because the intensity of adoption externalities varies with their maturity. These two causes are discussed below.

Adoption externalities

The knowledge dilemma described above results in an underinvestment in R&D activities compared to its socially optimal level. This analysis however relies on a simplified view of knowledge. Indeed, knowledge externalities can be decomposed into two components:

knowledge from research and knowledge from adoption. While the former corresponds to the basic definition of a knowledge externality given in 1.2.1, the latter slightly differs from that definition.

Schumpeter has analyzed technological change by distinguishing three phases: invention (generation of new ideas), innovation (conversion of inventions into marketable products and/or processes) and diffusion (spread of the innovation across the market). The last phase is influenced by several forms of adoption externalities that can be corrected through public intervention (Jaffe et al. 2005, (78)). Three kinds of adoption externalities can operate during the diffusion of a new technology: learning-by-doing, learning-by-using spillovers and network externalities. **Learning-by-doing** is how the unit cost of production decreases with the cumulative amount of produced output, which is a proxy of the experience gathered in the production process (Arrow, 1962, (4)). When this experience is not fully internalized by a firm and spills toward other producers, the regulator could implement support policies to stimulate the diffusion of the new technology in order to reduce the overall production cost. The assumption of learning-by-doing in renewable energy sectors has been validated in several studies by estimating learning curves (for a review of these studies,see Neij, 2008, (125)). Following the idea of learning-by-doing, learning curves describes how the unit cost of production decreases by a constant fraction with every doubling of the cumulative output. Thus, it makes sense to stimulate the diffusion of a new technology at the beginning of the diffusion process before further cost reductions become unduly costly and difficult to achieve. The same applies for learning-by-using. **Learning-by-using** plays on the demand-side of the adoption phase. Similarly to the producers of renewable equipments, their potential adopters will obtain a gain of information from the adoption of the new technology by other users. Deployment policies can provide for an incentive to adopt a new technology in order to make this information available to other agents. Learning-by-doing and learning-by-using operate during the adoption phase of every new technology, and not only RETs. Nonetheless, the specific features of each market raise doubt about the efficiency of an hypothetical technology-and-sector neutral policy aiming at bringing the actual levels of adoption of new technologies closer to their social optimums. Indeed as learning-by-doing and learning-by-searching evolve with a technology's maturity a specific support is more efficient. The third type of adoption externalities are **network externalities**. They operate when a user receives an additional reward that positively depends on the amount of individuals using the same technology[5]. In the context of renewable energies there is little

[5]For instance, the value of an electric car depends on the size of the refuelling stations network that depends itself from the number of electric cars.

evidence about the existence of network externalities at the technology level (Gillingham and Sweeney, 2010, (179)).

Additional barriers to the diffusion of RETs

The diffusion of RETs takes place in the very particular context of the energy sector, characterized by various and multifaceted market distortions, raising additional issues for policy making.

Energy industries have high fixed and partly recoverable costs and it has several implications. First, the nature of the costs makes existing firms having major incentives to delay the introduction of new technologies (Weyant, 2011, (167)). Second, the markets tend to be naturally concentrated and imperfect competition hampers the efficiency of environmental policies based on Pigouvian taxation[6] (Buchanan, 1969, (20); Lee, 1975, (103); Barnett, 1980, (8)).

Edenhofer et al. emphasize another failure of the energy market linked to their incomplete feature. They refer to the work of Stiglitz who demonstrates that a price system is unable to optimally perform its coordinating role with respect to long-term investments (Stiglitz, 1990, (191)). This is due to the absence of future markets providing for a long term signal to investors; without such markets there is no guarantee that investments are efficient. This is a barrier to investment in the energy sector because the lifetime of power plants is typically above 20 years, which is well above the span of the future contracts for energy delivery (Edenhofer et al., 2013, (48)). In the case of RETs, the absence of future market is combined with a regulatory uncertainty on the environmental policies that further reduces the willingness to invest of the private sector (Jaffe et al., 2005, (78)). As discussed below, demand-pull instruments can help creating an artificial long-term market for renewable energy.

1.2.2.4 The strong double externality problem

The problem of double externality can be considered in a framework similar to that of price fundamentalism. Hence, it relies on two assumptions: (1) the regulator has no constraint on the environmental policy and it excludes the problem of second-best policies depicted above; (2) she can perfectly fine tune additional deployment policies to technological heterogeneity (both in terms of learning and sectoral barriers) and it is equivalent to elude the question

[6] A Pigouvian tax is equal to the marginal damage of pollution so that the taxpayer is incentivized to take into account the environmental consequences of its actions (Pigou, 1932, (189)).

of adoption externalities and additional barriers to RETs. Within this framework, correcting separately the two market failures on environment and knowledge, as stated by price fundamentalism, may not be the best solution — although a strict demonstration is not provided here. Rather we illustrate the idea behind the strong double externality, which is the nexus between the appropriability of an invention and the pricing of the environmental externality. We proceed in two times.

First, considering a regular innovation that reduces the production cost of a good and has, as explained above, two dimensions reflected by : a social rate of return $r^s_{regular}$ and a private rate of return $r^p_{regular}$. Both depend on the reduction cost from the innovation and on its appropriability. If the latter is nill, $r^s_{regular}$ reaches a theoretical upper bound[7] because every agents can use the new knowledge embodied in the innovation. On the contrary, $r^p_{regular}$ is minimum because the inventor will not earn any benefit from selling the innovation. Hence, she will be discouraged to undertake innovative activities, the only reward being her own use of the new process. Patent systems, and more generally IPRs, aim at conceding a partial appropriability to the inventor to provide an incentive to innovate. The regulator faces a well-known tradeoff between the incentive to innovate from increasing $r^p_{regular}$ and the welfare loss from decreasing $r^s_{regular}$ compared to its theoretical upper bound; the policy variable being the level of appropriability[8].

Now, considering the case for an environmental innovation that reduces the environmental damage from the production of a good. Again, the social rate from this innovation, r^s_{green}, depends negatively from its appropriability and positively from the reduction of the environmental damage. The private social rate however, denoted r^p_{green}, depends positively from the appropriability of the innovation and positively from the environmental pricing policy that translates the reduction of the environmental damages into private gains. The latter being, contrary to the regular innovation case, a policy variable.

The idea of the strong double externality is to consider that a more efficient policy to promote environmental innovation can be achieved by: (1) conceding a smaller appropriability to the innovator (increasing r^s_{green}); (2) compensating the decrease of r^p_{green} resulting from a smaller appropriability by an adjusted environmental taxation that is more favorable to the inventor, in order to maintain an incentive to innovate. For instance, a firm that discovers a new process will obtain a shorter patent combined with a smaller environmental

[7] This upper bound is theoretical because it always remains a residual appropriability of an innovation due to industrial secret, for instance.

[8] Of course, an additional mean to increase the incentive to innovate is to lower the cost of R&D. For clarity it is not discussed in this illustration, the analysis being robust to an additional policy support to R&D because it always remains a partial appropriability of the innovation (at least residual if not regulated).

tax, compared to is competitors. The obvious limit of the reasoning, as in the price fundamentalism policy blueprint, lies in the assumption that the regulator has no constraints on environmental policies and that she is able to perfectly adapt the innovation policy the supported technology.

Synthesis of the subsection

Four policy blueprints for environmental innovation have been presented. Through a more empirical approach, we now discuss how policies have addressed the underinvestment in innovation toward RETs. It appears that they have been implemented by taking into account both the technological heterogeneity and the underpricing of the environmental externalities, sometimes in an inefficient way as depicts subsection 1.2.4.

1.2.3 Demand-Pull and Supply-Push approaches

Looking back at the history of policy support to innovation in RETs, it can be observed that policymakers have generally chosen to implement such policies before pricing environmental externalities[9], despite the economic intuition suggesting the reverse. This is mainly due to the fact that these policies have been perceived as substitutes to environmental policies. We now discuss their architectures. Innovation process covers several stages: from basic research through the development, demonstration, marketing and eventual spread of the innovation. Feedback of various kinds provide guidance to developers on the market reaction and enables them to adjust policy supports. The question of the repartition of public support between the stages of innovation process is addressed by the economic literature by distinguishing two families of instruments:

- Supply-push instruments that target progress in science and act on the initial stages of the process by supporting producers/business/scientists in innovation on products and production techniques.
- Demand-pull instruments that are involved in the downstream part of the process and create a favorable market for supported technologies.

The debate on the instruments to be put in place to stimulate innovation goes back to the late 1950s (see the critical review of Mowery and Rosemberg, 1979, (122)). The use

[9] See Bonnet, 2013 (196) for a review of the energy transition policies in Denmark, Germany and China.

of supply-push instruments stimulates R&D expenses and helps develop the 'absorption capacity' of new technologies, i.e. the propensity of an industry to integrate and put into practice the new opportunities provided by an invention. Depending on the supply-push given to various industries, there are differing rates of adaptation and development in response to technological breaks (Mowery, 1983, (123); Rosemberg, 1990, (146)).These differences across sectors justify to implement specific technology policies. However, the main critic to supply-push instruments is that they might favor technologies disconnected from consumers' preferences. Another risk is that these instruments deeply rely on informational structure and might be cost-inefficient for the regulator. Demand is also an effective driver of technological change: the size of the market and consumer expectations influence the expected private income that the innovative firm would obtain from a new product or production method. The major limitation of support for demand is that it focuses on existing consumer needs and risks missing out the most important innovations (Mowery and Rosenberg, 1979, (122)). Demand-pull instruments may be ineffective in stimulating fundamental research because any potential market emerges in the long term and involves a high level of uncertainty. Support for demand therefore primarily promotes incremental innovations. Indeed, public support is of major importance for the development of radical innovations, since they are "discrete, discontinuous events, usually involving deliberative effort; and they may have only a minor relatedness to existing products" (Nemet, 2009, (127)). Yet if even widely adopted, incremental innovations will not be able to meet GHG emissions targets at the lower cost. The optimal strategy is to implement supply-push and demand-pull supports to promote both R&D and deployment. The balance between the two approaches depends on the technology in question and on its maturity (Sagar and van der Zwaan, 2006, (148)).

The implementation of technology policies toward RETs has suffered from several pitfalls discussed in the next subsection.

1.2.4 The pitfalls of technology policies for RETs

In addition to the (more) theoretical insights developed in the subsection 1.2.2, we emphasize three recommendations drawn from the experience accumulated in the implementation of technology policies for RETs.

The need for a balanced support

In Europe, RETs support faces a deep imbalance between supply-pushing and demand-pulling. Zachmann et al. (2014, (193)) use the International Energy Agency (IEA) data to compute the expenses of six European countries in each type of support. They conclude that there is an astonishing difference: for the five largest countries in Europe plus the Czech Republic, the deployment cost of wind and solar energies (induced by demand-pull instruments) for the year 2010 is equal to 48,298 million €. In parallel, the amount of public R&D expenses realized during the same year and directed toward the same technologies has been 315 million €.

There are several advantages that could be derived from a more balanced support. Peters et al. investigate the respective roles of demand-pull and supply-push policies in fostering innovation in solar PV technology and pay particular attention to their geographical zone of application (Peters et al., 2012, (134)). They question the existence of cross-country knowledge spillovers for both types of policy and conclude that national supply-push policies have a positive impact on domestic innovation whereas no evidence is found that they influence foreign innovation. Conversely, national demand-pull policies foster innovation both inside and outside a country and there is no indication that domestic demand-pull policies lead to more domestic innovation than foreign demand-pull policies. From a policy perspective, supply-push instruments help a country to better internalize the newly created knowledge and it increases their social acceptability. Moreover, demand-pull policies create a prisoner's dilemma because each country has an incentive to reduce its demand-pull support to benefit from foreign markets[10]. A related study by Dechezleprêtre and Glachant (2014, (39)) carries complementary nuances about the results evoked above: studying the impact of demand-pull policies on wind power innovation, they find that the marginal effect of domestic demand on innovation is 12 times larger than the marginal effect of foreign demand. They explain the difference of their results with those of Peters et al. (2012, (134)) by the different technological maturity of solar PV and wind power. An additional explanation is the higher transport cost of wind turbines compared with solar panels. Finally, the literature on multiple factors learning curves indicates that learning-by-searching, generally measured by the cumulative R&D expenses, contributes to reduce the cost of RETs as well as the learning-by-doing resulting from demand-pull policies (Watanabe et al., 2000, (166); Klaassen et al., 2005, (90); Kobos et al., 2006, (92); Jamasb, 2007; (79)). The cost of technology support can be reduced through a balanced allocation of funds between technology deployment and R&D expenses.

[10]The experience of European demand-pull policies with the Chinese solar PV manufacturing sector is illustrative of the problem of subsidy leakage (Bonnet, 2013, (196)).

The electricity market crisis and the demand-pull support for RETs

In the early 1990s, many developed countries have chosen to liberalize the electricity markets. Before the electricity market liberalization the dominant model was a fully vertically integrated state owned utility which was fulfilling the role of a natural monopoly and dispatching electricity in its geographical zone. The problem was clear: how to satisfy the electricity demand and supply safety at the lowest cost. Market liberalization has changed the organization of electricity markets. The goal was to put in competition multiple generators in order to improve the market efficiency by minimizing electricity generation costs. The problem is that renewable energy support through demand-pull instruments has impacted the electricity price, hence resulting in a wrong price signal. This is due to two factors:

- Demand-pull policies provide an additional reward to renewable energy generators. As they receive a payment out of the market they are willing to sell their electricity at a lower price. Moreover, it is very often the case that renewable electricity has a priority access to the grid, hence ousting the other means of generating electricity. This distortion results from the design of the policy support in itself.
- Leaving aside the design of the demand-pull instrument, the marginal costs of solar power and wind power are almost nil (operation and maintenance costs are low). Following the merit order effect described below, these energies are injected first on the market, thus, lowering the electricity market price. This factor results from the design of the electricity market and its pricing rule.

As electricity is still too expensive to be stored at a large scale, the system operator has to balance supply and demand in real time. The pricing rule follows a merit order: the power plants with the lowest marginal cost of generation start to generate the first demanded units of electricity until their full capacity is used, followed by the power plants with the next higher marginal cost of generation, and so on until the demand is fully addressed. The graphical representation of the merit order effect is given in the Figure 1.1.

As a result of the introduction of wind and solar power on the electricity market, the supply curve moves to the right[11]. The introduction of variable energies, in addition to lowering the price, negatively impacts the rate of marginality[12] of conventional technologies and consequently the power plant's profitability. Here starts the problem of 'missing

[11] In a short term dynamic setting the demand may be higher or lower

[12] The rate of marginality of a technology is defined as the fraction of the year during which generators using this technology are marginal generators.

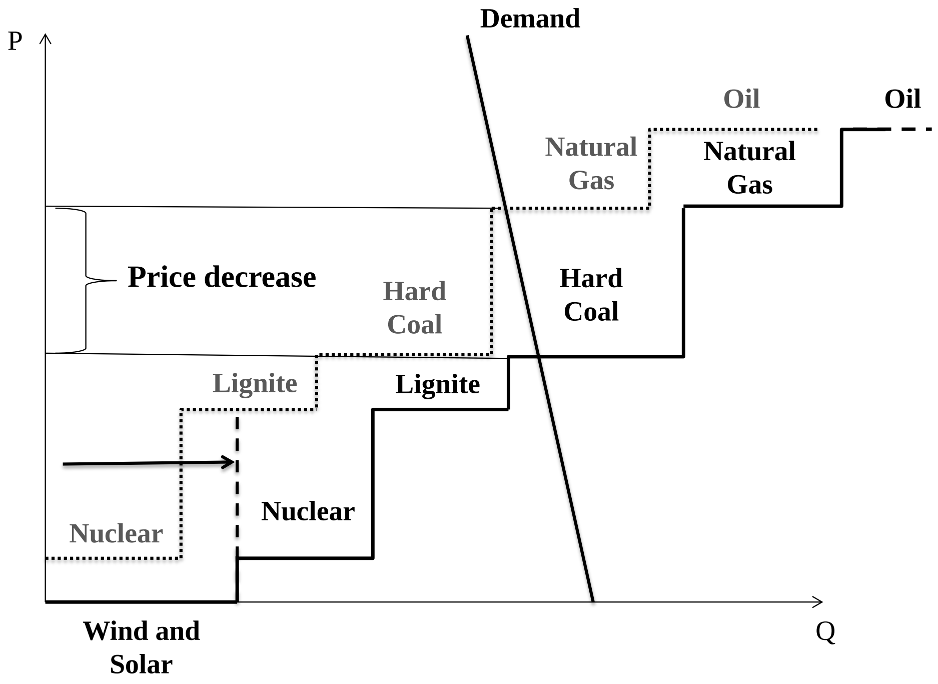

Figure 1.1: Merit order before and after the introduction of (almost) nil marginal cost energies: wind and solar.

money' that weakens the electricity sector (Cramton and Stoft, 2006, (199)). It denotes the underinvestment in new generation capacities due to the inability of the market to provide for sufficient net revenues to electricity generators. Consequently the safety of supply might not be insured and investments that are complementary to renewable energies, such as storage capacity and smart grids, cannot be undertaken. Another inefficiency source of demand-pull instruments is that it shifts the merit order, but does not change it with respect to technologies emission factors. For instance, the lower emission factor of natural gas compared to hard coal and lignite is not taken into account in demand-pull support scheme. Hence, they cannot substitute to carbon pricing policies.

Innovation policies reducing the efficiency of environmental policies

We have exposed several reasons to implement technology policies dedicated to RETs in addition to environmental policies. In practice however this could prove counterproductive. The electricity sector crisis is interrelated with the European Union Emissions Trading

Scheme[13] (EU ETS). Theoretically the EU ETS is supposed to give the right signal to investors through a high enough price of the emission permit, the EU allowance (EUA), that reflects the environmental damage from carbon emissions. As a result generators should invest more in clean technologies and decommission more polluting power plants. Since the second phase of the EU ETS (2008-2012) the electricity sector is covered by this environmental policy. During this phase, emissions from this sector have been reduced by 14.2%. However, the contributions of each technology to this decrease do not correspond to their emission factors suggesting that the EUA price was not the main driver of abatement. This is further corroborated by the decrease that the EUA price has experienced during the second phase: it fell from 30€per ton of carbon in 2008 to 5€in mid-2013. With a EUA price high enough to drive the emission reductions from the sector one would expect the more polluting power plants, being coal-fired power plants, to be at least temporarily stopped. On the contrary, the reduction of emissions came mainly from natural gas and oil plants[14] (34% and 30% of the emissions reduction between 2008 and 2012, respectively). Koch et al. (Koch et al., 2014, (93)) emphasize several factors that explain the low EUA price: (1) the economic crisis that has reduced the production of the firms covered by the scheme, and consequently their demand for EUAs; (2) the effect of demand-pull policies promoting the deployment of solar and wind energies. Indeed, these policies have reduced the emissions within the EUETS and contributed to decrease the demand for EUA and its price. Nonetheless, the effect of demand-pull policies remains moderate (*ibid.*). The combination of a carbon price and an additional support to renewable energies raises the issue of overlapping climate policies. Because demand-pull instruments cannot efficiently replace a carbon price their role should be restricted to correct market failures on technological change but should not substitute to environmental policies.

1.2.5 Evaluation criteria of the efficiency of economic instruments to support RETs

From the analysis developed in the present section emerge several evaluation criteria of the efficiency of public support for innovation in RETs. Because price fundamentalism and strong double externality do not take into account the issue of technological heterogeneity

[13]The EU ETS is an European tool to reduce industrial GHG emissions. It works on the cap and trade principle: a cap on the total emissions is set and allowances are distributed among polluting firms. In order to meet their requirements firms can buy or sell emissions permits depending on their past abatement efforts.

[14]As precised by Berghmans and Alberola (2013, (195)) the decrease of the EUA price is not the only factor explaining the regain of competitiveness of coal-fired electricity — the second one being the falling price of coal due to exports from USA.

they are not retained to assess the efficiency of the economic instruments discussed in the remainder of this chapter. Hence, we rely on the two versions of the weak double externality and advocate for instruments dedicated to RETs. The economic instruments we review are assessed based on the three following criteria.

First, adoption externalities resulting from the diffusion of RETs should be rewarded through demand-pull policies. Adoption externalities are due to learning-by-doing and learning-by-using and their positive effects tend to decrease with the diffusion of a new technology. Indeed, production cost reductions and additional gains of information become more and more difficult to generate as a technology is approaching its maturity. An efficient demand-pull scheme should be aligned with the diffusion of the technology. By doing so the regulator reduces the risk of an overlap between environmental and technology policies: once a technology becomes mature the demand-pull support is taken up by the environmental policy.

Second, technology policies must avoid the pitfall of creating technological lock-in situations. A technology-specific policy support is a good strategy for the early development phases of a new technology but the schemes should converge toward technology neutrality. Again, the regulator should align the policy support with the stage of diffusion of a technology. In the same idea, picking the winner(s) by encouraging a small number of firms is a counterproductive strategy for the regulator as it may induce technological lock-in situations and increase the risk to see adoption spillovers internalized by few firms.

Third, in order to minimize price distortions on the electricity market, demand-pull instruments must be designed to improve the sensitivity of renewable producers to market signals. This is particularly important for renewable energies that are the more injected into the grid, i.e. solar PV and wind power that cause the stronger distortions. Moreover, as these energies are variable, the sensitivity to market signals increases the incentive to take into account the time profile of demand for electricity and it rewards enhanced storage capacities and better supply management. Hence, an incentive to innovate is maintained during the whole lifetime of the support scheme.

Meeting these criteria implies that policy support evolves with the development stage of a technology. It is difficult for a regulator to assess whether or not a technology is mature, however the price competition that prevails in liberalized electricity markets makes grid parity a relevant measure of a technology's maturity. Grid parity is reached when a utility is indifferent between buying the electricity from a renewable energy source or from conventional sources. Periodic assessment of the cost of renewable energy should mark the evolutions of renewable energy support schemes. Demand-pull and supply-push instruments are presented in the next two sections. We highlight their features considering the several criteria presented above. We will show that for demand-pull instruments, the flexibility of design allows for a significant room for improvement. In contrast, ambitious and efficient supply-push instruments for RETs remain to be built.

1.3 Demand-pull instruments and their impact on innovation

In this section, we review the existing demand-pull instruments. They are presented following a specific order: we start with the instrument that makes the generator of renewable electricity the more sensitive to electricity market signals (feed-in premiums) and end with the schemes that do not provide for any market signal (feed-in tariffs and tradeable green certificates). The other instruments lie between the two sides of the spectrum of sensitivity to the electricity market. In each subsection we emphasize the importance of instrument's design that demonstrates that if the choice of the instrument is important, its design may be even more.

1.3.1 Feed-in premiums

Definition and examples

The feed-in premium (FIP) consists in adding a premium to electricity spot price for renewable electricity. Combined with a priority access to the grid and a purchase obligation, renewable energy generators receive the electricity spot price and the premium. FIPs are usually implemented to improve the compatibility of the support scheme with the electricity market because it makes generators sensitive to market signals.

As explained above, an efficient technology policy does not overlap with environmental policy. Denmark constitutes an interesting example of how to combine a FIP with an environmental pricing scheme. Generators receive a premium for each generated kWh until a certain amount of full load hours is reached. It provides to producers a minimum revenue. The number of guaranteed full load hours and the premium's value change over time in order to take into account cost evolutions of renewable energy equipments. Once the guaranteed number of full load hours is reached a new premium replaces the former. The new premium corresponds to the environmental tax on electricity: as renewable electricity does not pollute, the green tax is refunded to producers (Irena, 2012, (221)). Another case of a FIP scheme is the Spanish one and illustrates the risks of demand-pull support instruments. The Spanish support scheme gave to producers the choice between a premium and a fixed tariff. After the royal decree 436/2004 has modified the payments to renewable electricity, a growing number of wind power producers opted for the premium option. The share of generated wind electricity under the premium option increased from 2.5% to 93.8% between 2004 and 2007 (Schallenberg-Rodriguez and Haas, 2012, (149)). Producers were attracted by windfall profits and the accumulated wind power capacity rose from 8,460 MW in 2004 to 16,689 MW in 2008. The Spanish government was forced to stem the market growth by implementing a cap on the total payment. The growing cost of the support scheme that was financed by emitting public debt bonds, combined with a depressed economic situation, led the government to suspend the support in 2012 (Royal Decree 1/2012). These stop-and-go policies are very costly for renewable energy sectors and adjusting payments to the development stage of the technology improves the financial sustainability of the support scheme.

Pros and cons

The greatest advantage of a FIP scheme is to be a market-oriented instrument. In other words it makes renewable electricity producers sensitive to market signals: to maximize the final payment a producer would be willing to sell her electricity during high price times (i.e. high demand). To this extent, intermittent intermittent electricity generators have an incentive to improve the flexibility of their supply and to increase choose their locations in order to increase the covariance between energy supply and the electricity price (Schmidt et al., 2013, (153)). Hence, storage and better supply management are attractive because they allow producers to sell when prices are at their peak.

On the other side, the main pitfall of FIP is the influence of market uncertainty on final payment. From the producer's point of view a new source of uncertainty is added to an already existing uncertainty, i.e. the regulatory one. Compared to a fixed tariff, the average payment derived from a premium needs to be higher to trigger new investments in renewable power plants. Using a mean variance approach, Kitzing (2014, (89)) shows that producers demand a risk premium to compensate for market uncertainty, making the overall cost of support higher than a fixed tariff. Based on the Spanish experience, Schallenberg-Rodriguez and Hass pointed out that a premium leads to a more costly support compared to a fixed tariff (Schallenberg-Rodriguez and Haas, 2012, (149)). Nonetheless, they admit that their conclusion should be nuanced as it does not consider distortion's reduction.

An efficient design of the instrument

The incentive to innovate from a FIP can be improved through its design modalities[15].

Payment degression. This is a very often used option. The rate paid to a cohort of generators[16] is the same throughout the lifetime of the project, but tends to decrease from one cohort to the next so to reflect the learning process and to account for decreasing costs. The expectations of the decrease of payment over time encourage renewable equipment manufacturers to lower production cost. The degression rate is also a mean to reduce the overall cost of the support and regulate the flows of new entrants. The higher the degression rate, the stronger is the pressure to innovate. However, if this rate is too high it does not allow new entry in the market. Whatever the degression rate is, it is imperfect since the technological change is difficult to forecast and it creates a regulatory uncertainty about the evolutions of the payments. Hence, the degression rate needs to be adjusted on the basis of periodic and scheduled backwards assessments of the production cost of electricity from renewable sources.

Cap and floor payment. Policymakers will be tempted to put a cap on the total payment in order to avoid windfall profits. This strategy is efficient to reduce the support cost but weakens the incentive to improve the flexibility of the power plant. On the contrary, setting a floor price insures a minimal revenue to producers and stimulates their entry.

Flat versus specific payment. A flat payment means that all RETs receive the same remuneration. When a flat payment is implemented, generators will choose the technology with the lowest LCOE[17]. This could be a good strategy for the regulator when she aims at discriminating technologies with rather similar degrees of maturity. For less mature technologies that are still far from achieving grid parity, the regulator should prefer technology-specific payments based on an assessment of the cost of cutting-edge technologies.

Alternatives to cap and floor payments. Rather than a floor payment it is possible to set a higher payment for a pre-determined number of full load hours. It enables to discriminate between plants depending on their localization (in the case of variable energies) and to secure the investment realized. Second, a cap on the total payment can be replaced by a sliding premium, i.e. a premium that decreases with the electricity market price. It lowers the sensitivity to market signals but reduces the cost of the instrument.

[15] Most of these modalities are common to feed-in premium and feed-in tariff.

[16] We define a cohort of producers as the producers who enter market the same year.

[17] the Levelized Cost of Energy (LCOE) is calculated by accounting for the expected sum of all the costs though the entire lifetime of a power plant divided by the expected generated output.

1.3.2 Public tenders

Definition and examples

A public tender is a largely used process aiming at delegating to the private sector the procurement of public goods and services. In the case of RETs, public tenders support the building of power plants and the sale of electricity: firms compete for a purchase agreement resulting from the tender process. Hence, tenders are generally based on the electricity prices claimed by firms through their bids. In theory, it enables to simulate the perfect competition conditions and to minimize the cost of electricity generation. Therefore, the effective choice of public authorities can rely on additional criteria: economic and environmental outcomes, generation technology or firms' nationalities.

Due to their high transaction costs, public tenders have been preferred to support demonstration projects of less mature technologies. For instance, the United-Kingdom has implemented public tenders for five projects of tidal turbines in Scotland and Northern Ireland. Public tenders can also be used for larger scale deployment. In 2003, the Chinese government has implemented a system of public tenders for large scale wind power plants. The tender is based on the purchase price of the generated electricity but not only: the nationality of equipments manufacturers was also a selection criterion in order to stimulate the domestic demand for Chinese turbines. Another example is the public tenders dedicated to offshore wind power in France between 2001 and 2013. Participants were rated according to several criteria among which the 'industrial and social project' was weighted 40% of the final score. The 'industrial and social project' was aimed at creating jobs and favoring the emergence of a national industry.

Pros and cons

On the one hand, public tenders present some advantages compared to other demand-pull instruments. First, they generate competition between firms and provide a cost efficient instrument which reveals (ex-post) the generation cost of electricity to the regulator. Second, they promote knowledge spillovers as firms can constitute a consortium to propose a common project. Finally, tenders can be designed to promote regional employment and favor national firms. Hence, it is expected to increase the social acceptability of the support scheme and to insure a partial internalization of the gains of knowledge associated with the project.

On the other hand, public tenders suffer from several disadvantages. First, contrary to a FIP, public tenders are not dynamically efficient, i.e. they are not able to maintain an incentive to innovate all along the contract duration because firms compete for a fixed purchase price. Second, the main weakness comes from the transaction and administrative costs induced by public tenders. This is due to the complexity of bidding procedures. Examples of public tender programs such as the AER (Ireland), the NFFO (United-Kingdom) and the EOLE (France) were subject to high transaction costs (del Rio and Linares, 2014, (42); Grubb and Vigotti, 1997, (181)) .These high cost can be mitigated by the design of tenders but make it a more suitable instrument for small-scale deployment and demonstration projects. Third, the cost of preparation for the bid (i.e. project definition and assessment) is recovered only if the firm wins. The uncertainty about winning the tender deters small producers' participation, thus resulting in a lower competition degree. Finally, tenders correspond to a moral hazard situation due to the asymmetry of information between firms and the regulator. This induces an incentive for competitors to make untenable propositions (i.e. underbidding problem) and repeating tenders with a small number of the same actors prepares the ground to collusion between bidders and greatly biases the competition[18]. Moreover, this last factor increases the risk of spillovers internalization.

An efficient design of the instrument

Public tenders are flexible and weaknesses could be addressed in different ways.

Tender process design. On a normative basis and given the existence of asymmetry of information, the goal of tender's design is to define a process inducing that bidders' strategic reactions lead to an optimal price. According to the economic theory, the optimal price must be equal to the marginal production costs. To reach this optimum, Vickrey's tenders are the best solution (see Appendix 1.A for a Tender and Auction typology). Vickrey's tenders are sealed tenders in which the public authorities announce that they will retain the second lowest price (Vickrey, 1961, (165)). Despite this theoretical result, Vickrey's tenders have never been implemented for renewable support[19]. The two most often used systems are uniform price and pay-as-bid tenders. The first one should be avoided since it favours collusive equilibrium and produces inefficient results (Wilson, 1979, (168); Ausubel et al., 2014, (7)). The second does not guarantee market efficiency.

[18]Based on the folk theorem it can be demonstrated that tacit collusion is a Nash equilibrium. It holds true for a game that is repeated an indefinite number of times: there is a risk that the competing firms agree to set a price higher than the marginal cost. The conditions that increase this risk are a low number of firms, high discount rates and complete information about the defection of other participants (Gintis, 2009, (180)).

[19]In fact, there are only few historical examples of tenders or auctions that have strictly followed Vickrey's principle. An interesting exception is the market for collectible stamps. Indeed, an historical work done by Lucking-Reiley indicates that stamp auctioneers have used second-price auctions at least 65 years before Vickrey has published his work (Lucking-Reiley, 2000, (112)).

Implement a fixed premium instead of a fixed rate. Historically, public tenders for RETs offered a fixed rate to producers. It is efficient to replace it by a fixed premium paid for each produced kWh and to encourage producers to sell their production on the wholesale market. Therefore the incentive to innovate is maintained all along the contract, increasing the dynamic efficiency of the instrument.

Lengthen the maturing period of projects. The regulator must communicate the bidding process to the applicants as sooner and as clearer as possible. This is a good strategy for tender aiming at supporting demonstration projects. It creates a pre-competition period during which projects get richer in quality. The more this period lasts the more the demonstration tends to be accurate.

Avoid underbidding. In order to avoid underbidding the regulator must set a penalty if the project fails. It forces bidders to announce realistic production costs.

1.3.3 Contract for difference (CfD)

Definition and examples

A contract for difference (CfD) is halfway between a feed-in premium and a fixed feed-in tariff. A fixed tariff, called the strike price, is set by the regulator. First, producers sell their electricity on the wholesale market or through power purchase agreements (PPAs) negotiated with aggregators. Then, they receive the difference between the strike price and the price at which they have sell their electricity. It has the same flexibility design as a FIP or a FIT, i.e. technological discrimination, payment degression, higher payment for the first produced kWh, etc. The strike price is traditionally guaranteed during 10 to 20 years before producers only receive the market price. An important feature of this instrument is that each time the market price exceeds the strike price generators have to return the difference to the regulator.

More recently, the CfD is increasingly used due to its better compatibility with electricity markets compared to a feed-in tariff and a lower market uncertainty compared to a premium scheme. In 2012, Germany gave to generators the possibility to choose between a fixed rate and a more complex instruments' portfolio mixing a premium with a CfD. The premium part is called the management premium and remunerates producers for being more reactive to market signals. This management premium depends on technology and is higher for wind and solar technologies, in addition generators are supported through a CfD. By examining the new law (EEG 2012) it appears that the premium/contract for difference option is first dedicated to wind generators who benefit the most from it[20]. More recently, France has also opted for a CfD scheme to support renewable energies. As in the German case a distinction is made between an energy component and a management component that compensates the administrative and management costs borne by generators from selling their electricity on the market and from the balancing mechanism.

Pros and cons

In the simplest form, a CfD presents a definite advantage: it reduces the long term cost of support by developing a risk sharing between producers and payers[21] since producers have to return the excess of payment when electricity price is higher than the strike price. Then, the difference with a fixed rate paid to the generators is the reduction of the financial burden of the scheme. However, whatever does a generator she will finally receive the same payment. Hence, there is no market signal from a CfD but this limit can be easily corrected through the instrument's design as explained below. Finally, the support scheme induces higher transaction costs and needs further follow-up from public authorities, compared with a FIP or a FIT, because the payment is adjusted to the market price.

An efficient design of the instrument

A CfD is a flexible instrument and can combine several strengths from other demand-pull instruments.

Revenue differentiation. It is more efficient to differentiate the market revenue from the non-market revenue in order to maintain a market signal. Two options are possible. First the CfD may concern only a part of the generated electricity. For the remaining production, generators have to rely more on the market to sell during high price times. A second option consists in paying only a share of the difference between the strike price and the market price. For instance, if the wholesale price amounts to 50% of the strike price at time t, only 95% of the remaining 50% will be paid to the generator. Similarly to the FIP, it maintains an incentive to innovate during the entire contract.

Strike price estimate. The strike price can be negotiated between the regulator and the generator. This negotiation can take the form of a tender and has the same strengthens and weaknesses than those described earlier. An efficient strategy is to implement periodic

[20] By choosing the premium/CfD option wind generators obtain the tariff of the current year. Since the payment decreases after an amount of produced kWh is reached under the feed-in tariff option, the producers are tempted to avoid this decrease by moving to the premium/CfD option. For more details see Fulton and Capalino (2012, (208))

[21] The regulator, the taxpayers or the consumers depending on the funding mode.

tenders and to use the resulting price as a benchmark of the strike price for future power plants. This benchmark is re-assessed after each new round of the tender.

1.3.4 Feed-in tariff

Definition and examples

Feed-in tariffs (FITs) are the most frequently used demand-pull instruments for promoting RETs development. Coupled with a purchase obligation they make it compulsory for distributors to buy electricity from renewable energy sources at a given rate, higher than the market price. These tariffs are fixed and defined for a given period, usually 10 to 20 years, and thus ensure the security of investment (Percebois, 2014, (133)). An example of FIT's ability to trigger a huge capacity deployment is the German case. Nowadays, the German FIT has been replaced by the EEG law 2012 but before this replacement it created a market bubble for solar photovoltaic panels. The German public authorities have tempered the market bubble by adjusting the degression rate of the tariff to the installed capacities. For that purpose a 'volume responsive corridor' on the degression rate have been created in 2008. From a cohort to the next, the FIT could be decreased from 5% to 7.5% depending on the newly installed capacities over the past year in order to regulate new market entries. In 2010, the range was 6% to 13% depending on eight possible scenarios of installed capacities. It has minimized the cost of support while reducing the uncertainty face by investors by insuring them against a too large decrease in payments.

Pros and cons

The obvious advantage of the FIT is that from the investor's point of view it is the most secure instrument (del Rio and Bleda, 2012, (40)). In fact it provides for a risk-free revenue totally disconnected from the electricity market. Consequently, the unique channel through which incentive to innovate passes is that producers will choose the best equipments. Thus, they have no incentive to manage their production and the more the tariff exceeds the cost of electricity generation, the less the producers will need to choose cutting-edge technologies. Hence, the efficiency of the scheme decreases as the regulator overestimates renewable electricity cost.

An efficient instrument design

There are several ways to improve the FIT's efficiency compared to its 'old' form; i.e. a fixed rate for the whole lifetime of the power plant and a technological progress approximated by an annual and fixed degression rate. We present here two opportunities of improvement:

A FIT that covers only a share of the production. As for CfDs, the fixed rate can be paid only to a share of the overall production of a power plant. This share may be defined in three ways:

- For a certain amount of full load hours.
- For a certain percentage of the annual production of green electricity.
- For the first years of the power plant's operation; this is a widely used option but the less efficient because it does not differentiate the payment between power plants depending on their productivity and thus creates windfall profits.

In this configuration, a producer is entitled to sell the remaining production on the electricity market. As the share of production paid at a fixed rate decreases, incentive for production management but also uncertainty of outcome raise.

Periodic generation cost assessment. Public authorities must frequently assess the technological state of the art and the possible evolutions in the future. This has been the main weakness of the FIT: the gap between tariffs and electricity production costs has generated windfall profits. A solution is to establish a frequent rescheduling of the rate depending on technological assessments. This assessment can serve as a basis for expectations about future cost decreases, giving technical grounds for setting an accurate degression rate.

1.3.5 Tradable green certificates (TGCs)

Definition and examples

A quota purchase obligation is a quantity-based instrument, in contrast to price approaches presented above. The simplest form is to set a minimum required quota of green electricity. It may be expressed as an amount (in terms of energy or power) or as a proportion of total quantity used/distributed. The support mechanism operates not only through the existence of quotas, but by the establishment of a parallel certificates market (Berry and Jaccard, 2001, (14)). The distributors are entitled to present an amount of 'green' certificates to prove the injection on the grid of the equivalent quantity of renewable electricity. The price resulting from the matching of the producers' supply and distributors' demand for TGC is the financial supplement that is added to the market price of electricity.

An example of green certificates is the Renewable Obligation (RO) implemented in 2003 in the United-Kingdom. It illustrates the weaknesses of the scheme. We can emphasize two major pitfalls of the ROs (Gross and Heptonstall, 2010, (62)). In its first form, the RO scheme was technologically neutral, i.e. the equivalence between a generated MWh from a given renewable source and renewable obligation certificates (ROCs) was the same for all the technologies. This feature was founded on a principle of technological neutrality that is relevant if applied to technologies exhibiting similar maturity degrees; which was not the case. As a result onshore wind power plants achieved high Internal Rate of Return (IRR), up to 15%, when the real required IRR to trigger investment was close to 7.75% (LEK consulting and the Carbon Trust, 2006, (197)). This windfall effect has benefited to onshore wind generators because it was the only viable technology. Certificates' price has to reach a higher level before the next technology can be pulled through. During this maturing period, the support scheme is inefficient. In order to address this problem, the scheme has been revised in 2009 to differentiate the support between technologies. The second pitfall of RO is the additional uncertainty on investment it creates compared to a FIT or a FIP (Lemming, 2003, (105)). This additional uncertainty is due to the variations of the certificate's price. It generates important leakages in subsidies. First, financial institutions take into account this higher uncertainty when making their lending decisions and propose a more expensive credit for renewable energy projects. Second, in order to be covered against the uncertainty of the certificates market, renewable electricity generators ask for Power Purchase Agreements (PPAs) to electricity suppliers. The counterpart for risk hedging is that the electricity suppliers capture a significant share of the certificates price (LEK consulting and the Carbon Trust, 2006, (197)).

Pros and cons

TGCs are distinctive in being exchangeable between the actors subject to the purchase obligation and it is expected to minimize the total generation cost because renewable electricity generators will compete on the certificate market. This instrument also maintains an incentive to innovate during the power plant functioning. However, this incentive depends on banking and borrowing rules (B&B) and may be disconnected from the electricity market and therefore be ineffective. The possibility for B&B constitutes a disadvantage for TGC schemes. If B&B is allowed, as it is generally the case, profit maximization becomes a trading issue rather than a generation's management one. Indeed, the B&B makes the certificates market having its own timing, regardless of the actual needs of the electricity market. Consequently the additional reward from the certificates does not encourage to fit more the electricity market. Finally, the major defect of TGC is the uncertainty on the certificates' price. It brings the uncertainty sources to three: the electricity market, the certificate market and the regulatory decisions. As a result generators apply for risk hedging, making the total support more costly.

An efficient design of the instrument

There are several means to improve a TGC system.

Increasing the link between the certificate market and the electricity market. The fact that the TGC scheme does not induce the right signal to renewable generators is restrictive. For a given output, a generator receives the corresponding amount of certificates and can sell them on the certificates market. Hence, a renewable electricity generator can be encouraged to generate more electricity if the certificate price is high and the electricity price low because the former constitutes its main remuneration. Then, there is a small incentive for electricity storage and production management. A solution would be to link the two markets, for instance by suppressing B&B rules. In this case the additional revenue from the certificates becomes perfectly correlated with the electricity market.

Reducing the cost of the support by mitigating uncertainties on the certificate's price. Generally, price for certificates are bounded. Indeed, the upper limit is equal to the fine paid by bondholders when they do not comply with the quota. The introduction of a lower bound is optional and can provides investors with a minimum revenue. Nonetheless, when setting a floor certificate price the regulator should take into account the reduction of the demand for certificates that can reduce the overall payment to renewable electricity producers. Hence, the B&B rules that influence the elasticity of the demand for certificates must be jointly designed with the low bound set on the price[22].

Synthesis of the section

There is a wide range of economic instruments creating a dedicated market for RETs. In Europe, as the carbon price became weaker in the last few years, markets for RETs are now almost fully dependent on these demand-pull schemes. But as explained in the previous section these instruments cannot fulfill the same role than a carbon price. In order to avoid overlapping policies and provide for a more efficient balance between supply-pushing and

[22]Considering the following example. The regulator observes an excess of certificates on the market that lowers its price. She implements a floor price but the excess of certificates has allowed the firms to bank large amounts of certificates. After the floor price is implemented, firms will prefer to use their banked certificates instead of buying certificates at a higher price. As a consequence, the total revenue of renewable electricity producers can be smaller after the introduction of a floor price on the certificates market.

demand-pulling, public intervention should rely more supply-push instruments to correct the knowledge externality. We discuss in the next section these instruments, for which almost everything remains to be done.

1.4 Supply-push support instruments for RETs and their impact on technological innovation

The near non-existence of supply-push instruments dedicated and automatically granted to support RETs innovation projects is surprising[23]. As said in section 1.2 policymakers have privileged a demand-pull approach to support innovation in RETs to the detriment of supply-push instruments. A widely used supply-push instrument is the research tax credit (RTC). Through the RTC, part of R&D expenditures is tax deductible for a company, so as to encourage it to invest in innovative projects. Unlike a regular tax reduction, RTCs can allow to a refund from the tax authorities if and only if the tax credit exceeds the tax payable by the company. The advantage of such a tool is that it assigns R&D to the private sector and thus benefits from its knowledge of the market and consumer expectations (Atkinson, 2007, (6)). In the USA, a RTC dedicated to energy technologies exists: the Energy Research Consortium Tax Credit. Nonetheless, it applies to projects oriented towards the theme of energy in general. Hence, it covers renewable energy as well as fossil fuels and energy efficiency projects. There are very few examples of automatic RTC dedicated to RETs that are generally supported only through one-off schemes such as cash grants (Deloitte, 2014, (202)). We do not discuss further the design of RTC but propose several ways of improving the innovation supply-push in RETs. We emphasize the role of the State in financing Small and Mediums Enterprises' innovation projects in subsection 1.4.1. Then, we discuss the advantages of technological cluster and its compatibility with the European Union (EU) state aids rules in subsection 1.4.2. Finally, we examine how supply-push instruments can be combined with other instruments to target RETs in subsection 1.4.3.

[23] In Europe, a rare exception is a research tax credit for environmental technologies implemented in Belgium.

1.4.1 Escaping from technological lock-in: the role of Small and Medium Enterprises (SMEs)

A technological lock-in arises after several increasing returns technologies compete for adoption (Arthur, 1989, (5)). Historical and a priori insignificant events can give an adoption gain to one of these technologies compared to the others and it leads to a situation of technological lock-in in the sense that the technology that will become dominant is not always the most performing one. Unruh states that developed economies are preys to a carbon lock-in that maintains a persistent dominance of fossil-fueled energy systems over low-carbon alternatives (Unruh, 2000, (162)). The co-evolution of a technological paradigm and the structure of an industry has been investigated by Nelson. Once a technology starts to dominate an industry, firms that started to adopt this technology will benefit from a competitive advantage on competitors producing with technological variants who will be forced to exit the industry (Nelson, 1991, (126)). The competitive advantage is stronger for capital intensive industries, as it is the case in the energy sector. This situation slows down the diffusion of RETs. As stated by Weyant, incumbent firms of the energy sector will have an incentive to delay the introduction of new technologies and this incentive is reinforced by the oligopolistic competition that generally prevails in these industries (Weyant, 2011, (167)). Based on these findings we discuss how the regulator can support SMEs through financial instruments and we take as an illustration the German public bank: the KfW bank.

Due to imperfect and asymmetric information, the capital market is unable to assess accurately firms' R&D projects. This situation impacts more SMEs because financial institutions know that: (1) compared to larger firms, they are more risky due to the lower diversification of market product risks; (2) the information on the firm is less available for SMEs than it is for larger firms; (3) the borrower has less business experience than the lender and this asymmetric situation benefits to the latter (Storey, 2005, (192), pp. 441). These three factors should result in a higher risk premium for SMEs, i.e. more expensive lending conditions. Higher risk premium is not always observed however because, in a situation of imperfect information, banks may ration credit and the market does not clear through the price mechanism (Stiglitz and Weiss, 1981, (158)). In the case of renewable energy R&D projects, the regulatory uncertainty of the climate policy adds to the intrinsic uncertainty related to every R&D project and justifies a pro-active role of the public sector. To address the problem of credit rationing public authorities have several possibilities: to provide for a low-cost credit through helped loans, to participate in the capital of the firms through public-private equity or to subsidize the most promising projects.

The KfW, a German public bank created in 1948 to manage the funds from the Marshall Plan, is an interesting illustration of the role the state can play in funding low-carbon innovation. Originally, the bank was created to manage and invest the Marshall funds and now, the bank is mostly funded by emitting bonds and selling it on the capital markets. Mazzucato and Penna provide for a rich description of the KfW's activities (Mazzucato and Penna, 2015, (119)). The KfW is constituted of four divisions among which the *Mittelstandsbank* that is dedicated to SMEs. The *Mittelstandsbank* uses promotional loans, equity finance products and other capital ventures to fulfill the funds gap that deters innovation in SMEs. Historically, the *Mittelstandsbank* has been heavily involved in the financing of environment-related projects within the framework of the German energy transition ('Energiewiende'). Indeed, the bank's division is in charge of the Renewable Investments Program and the Innovation Investments. A massive effort has been realized toward renewable energy: between 2008 and 2013, 66% of the green investments of the *Mittelstandsbank* were dedicated to RETs. To support SMEs, the KfW propose low-rate loans, free from agio and over long-term period up to 20 years. It can finance up to 75% of the project (de Jager and Rathmann, 2008, (201)).

1.4.2 Technological cluster as an instrument to promote inter-firms knowledge spillovers

Policy helped technological clusters

The geographic localization of firms is a determinant of their innovative activities (Porter, 1990, (139)). A cluster is defined as a geographic concentration of related companies, research organisms, organizations and institutions. The advantages firms obtain from locating near to each other are the economies of agglomeration due to economies of scale and network effects. Indeed, cooperation within the cluster has a positive impact on the innovative output of each firm (Czarnitzki et al., 2007, (34); Fornahl et al., 2011, (51); in both studies firms' innovative output are measured by their patenting activity.). A study by Cantner et al. investigate the role of German clusters pertaining to two renewable energy technology fields: solar PV and wind power (Cantner et al., 2016, (24)). They estimate the effects of support instruments on the size and the structure of co-inventor networks. The instruments they take into account are federal R&D spending, grants for cooperative research (that capture the existence of technological clusters) and demand-pull policies (feed-in tariffs and deployment programs). Their results indicate that cooperative research projects increase the size of the co-inventor networks and act as a complement to other policy instruments.

Having a research support strategy based on clustering needs to consider two risks. First, as in every R&D project there is a path dependency. The first decision will determine the technological path that the cluster will follow. It is possible to depart from this path but it becomes more and more difficult as the project size gets bigger (which is the case with technological clusters). Then the larger the cluster is, the higher is the risk of technological lock-in. This risk can be reduced using applied and demonstrative projects. Second, cluster policies may create a free riding problem. Firms are tempted to make as least as possible efforts to reduce their costs and to benefit from the final outcome of the project. This problem can be circumvented with efficient sharing rule about the cluster's output(s) and the incurred costs. We can distinguish two types of technological clusters: those resulting from a spontaneous and private initiative and those launched by the governments. The two are not strictly different since a cluster may have been kick-started by the government before being independent, or the contrary. Focusing on technological clusters benefiting from public support we discuss the latitude that public authorities have with respect to EU state aid rules.

European Union state aid rules and technological clusters

The EC differentiates between three groups of state aid[24]: (1)incompatible aids that distort competition, (2) compatible aids and (3) potentially compatible aids for which a state aid must be notified to the EC before being applied. The last group is the one we are interested in because it contains R&D policy support. Indeed, potentially compatible aids bring together four subgroups that are exempted from any prior notification to the EC (without being considered as compatible with the common market) including the promotion of R&D and innovation and the protection of the environment because of the market failures on knowledge creation and on environment. In our case, we are both relying on R&D and environment protection domains. Nonetheless, the EC does not allow accumulating aids when costs partly or entirely straddle the two categories. Considering the EC treatment of technological clusters and according to the Commission Regulation (EC) No 800/2008 of 6 august 2008, "a large investment project should be considered to be a single investment project if the investment is undertaken within a period of three years by the same undertaking or undertakings and consists of fixed assets combined in an economically indivisible

[24] A more detailed description of the place of technological clusters in the EU state aid rules is given in the Appendix 1.B.

way". For such large investment projects, identified as technological clusters, the EC allows Member States to provide for an additional support by raising the usual thresholds of total eligible costs[25] by 15% with an upper boundary of 80%. Moreover, according to the article 101 of the Treaties For the European Union (TFEU), Member States can provide for 200,000 € to any business over a rolling period of three years. These aids, called *de minimis* aids, do not need to be notified to the EC.

Technological clusters and Intellectual Property Rights (IPRs)

Clusters and the associated risk of free-riding involve a sharing of the new knowledge created by the cluster through IPRs. It has two effects on its creation. First, the participating entities might be in competition with each other after the cluster period: in this case having a property right on an invention constitutes a competitive advantage. Second, new knowledge is built on old knowledge and, thus, the sharing contract has to insure a fair payment for each participants of the cluster depending on their past skills. A cornerstone of the technological cluster efficiency is the consortium contract. Hereafter, we will only detail the French case for the sake of brevity. Nevertheless, it illustrates the major implications of a cluster on intellectual property sharing contracting. In France, participants of clusters face three choices:

- *Option A*: The sharing is based on areas of application and consequently it is possible to use it if and only if they are severable. At the beginning of the cluster, each participant defines one (or several) area of application for herself. If an invention occurs, the new knowledge goes to the participant possessing the area of application corresponding to the invention. Then the owner of the new knowledge has to pay the other participants for their involvement following the rules pre-established in the consortium contract.
- *Option B*: Created knowledge is co-owned by all the partners. Each entities' share is defined following the rule established in the contract. There are three rules: (1) Equal share for each participant; (2) a share in proportion of the participant's contribution; (3) A fixed share defined in the consortium contract.
- *Options A and B*: If one of the participants develops a new knowledge by herself, she obtains the exclusive benefit from it. In order to compensate her partners, two options may be subject to contract. First, if a participant asks for it, an exploitation license of the new invention has to be granted to her. The license relates only to the

[25] 100% for basic R&D, 50% for industrial R&D and 25% for experimental development.

claimant's area of application or to the whole project's area of application depending on the contract. Second, a remuneration (fixed or flexible amount of money depending on the sales) is given to each participant.

Policy implications for cutting edge technology clusters

We can define several good policy practices of technological clustering:

- According to Porter (1998, (140)), the government should not target few technology fields but rely on already existing technological clusters. In other words, the government should not try to be the architect of the spatial distribution but has to facilitate cooperation between agents while remaining neutral concerning geographic localization (OECD, 2009, (223)). This is based on the assumption that the private sector has better information about the economies of agglomeration expected to be generated by the cluster.
- The government should implement a safe and clear system of IPRs to insure an income to innovative clusters. In most cases, the innovative firms apply for a patent first in their national patent office and then in foreign patent offices. A patent application is costly and the first application plays a key role because it provides for a research report indicating the potential prior art. The faster this research report is given to the applicant, the easier it is to organize her business strategy and if necessary, the easier to apply for patents in foreign offices (on this point see below the fast tracking green patent application).
- Regional governance should be preferred to the national level since regional authorities have access to better information on their competitive advantages. It is particularly true for RETs when demonstration projects are located near the cluster because these technologies are highly dependent from their geographic environment (e.g. sea or geothermal energies).

  It is particularly true for RETs that are highly dependent from their geographic environment.

On the basis on these good practices, regulator can foster knowledge spillovers and better fit to the specific needs of the targeted technological field. However, this instrument is one of the several ways to implement a policy support dedicated to RETs. Another strategy is to combine dedicated instruments with generic instruments. It is investigated in the following subsection.

1.4.3 Linking generic instruments with environmental policies: the proxy of an instrument dedicated to RETs

We propose some options for linking innovation policy instruments and environmental policy instruments. These propositions are considered here as second best solutions, contrasting with the dichotomy of *Price Fundamentalism* described earlier.

Capacity markets and supply-push instruments

Regarding renewable energy deployment, the last few years have witnessed the emergence of capacity market policies. Capacity markets result from the introduction of variable energies with a priority access to the grid. This priority access undermines peak load generation power plants since they are less and less used for electricity generation as the share of renewable energy grows. As a result, investments in peak load generation plants are no more profitable. A capacity market may be implemented to support peak load power plants and insure a payment disconnected from the generated output. The rationale is to guarantee the electricity system safety and the supply-demand equilibrium. Thereafter, we investigate the case of capacity market dedicated to RETs. Usually, capacity markets and RETs deployment are perceived as being in opposite direction, the latter being a remedy to the former. However they are few examples of capacity markets dedicated to renewable power plants. Among them, the Indian experience is a good example of what should be avoided. The major issue of supporting renewable power plants depending on the installed capacity is the 'steel in the ground' problem[26]. The principle is quite simple: investors build power plants regardless of the location and the site's productivity. This weakness makes the capacity mechanism a bad candidate for promoting renewable energy deployment. A better strategy passes by the extension of capacity markets to electricity storage capacities. Just as peak load power plants, storage capacities must be rewarded depending on their availability. The most mature storage technologies are constrained in term of capacity (it is typically the case for hydro storage). In this extent, it is relevant to couple ambitious research programs on electricity storage and a long term incentive for installed capacity of electricity storage. An efficient mechanism to maintain an incentive to innovate is to give the payment under the condition of production's availability: if the storage operator fails to fulfill her engagement then the capacity payment is decreased by specific coefficients. This mechanism will contribute to foster the technological development of promising technology such as the power-to-gas that might play a crucial role in the valuation of the excess of renewable

[26] As its name indicate it initially occurred for wind turbines.

electricity generation. The conversion of this surplus into gas will allow to overcome the existing barriers on storage capacities and system flexibility. In France no distinctions are made from a regulatory perspective between generation plants and storage plants. However the capacity market enshrined by the NOME law (2010) may include a requirement for storage capacity. Going further, an efficient scheme for storage technologies support may rely on deep interrelations between a research program benefiting to several companies and an auctioned capacity payment. By doing so, research program's participants will be able to submit more ambitious projects to public authorities.

Green patenting and technology-neutral subsidies to R&D

IPRs systems aim at guaranteeing to inventors their invention's appropriation. A company that wants to use the new patented process or product has to buy a license to the patent owner. Hence, the expected private reward from an innovation depends on the patent system. Due to the major increase of patenting in the renewable energy fields depicted on

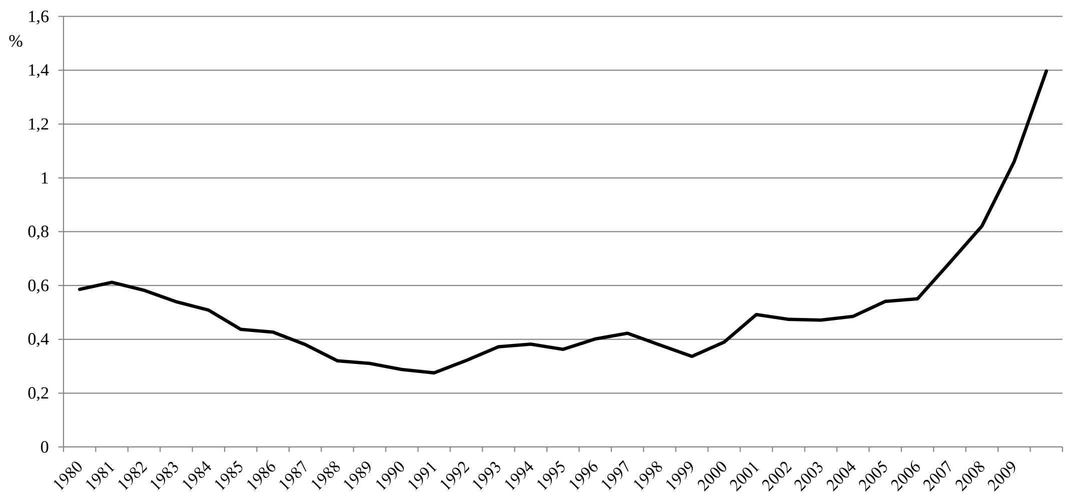

Figure 1.2: Share of renewable energy inventions in the global amount of patented inventions.

Figure 1.2 the patent system has been considered by governments as a mean to impulse technological change[27]. As a result, some patent offices have decided to implement fast-track 'green' patent applications programs. The goal of these programs is to accelerate the process of patenting for inventions of an industrial nature. These systems focus on so-called 'green' innovations, although their definition varies according to the concerned country. Among

[27]We use the Patstat database and consider priority filings. We identify as belonging to RETs the inventions related to biofuels, sea energy, fuel from waste, geothermal energy, hydro energy, PV energy, solar thermal and wind power. We use the 'Y02' classification of patents, see Chapter 3 for more details about this classification scheme.

the first countries to set up programs of this kind were the United States, the United Kingdom, Japan, Israel and Korea in 2009. More recently in 2011, Canada, Australia, China and Brazil have also opted for such systems. The selection criterion differs slightly from a patent office to another but the common denominator remains the environmental concern: if the inventor justifies the 'green friendly' feature of its invention she is allowed to apply for fast tracking. Among these countries, the average waiting period for all patents over the period 2009-11 was 40 months in the United Kingdom against less than a year through fast-tracking, eight years against two and a half in Canada, and almost three years in the United States against a year and a half (Dechezleprêtre, 2013, (38)). In his study, Dechezleprêtre shed light on the efficiency of these fast-track procedures. He demonstrates positive effects on two points:

- The value of patents, measured by the number of claims and the number of Patent Offices in which the patent is granted. The study concludes that patents which have benefited from the fast-track system have greater value.
- Technological diffusion, measured by the number of citations the patent receives. The author's empirical study shows that patents granted through fast-track procedures are cited twice as often as patents in the same technology segment, controlled from the value and granted at the same time.

Fast-track 'green' patent applications could become a key instrument of green technology policies. It induces an incentive for private sector to develop new environmental technologies and gives an orientation to both private investments and generic public subsidies to R&D. However, a shorter period of delivery constitutes a minor change, the two key features being the patent's length (the protection period) and the patent's breadth (the extent to which a patent covers the field it pertains).

1.5 Conclusion

Support toward renewable energy has now a long history in developed countries. These policies were put in place for several reasons such as energy security, nuclear phase out and climate change. This chapter begins by discussing how efficient support policies should be designed. To guide our thinking, we consider both theoretical arguments and empirical findings. We argue that policy support toward RETs may miss important points if it is build on 'price fundamentalism' dichotomy which involves combining a generic, i.e. sector-neutral and technology-neutral, support to innovation with a carbon pricing policy. At the contrary, we advocate for support policies that are exclusively dedicated to RETs in order to be able to take account the technology-specific adoption externalities, the technological inertia inherent to energy systems and the regulatory uncertainty about the policy response to climate change. There are however several other factors that need to be considered: the risk of overlapping policies, the interaction of renewable energy support with the electricity sector and the actual imbalance between supply-push and demand-pull supports. We propose three assessment criteria of the efficiency of support policies. First, the subsidies to RETs deployment, namely the demand-pull policies, should reward the adoption spillovers. In this extent, they should be aligned with technologies' development stages and they should not substitute to a carbon pricing policy. Second, support policies should avoid the pitfall of technological lock-in. Hence, a technology-specific support for the early stages of development allows the regulator to differentiate the magnitude of adoption spillovers. It should converge however to technological neutrality as the supported technologies become more mature. Third, policy instruments should minimize the price distortions on the electricity market. In this extent, more developed (and thus deployed) technologies are more efficiently supported through market-oriented instruments that reduce price distortion and maintain an incentive to innovate throughout the plant's lifetime. These three efficiency criteria can be met through a policy support evolving with the development of the technology, starting from specific policies that converge toward technological neutrality before being relayed by a carbon pricing scheme. As the development stage of a technology is difficult to accurately know, a proxy that makes sense with regard to the electricity sector is the gap with respect to grid parity. Periodic assessments of the technological state of art provide for guidance to public authorities in order to adjust the innovation support.

The two last sections of this chapter present the economic instruments available to the regulator. We first discuss demand-pull support instruments and their design options. With regard to the large choice of instruments and the flexibility allowed by their respective design, a continuum of policy options are available to the regulator starting from a very specific support guaranteeing security of investment to a technology neutral one, closer to market conditions. Considering supply-push instruments, there are very few examples of policies that are dedicated to RETs. Hence, we emphasize the importance of SMEs in the transformation of the energy sector and present an example of the pro-active role a state bank can play to fund such firms. We then discuss the opportunity given by the EU rules on state aids to support technological clusters and detail how they may constitute a instrument to stimulate innovation. Finally, we present several ways of coupling dedicated with generic instruments of support to target exclusively RETs.

From this review of the instruments of support to innovation in the fields of RETs, several research questions arise. One relates to the influence demand-pull policies have on the deployment of new technologies. This is particularly important because there was a major imbalance in favour of a demand-pull approach at the expense of a stronger supply-push support. Hence, it calls for an ex post assessment of the former. A second question addressed is how these two approaches should be combined to reach an efficient policy support. They both may have had an impact on innovation, however on should consider how much they have participated to create new knowledge and how they interact with each other. A prerequisite to this assessment is to dispose of an accurate and robust measure of innovation. Finally, further research is needed to investigate the opportunity provided by a dedicated supply-push instrument to low-carbon innovation. Finally, as precised at the beginning of this chapter the question of the interaction between the environmental and the knowledge externality has been let apart to investigate the role of additional market failures and barriers to innovation related to RETs. Nonetheless, it should be investigated to fully understand how to support environmental innovation.

Appendix

1.A Appendix A: Tender and auction typology

Different types of tenders exist and we define them following the auctions' typology. Symmetrically, in an auction process there are one seller and n purchasers whereas in a tender there are one purchaser and n sellers. In a tender the purchaser, invites bids from the sellers and selects one or several winners on the basis of their bids.

Single-unit tender covers only one item. For RETs, it can be a long term contract or a certain amount of installed power. There are two kinds of single-unit tender:

- Revealed tenders: all bids are known. Purchaser calls for an ascending price (from the lowest bid to the highest until a seller accepts the offer at this price) or a descending price (a high price is asked by sellers until the purchaser accepts to buy the good).
- Sealed tenders: all the bids are sealed. At the end of the tender, the good can be sold at the first price (i.e. the lowest price) or the second price (i.e. the second lowest price). Second price tender is the equivalent of second price auction, also known as Vickrey auction. It does not induce the same behavior in bidders. It has been demonstrated that they are efficient contrary to first price auction (Vickrey, 1961, (165)).

Multi-unit tender covers several items. We consider here only multi-unit tenders with homogeneous goods. They are two additional types of multi-unit tender (in addition to the generalized forms of single-unit tender):

- Uniform price: generally, this kind of tender is sealed. Bidders announce both the quantity they want to sell and the unit price required. The purchaser starts to buy the quantity proposed at the lowest price, continuing with the second lowest price and so forth until the demand is addressed. The price paid by the purchaser is the highest winning price (being the last bidder's price).

- Pay-as-bid tender: this tender is sealed and each bidder receives the price she asked for. It enables discrimination between sellers but it does not guarantee market efficiency since they can overestimate or underestimate the price they are willing to accept. A result of this type of tender is the 'winner's curse' (Chari and Weber, 1992, (27); Percebois, 2014, (11)). If the winner realizes that she won the tender because of her lowest price she will expect additional revenue from a slightly higher price that will preserve his position. Anticipating this curse every player act the same and the merit order tends to shift upward.

1.B Appendix B: Technological clusters and state aid at the light of European rules

Incompatibility with the common market:
- There must be an intervention by the State or through state resources.
- It must confer an advantage to the recipient.
- It must distort or threaten to distort competition.

Compatibility with the common market (no prior notification to the EC is required):
- Having a social character granted to consumer without condition on good's country of origin.
- Making good the damage by natural disasters.
- Helping the economy of certain regions of Germany affected by the former division of that country.

Aids that could be regarded as compatible:
- Promoting a common project in EU.
- Helping the economic development of areas affected by economic difficulties.
- Remedying a serious disturbance in the economy.

Aids that should be notified to the EC, among which

1/Aids granted to SMEs:
- Employment in SMEs (limited to 7.5 euro M/enter./project).
- Industrial Property Rights obtention (limited to 5 euro M/enter./project).
- Consultancy services to SMEs (limited to 2 euro M/enter./project).
- Participation in fairs and exhibitions (limited to 2 euro M/enter./project).

2/Promoting R&D and innovation:
- Basic R&D (limited to 20 euro M/research organism/project).
- Industrial R&D (limited to 10 euro M/research organism/project).
- Other (limited to 7.5 euro M/research organism/project).
- EUREKA project, thresholds are doubled.

3/Promoting employment:
- Training aids for employees (limited to 2 euro M/enterprise).
- Aids for the recruitment of disadvantaged workers (limited to 5 euro M/enterprise/year).
- Aids for the recruitment of disabled workers (limited to 10 euro M/enterprise/year).

4/Protecting environment and natural resources:
- No cap for aids allowing for compliance with Community standards.
- 35% of the eligible costs for going beyond Community standards (the share may vary depending on the type of projects).

Focus on clusters: as for the three other categories, thresholds are also expressed in terms of percentage of total eligible costs (100% for basic R&D, 50% for industrial R&D and 25% for experimental development). These thresholds are raised under several conditions among which clustered R&D&D:

- If the research project is build on the cooperation of at least two independant firms and:
  - None of the firms bear a cost superior to 70% of the total eligible costs.
  - The project implies the cooperation with at least a SME or between two member states.

- If the research project is build on the cooperation of at least an enterprise and a research organism and:
  - That the research organism does not bear more than 10% of total eligible costs.
  - That the research organism has the right to publish every research results.

Then thresholds are raised by 15 points with an upper boundary of 80%.

Chapter 2

Demand-pull instruments and the development of wind power in Europe: a counterfactual analysis

2.1 Introduction

In November 2014, the European Union has reaffirmed its ambition to produce 27% of its electricity from renewable sources by 2030. As most renewable energy technologies are not yet cost-competitive, increasing their share in the energy mix needs support from public authorities. Indeed, well before the establishment of the European Union Emission Trading Scheme (EU ETS) in 2005, several European countries had already taken the initiative to implement national policies to support the development of renewable energies. They were motivated by both global warming issues and national-specific issues, such as nuclear phase-out and energy independence. In the late 2000s the bulk of European countries had implemented public policies dedicated to the promotion of renewable energies (Ragwitz et al., 2012, (225)). Among these policies, there is a clear predominance of the demand-pull approach over the supply-push alternative (Zachmann et al., 2014, (193)). The former aims at stimulating the deployment of new renewable energy generation capacities whereas the latter targets the development of innovative solutions. Among renewable energy technologies, onshore wind power became a symbol of national ambitions and is frequently considered as one of the major sources of energy for the future. Now that electricity produced with onshore wind power is close to grid parity after years of public support, more attention is being paid to the balance between environmental gains on the one hand and the cost of support borne by society on the other hand. This paper contributes to this trend by providing a counter-factual analysis of the impact of demand-pull policy instruments on the deployment of wind power installed capacities in six European countries (Germany, Denmark, Italy, Spain, Portugal and France[1]). By contrast with the burgeoning literature that analyzes the drivers of the development of renewable energy generation capacities with *ad hoc* econometric models (Marques and Fuinhas, 2011, (115); Marques and Fuinhas, 2012 (116); Jenner et al., 2013, (80)), such a counter-factual analysis relies on a structural model of the commissioning of new wind power units. Counter-factual analysis is a key concept for the *ex post* analysis of public policies, either to characterize what the situation would have been in the absence of the policy or, conversely, to identify what the situation could have been if a given policy had been implemented. For instance, Hamilton, Ruta and Tajibaeva (2006, (66)) conduct a counter-factual analysis to determine how much produced capital would resource-abundant countries have today if they had actually followed the Hartwick rule over the last three decades. Our counter-factual analysis proceeds in three steps.

First, a micro-founded diffusion model of new technologies is developed. The model builds on the work of Kemp (1998,(86)) who proposed to reproduce the diffusion pathway of a new technology by representing the investment decision at the individual level. His approach sharply contrasts with the usual holistic approach that dates back to the seminal works on technology diffusion of Griliches (1957, (59)) and Mansfield (1961, (114)). In the present paper, the investment is more specifically triggered by the expected return-on-investment (RoI) of a MW of wind power capacity which is referred to as the benchmark value of the RoI. Differences in climatic conditions or site accessibility, among others, generate heterogeneity across the levels of RoI reached by actual sites. A distribution of actual values of the RoI around the benchmark value (the expected RoI) is thus introduced to capture this heterogeneity. The micro-founded version of the diffusion model proposed in the paper exhibits several interesting and realistic properties: i) the need for a public support to impulse the technology diffusion in the case every MW of wind power is not profitable; ii) the possibility for the diffusion process to be stopped before the full deployment is reached; iii) the role of the variations of the RoI from year to year and iv) the contribution of the cumulative deployment at time t on the decisions taken in $t + 1$.

[1]Despite its relatively high amounts of installed capacities of wind power, United-Kingdom is not included in the analysis as this country chose a system of certificates to support renewable energy diffusion. The system has suffered from a leakage of subsidies as a high share of the value of the certificates was captured by electricity suppliers (Carbon trust, 2016, (197)). Hence, this is difficult to estimate the actual revenue of wind power producers.

Second, we describe how the expected RoI is computed from a period to another. Two types of factors impact the level of expected RoI: exogenous factors and endogenous factors. Exogenous factors are for instance the price paid to the producer per generated kWh. It represents the demand-pull support policies in the scenario that reproduces the observed diffusion of wind power and it takes a lower value when simulating the counter-factual scenarios. Metals prices are also treated as exogenous and incorporated in the model as they have strongly impacted the cost of wind turbines (Bolinger and Wiser, 2012, (18)). Endogenous factors are all the factors that intervene in the expected RoI and that depend on the level of deployment. More specifically, a learning curve approach is adopted to capture the evolution of investment cost. The learning dynamics also encompasses the role of scaling that has contributed significantly to the increase in turbines prices (*ibid.*).

Third, we use yearly data, at the country level, on installed wind power to calibrate the diffusion model. The counter-factual analysis then builds on the causal relation between the dynamics of the benchmark RoI and the newly built units of generation (in MW). More precisely, the payment received by producers under a demand-pull scheme are replaced by the counter-factual values of payment that would have prevailed in the absence of a given policy instrument in order to generate the counter-factual deployment of wind power. Beyond the analysis of the effect of the national policy of each country as if it was isolated, the paper stresses the importance of the interplay between these policies of support that benefit from reciprocal spillovers. Indeed, even if some European countries have play a leading role in the development of wind power whereas others may be considered as laggards, the relevant market for wind turbines is rather European than domestic-wide. A major consequence is that support policies in neighbor countries may have substantially contributed to learning for the benefit of each country. Assessing the corresponding spillovers helps dealing with cooperative *versus* non-cooperative strategies in the development of wind power.

The research strategy followed by the paper is introduced in section 2.2. The model is developed in section 2.3. Subsection 2.3.1 details the micro founded diffusion model which properties are then discussed in subsection 2.3.2. The profitability index used as the driver of development decisions and its link with the demand-pull instruments are presented in section 2.4. After a short review of the use of a Return-on-Investment index in subsection 2.4.1 its modeling is developed in subsection 2.4.2. The focus of subsection 2.4.3 is on the sources of heterogeneity, both exogenous and endogenous. Section 2.5 presents the calibration of the model (in subsection 2.5.1) and the results of the counter-factual analysis (in subsection 2.5.2). Section 2.6 concludes by examining the policy implications.

2.2 Research strategy

The empirical analysis of the diffusion of a new technology finds its origins in the pioneering work of Griliches (1957, (59)) and Mansfield (1961, (114)). Originally, it was intended to formally reproduce the S-shaped time path of the rate of diffusion typically observed for many technologies. This analysis is usually said to be holistic as it provides an aggregated representation of individual decisions which are not explicitly analyzed but are assumed to interact through the transmission of information and feedback. The term "epidemiological" is sometimes used in place of the term "holistic" in reference to the dissemination of infectious diseases that also follows an S-shaped curve. If the role of economic and financial incentives was initially disregarded, some authors have sought to remedy to this weakness (see e.g. Chow, 1967, (28); Bass, 1969, (9); Bass, 1980, (10) ; Griliches, 1980, (60)). Usha Rao and Kishore (2010, (163)) propose a survey of applications of this approach to the case of renewable energy technologies. The approach, however, remains devoid of an explicit representation of a process of rational economic decision.

The micro-founded approach to the diffusion of onshore wind power proposed in this article is inspired by the work of Kemp (1998, (86)), although it was on a different technology. Unlike the holistic approach, the proposed model details the decision to install a MW of wind power. The investment is assumed to be realized if it is profitable as measured by the average return-of-investment per generated kWh over the turbine lifetime. However, under similar economic conditions, the profitability levels of new investments in wind power capacities are heterogeneous in a country. The heterogeneity of the levels of profitability results from differences in terms of climatic conditions, site access, local acceptability, design of the wind farm and of course from an element of chance. This is captured by a distribution of the profitability at the individual level around an average value. The average level of profitability, a position parameter of the distribution, will vary among years due to learning-by-doing effects, turbines scaling and some exogenous factors including demand-pull policies.

The micro-founded model of diffusion is constructed in order to explain the time path of diffusion of wind power by the variations of the average profitability over time. Hence, the theoretical profitability of a MW of wind power is computed and its variations over time will determine the path of diffusion of the technology.

In this study two geographical stages of learning influence the investment cost of wind power. First, for a given country the European learning from the experience accumulated by the other countries will lower the domestic investment cost. In this extent, it measures the learning-by-doing spillovers from the rest of Europe to the country. Second, each country experiences a national learning from the capacities installed within its borders. Hence, the assumption is made that for a given country the conversion of accumulated experience into cost reduction is not the same whether it is gathered at the national or regional (i.e. European) levels. Both types of learning react to the cumulative installed capacities of wind power which is considered as a good proxy of the accumulated experience (Lindman and Söderholm, 2012, (108)). Contrary to the holistic approach, economic incentives, learning and diffusion are thus tightly linked in the micro-founded model.

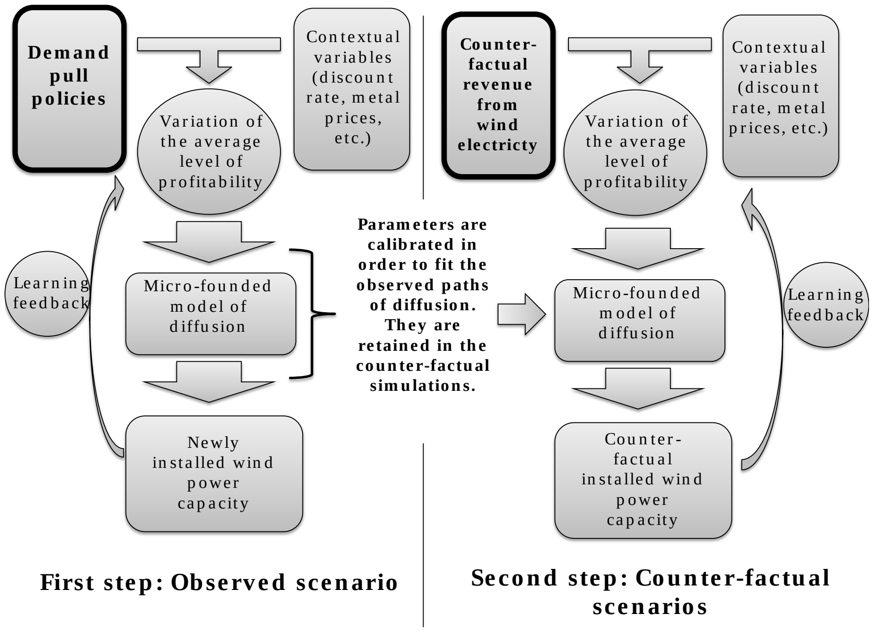

Figure 2.1: Schematic diagram of the research strategy.

The main steps of the method implemented to assess the impact of demand-pull policies are represented on Figure 2.1. It is divided in two steps. First, the parameters of the micro-founded diffusion model are calibrated in order to replicate, as good as possible, the observed time paths of diffusion of wind power technology in the six analyzed countries; namely Denmark, Germany, Spain, Italy, Portugal and France. More details about these parameters and the way they are calibrated are given in subsection 2.5.1. Both the inputs and the outputs of the model are known. The inputs are the payments received by producers, e.g. demand-pull policies, and some contextual variables that influenced wind power profitability. The outputs of the model are the newly installed capacities. The link from a time period t to the next is made via the impact of the cumulative capacities on the variation of the average profitability level.

In the second step of the research strategy, the same parameters values are retained for simulating counter-factual scenarios. Contextual variables do not change but the revenue from electricity does as producers do not benefit anymore from demand-pull policies. Hence, the cumulative installed wind power capacity is endogenously determined with respect to profitability and consequently influences: 1/ the learning that benefits to new cohorts of wind power installations, 2/the average rated power of newly installed turbines that drives its cost and its productivity. The investigated scenarios are presented in Table 2.1.

Observed Diffusion ($OD^{country}$)	Parameters are calibrated in order to fit as good as possible the observed national time paths of diffusion. Their values are different for each country. Hence we have six different $OD^{country}$ scenarios.
Unilateral Removal ($UR^{country}$)	Six scenarios are in which where a country unilaterally suppresses its demand-pull support scheme(s). The direct impact on the domestic installed capacities and the indirect impact on the other countries are assessed
Multilateral Removal (MR^{low} & MR^{high})	MR^{low}: the six countries do not implement their demand-pull policies so that wind electricity producers only receive the electricity market price. The electricity price is assumed to be equal to the observed market price over the analyzed period. The overall effect on the six countries is assessed.
	MR^{high}: Contrary to scenario MR^{low}, the electricity market prices are increased in order to capture the merit order effect.

Table 2.1: Presentation of the replicated and simulated scenarios.

Comparing the scenarios $OD^{country}$ with the counter-factual scenarios $UR^{country}$ and MR^{low} & MR^{high} allows to estimate the share of wind power capacities that is imputable to national demand-pull policies. For the purpose of counter-factual analysis, two types of scenarios are investigated and described in Table 2.1: Unilateral Removal ($UR^{country}$) and Multilateral Removal (MR^{low} & MR^{high}). Thereafter, we elaborate on how the electricity price is chosen in each type of scenario. In an alternative reality without demand-pull support, it can be assumed that producers would have received the market price. It is well known that the growing share of variable energies fed into the grid contributes to lower the spot prices of electricity (Senfuss et al., 2008, (154); Ketterer, 2014, (88); Hirth, 2013; (72); Gelabert et al., 2011, (54); Cludius et al., 2014, (30); Clo et al., 2015, (29); Brancucci et al., 2016, (19)). In this extent, when simulating counter-factual scenarios an ideal model would adjust electricity prices in accordance with the cumulative electricity generation. However, this effect is not considered when simulating $UR^{country}$ scenarios as the decision to invest in wind power relies on investors expectations. A reasonable assumption is that investors expect the

European electricity markets to be more and more integrated as supported by the European directive 96/92 and the European directive 2003/54 on the European electricity markets. Hence, it is assumed that, taken in isolation, the support policy of a country sees its impact on electricity prices being diluted in the European electricity markets. In other words, it is assumed that the demand-pull policy of an isolated country does not significantly impact the electricity market[2]. Nonetheless, this assumption is ruled out when considering that all national policies are jointly removed as done in the two scenarios MR. To address this issue two variations are considered. First, the observed prices over the analyzed period are retained in order to estimate the lower bound of what would have been the diffusion of wind power in the absence of demand-pull policies, this scenario is denoted MR^{low}. It is a lower bound as in reality it is likely that the prices would have been higher with a lower share of wind electricity fed into the grid. Consequently, investments in new capacities would have been higher. To tackle this issue the second variation, denoted MR^{high}, follows the same approach with slightly increased electricity prices to estimate the upper bound of the counter-factual diffusion of wind power when demand-pull polices are jointly removed. We follow Ketterer (2014, (88)) by considering that the electricity spot price has been 1.46% lower for every additional percent of wind power in the total electricity load of a country[3]. Although the study of Ketterer only focuses on Germany, we use this value as a rule of thumbs for the six countries. More precisely, in the scenario MR^{high} it is implicitly considered that wind integration does not impact electricity prices while in reality even a lower diffusion of wind power would have induce a decrease of the average electricity prices. In this extent, these two scenarios allow us to construct an interval in which the 'true' diffusion of wind power in the absence of demand-pull support would have lie.

Finally, it must be underlined that the counter-factual analysis investigates the case for a removal of financial support but cannot dispose from the assumption of priority access to the grid. Moreover, it is difficult to apprehend the time profile of the electricity generation from wind power that determines producers' revenue. Most of the time, windy hours correspond to off-peak hours, preventing wind producers from recovering their fixed costs (Percebois, 2014, (11)). In this analysis only yearly average prices are retained for computing profitability.

[2]This assumption is more fragile in the case of Germany as this country fed large amounts of wind electricity into the grid.

[3]Time series of counter-factual electricity prices are built by increasing by 1.46% the observed price for every percent of wind power in the electricity load.

2.3 The model

2.3.1 Model setting

The model deals with the decision to build a unit of installed capacity of wind power; the retained unit of diffusion of the wind technology is a MW of installed capacity. The investment is realized if and only if its profitability is positive. Since the level of profitability is heterogeneous across projects due, for instance, to climatic peculiarities we consider that the level of profitability R for a given cohort t follows a two parameters distribution with a partial density function $f(R; \mu_t, \sigma)$ where μ_t is the average Return-on-Investment and σ is the standard deviation. It allows us to capture the heterogeneity of the investment projects without having to collect detailed information project by project. It should be noted that the two parameters do change from a country to another. Moreover, the average level of profitability μ_t will vary in time due to modifications of demand-pull policies, variations of the investment costs and some other exogenous factors. The sources of variations of μ_t are detailed in subsection 2.4.2. The standard deviation σ is assumed to be independent from demand-pull policies so that its value is time invariant, whereas the mean μ_t changes among scenarios. The model intends to explain the diffusion of wind power by the variations of μ_t. An illustration of the effect of such a variation for a given year t is given by Figure 2.1. It illustrates the case of an increase of the average profitability, so that the distribution of the profitability level shifts to the right.

The general idea of the model is as follows. At the beginning of a given year t, all the MWs that are profitable ($R > 0$) are developed, or have been previously developed. It is expressed as a fraction $1 - F(0; \mu_t, \sigma)$ of the total potential, denoted k_{max} that represents a theoretical upper bound for the diffusion of wind power. Assuming an increase of the average profitability between t and $t + 1$, so that $\Delta\mu_t > 0$, the newly installed capacities are the difference between the total amount of profitable projects and the projects that were already profitable and consequently already developed. Hence, the capacities that are installed during the year t are $F(0; \mu_t, \sigma) - F(0; \mu_{t+1}, \sigma)$. In the case the average profitability decreases from year t to the next year it is assumed that no new capacities are installed.

Expressed as a fraction of k_{max}, the wind power capacities developed during year t may formally be written as

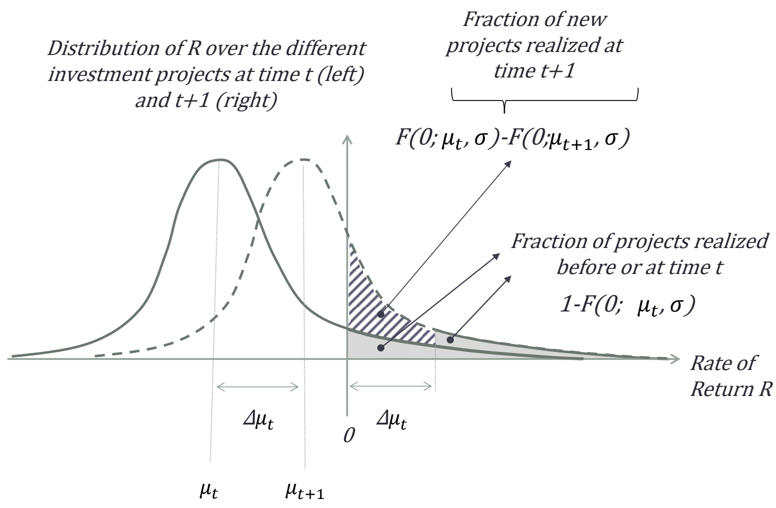

Figure 2.1: Micro-foundations of diffusion dynamics.

$$\frac{\Delta k_{t+1}}{k_{max}} = \begin{cases} F\left(0;\mu_t,\sigma\right) - F\left(0;\mu_{t+1},\sigma\right) & \text{if} \quad \Delta\mu_t > 0 \\ 0 & \text{if} \quad \Delta\mu_t \leq 0 \end{cases} \tag{2.1}$$

In practice, the model is implemented in a slightly different way. Indeed, our purpose is to replicate the observed diffusion, as best as possible, by calibrating the parameters of the model in order to realize a counter-factual analysis.

The counter-factual analysis relies on an openloop approach to the dynamics of diffusion. In order to be consistent with the data observed at the beginning of the period studied, two initial conditions have to be satisfied. These two conditions are written

$$\frac{F(R_{max};\mu_0,\sigma) - F(0;\mu_0,\sigma)}{F(R_{max};\mu_0,\sigma)} = \frac{k_0}{k_{max}} \tag{2.2}$$

and

$$\frac{F(0;\mu_0,\sigma) - F(0;\mu_1,\sigma)}{F(R_{max};\mu_0,\sigma)} = \frac{\Delta k_0}{k_{max}}. \tag{2.3}$$

Condition (2.2) states that the share of the wind power capacity that is installed at the beginning ($t = 0$) of the period studied amounts to k_0/k_{max}. Satisfying this condition generally requires to truncate the distribution of profitability. Indeed, assuming for instance a symmetric distribution of R and a positive value μ_0 of the initial average profitability which is also the median profitability. Then, more than half of the potential k_{max} would have been already developed at $t = 0$, which is obviously too restrictive. Therefore, we assume that F is truncated to the right by R_{max} so that the profitability does not exceed this level. However, the truncation introduces another unknown parameter R_{max}. We thus introduce the additional condition (2.3) which states that the share of capacities added during the first period of diffusion amounts to $\Delta k_0/k_{max}$. Conditions (2.2) and (2.3) can be rewritten as

$$\kappa = \frac{k_0}{F(R_{max}; \mu_0, \sigma) - F(0; \mu_0, \sigma)} \tag{2.4}$$

and

$$\kappa = \frac{\Delta k_0}{F(0; \mu_0, \sigma) - F(0; \mu_1, \sigma)}, \tag{2.5}$$

where $\kappa = k_{max}/\left(F(R_{max}; \mu_0, \sigma)\right)$. For known parameters of F, the value of κ is deduced from condition (2.5) and is sufficient to generate the dynamics of capacities. Indeed, adapting (2.1) to the truncated distribution yields

$$\Delta k_t = \begin{cases} \kappa \left(F(0; \mu_t, \sigma) - F(0; \mu_{t+1}, \sigma)\right) & \text{if} \quad \Delta\mu_t > 0 \\ 0 & \text{if} \quad \Delta\mu_t \leq 0 \end{cases} \tag{2.6}$$

The value of R_{max} is not required on (2.6) but it can be extracted from condition (2.4). In the next subsection the properties of the model are emphasized. Then, section 2.4 details how the variations of the average profitability are computed.

2.3.2 Properties of the diffusion process

A first interesting feature of the dynamics of diffusion is that, if the profitability is initially negative for all capacity units the diffusion process cannot start. This more specifically occurs if R_{max} is negative.

Two factors may trigger diffusion. First, national public policies and their positive effects on the revenue may allow the diffusion to start. Second, an increase of the European cumulative installed capacities, via learning-by-doing, may lower investment cost. This latter effect underlines the role of knowledge spillovers on the diffusion of a new technology. More precisely, it takes into account how foreign support policies may contribute to the national deployment of wind power.

Another interesting feature is that the diffusion can stop, at least temporarily, before the upper bound of wind power capacity is reached, i.e. before $k_t = k_{max}$. This arises when the expected profitability decreases substantially from a period to the next. It can result, for instance, from a deterioration of economic conditions, from an increase of the prices of metals used to construct wind turbines or from lower public supports. It may follow on from the shape of the distribution of R. Indeed, when many capacities have already been developed, the remaining potential MWs have their profitability level R on the left tail of the distribution represented in Figure 2.1. Given that the distribution is single peaked, the further they are on the left, the thicker is the tail and, consequently, the smaller is the proportion of new developed capacities for a given translation $\Delta\mu_t$ of the distribution to the right. It follows that the diffusion process is more likely to be stopped due to a decrease of average profitability when many capacity units have already been developed. This sharply contrasts with the holistic approach that is not able to explain why the diffusion process can stop before being completed. In the same idea, the diffusion could be restarted by exogenous shocks that positively affect the profitability. Such shocks are for instance a decrease of metals prices, a more profitable support provided by demand-pull policies or an increase of wind capacities installed abroad that benefits to national investors due to spillovers.

A last feature that substantially distinguishes the micro-founded model of diffusion from holistic models is that the dynamics of the proportion of developed capacities is led by the variations of the average profitability from year to year. Note that it does not mean that the policy support necessarily needs to increase over time to induce a diffusion of wind power as the learning effect positively affects the average profitability.

2.4 Variations of the profitability index

2.4.1 Renewable energy diffusion and the link with the profitability: a short literature review

For the purpose of modeling, using a single criteria to trigger investment in new generation capacities is a meaningful alternative to the traditional optimization led decision process. Mercure et al. (2014, (120)) develop a model of the electricity sector, driven by innovation, where investors make their decisions relative to the Levelized Cost of Energy (LCoE) of the different generation technologies included in the model. In order to gain realism, the authors apply a probabilistic distribution to these LCoEs, representative of the geographical heterogeneity. However, using the LCoE to approximate the competitiveness of variable energies and to deduce the investment decisions has drawbacks. As emphasized by Joskow (2011, (83)), the LCoE is a flaw metric that does not take into account the time profile of energy generation and the impact of its intermittent supply on the market revenue of producers. According to the same author, an alternative is to consider the expected profitability of power plants. In this vein, several studies have been realized using measures of the expected profitability of renewable power plants. Here, the focus is on the studies linking profitability and policy instruments supporting renewable energy. Mir-Artigues and del Río (2014, (121)) highlight the possibility to encompass several economic instruments by using the return-on-investment. They review all the combinations of three types of instruments (revenue improving instruments, investment subsidies and low rate loans) that lead to the same level of profitability. Profitability metrics also make it possible to assess the changes in the design of an instrument, as it is done in Danchev and Tsakanikas (2010, (35)) and Hitaj et al. (2014, (73)). While the former does not build the bridge between the return-on-investment of renewable energy power plants (more precisely, solar power plants in the paper) and the deployment of additional capacities, the latter does. In Hitaj et al. (2014, (73)) the Net Present Value (NPV) of total generation of a power plant is included in an econometric analysis. In our view, it is a first step to improve our understanding of the determinants of the investment in renewable energy power plants. Jenner et al. (2013, (80)) estimate a fixed effects model based on the computation of the return-on-investment of two technologies: solar photovoltaic and onshore wind. By doing so, they estimate the effects of the revenue improving instruments in 26 countries. Their study concludes that demand-pull policies have contributed to wind and solar power deployment. However, they do not consider the impact of newly built capacities on the evolution of the cost of renewable energies. Actually, the yearly LCoEs they use are estimated with learning curves that assume a steady decrease that contrasts with the observed data (Irena, 2012, (221)), especially with regard to the increase in turbines prices observed during the mid-late 2000s. Consequently, this assumption is ruled out in the present article as the factors explaining the rise of turbines cost are included in the model, as explained below.

2.4.2 Modeling the variations of the average profitability

In the model presented in section 2.3 a key role is given to the average level of profitability μ. The value of this parameter at $t = 0$ is calibrated and what is of interest for us is how its variations affect the diffusion of wind power technology. In order to represent these variations a theoretical level of profitability, denoted $RoI^{\omega}_{c,t}$, is modeled in order to integrate the effects of demand-pull policies, among other effects, on the profitability of wind power. Hence, the variations of μ_t are defined by

$$\Delta\mu_t = \Delta RoI^{\omega}_{c,t}.$$

The average return-on-investment per kWh of generated electricity over a turbine's lifetime for a wind plant installed at time t in country c in a scenario ω is computed as

$$RoI^{\omega}_{c,t} = \frac{Revenue(k^{\omega}_{t-1}) - Cost(k^{\omega}_{t-1})}{Cost(k^{\omega}_{t-1})}. \tag{2.7}$$

Cohort t represents all wind capacities that have been commissioned at year t and that are affected by the same economic conditions. $Revenue(.)$ and $Cost(.)$ are expressed as functions of the European cumulative capacity k^{ω}_{t-1} at time period $t-1$ in a scenario ω. The specifications of these functions are presented hereinafter and a detailed discussion on how they are constructed is given in Appendix 2.A.

The analysis seeks to investigate the role of demand-pull policies in wind technology diffusion. Obviously, theses policies have not only impacted revenue from wind electricity generation. Actually, demand-pull policies have been implemented with the main objective to stimulate wind power diffusion in order to reduce wind electricity cost through learning-by-doing. Hence, the investment cost for a given year t depends on the cumulative installed capacity at year $t-1$. Learning-by-doing is thus incorporated in $Cost(.)$ in order to take into account the impact of wind power diffusion on investment cost.

At first sight, it can be done by using the simple form of learning curve as expressed by the equation $C_t = C_{ref}(MW_{t-1}/MW_{ref})^{-\beta}$, where the cost C_t at time t depends on the cumulative installed capacity MW_{t-1} relative to MW_{ref} the installed capacity at the year of reference[4], on an initial cost value C_{ref} and on a learning-by-doing elasticity β. Hence the learning rate is computed as $1-2^{-\beta}$. Nonetheless, an increase in investment cost has been observed in all the countries considered in this analysis during the mid-late 2000s. Consequently, the analysis would be biased if using a simple learning curve in the counter-factual analysis as the investment cost would mechanically decrease while in reality it has increase. To solve this problem, the main factors responsible for the increase of investment costs have to be incorporated in the learning curve. According to Bolinger and

[4]The chosen year of reference does not impact the result, see Ferioli et al., 2009, (49).

Wiser (2012, (18)), 58 % of the increase in the prices of turbines in the US between 2002 and 2008 are imputable to turbines scaling and to higher metals prices[5]. Their diagnostic applies to Europe as the majority of the turbines imported in the US between 2002 and 2010 were European (in average, almost 61% of yearly turbines imports between 2002 and 2010 are from UK, Denmark and the Euro zone; *ibid.*). The two factors are included in the specification of the turbine cost. Other factors responsible for the increase of turbines cost such as labor costs, warranty provisions or profit margins are not considered here as they require hard-to-access data; energy prices are neglected because they only had a small effect. To incorporate the effects of turbines scaling and metal prices the investment cost is decomposed as

$$IC^{\omega}_{c,t} = (TC^{\omega}_{c,t} + BOS^{ref}_{c})(\frac{k^{\omega}_{national,t-1}}{k^{ref}_{national}})^{-\beta_c}(\frac{k^{\omega}_{regional,t-1}}{k^{ref}_{regional}})^{-\theta_c}, \tag{2.8}$$

where $IC^{\omega}_{c,t}$ denotes the investment cost, composed by the turbine cost ($TC^{\omega}_{c,t}$) and the balance-of-system and soft costs (BOS^{ref}_{c}). β_c is a national learning exponent and θ_c a regional learning exponent, calibrated to replicate the observed diffusion paths (see subsection 2.5.1). $k^{\omega}_{national,t}$ represents the cumulative amount of installed capacity at year t within country c's borders. $k^{\omega}_{regional,t}$ measures the cumulative installed capacities in the other European countries (EU-28). Hence we have $k^{\omega}_{t} = k^{\omega}_{national,t} + k^{\omega}_{regional,t}$. Turbine costs $TC^{\omega}_{c,t}$ is a function integrating the effects of turbines scaling and metal prices whereas BOS^{ref}_{c} takes country-specific reference values that decrease with learning but remain unaffected by other factors. Hence, it is assumed to be independent from these two effects.

The specification of $TC^{\omega}_{c,t}$ relies on several equivalence laws between a turbine's mass, its diameter and the corresponding rated power. These equivalences are detailed in Appendix 2.A and allow to express $TC^{\omega}_{c,t}$ in €/kW as a function of turbine's rated power $Cap^{\omega}_{c,t}$. The turbine cost is written as

$$TC^{\omega}_{c,t} = \left(\sum_{j=1}^{4} w_j (\frac{Cap^{\omega}_{c,t}}{Cap^{ref}_{c}})^{3/2} I_{j,t} + w_{other}(\frac{Cap^{\omega}_{c,t}}{Cap^{ref}_{c}})^{3/2} \right) TC^{ref}_{c}, \tag{2.9}$$

with Cap^{ref}_{c} the initial value of turbine's rated power in country c and TC^{ref}_{c} the corresponding cost (expressed in €/kW). The influence of metals prices is captured by the price

[5]When computing these shares, the effects of currency movements are excluded as they just represent the loss of value of the Dollar relative to the Euro.

indexes $I_{j,t}$ that take unit values at the year of reference. Four metals are considered: aluminum, steel, iron and copper. Their weights in the turbine cost, denoted w_j, are calibrated based on their shares in the turbine mass; the conversion from the turbine's mass to its rated power is deducted from the equivalence relations evoked above. In fact, equation (2.9) applies a correcting factor to the reference value of the turbine cost that captures the effects of turbines scaling and metal prices. Finally, $Cost(.)$ is written as a discounted sum of all costs, assuming that the investment cost (2.8) is paid at the first period of operation and that other costs are discounted at rate a_t. Hence, it is written

$$Cost(Cap^{\omega}_{c,t}, k^{\omega}_{t-1}) = IC^{\omega}_{c,t} + \sum_{i=0}^{T} \frac{Q^{\omega}_{c,t} O\&M}{(1+a_t)^i} \tag{2.10}$$

where $O\&M$ denotes the operation and maintenance costs per unit of generated kWh. Due to the lack of data on operation and maintenance costs are considered to be time invariant and equal among cohorts and countries. This assumption is made in order to reduce the uncertainty associated with arbitrary chosen country-specific values and the resulting distortions when comparing the levels of profitability. A value of 1.35 eurocents per kWh is taken as representative because it corresponds to an average estimate based on German, Spanish, Danish and English experiences (EWEA, 2009, (206)). Annual amounts of generated electricity are denoted $Q^{\omega}_{c,t}$ and are assumed to be constant over the lifetime of turbines. $Q^{\omega}_{c,t}$ intervenes both in $Cost(.)$ through $O\&M$ costs and in $Revenue(.)$. The revenue part of the RoI is computed as the discounted sum of yearly revenue flows:

$$Revenue^{\omega}_{c,t} = \sum_{i=0}^{T} \frac{P^{\omega}_{c,t,i} Q^{\omega}_{c,t}}{(1+a_t)^i}$$

where $P^{\omega}_{c,t,i}$ the average price at year i paid to a producer of cohort t per generated kWh. This variable is affected by national demand-pull policies and/or electricity market conditions. The negative effect of turbines scaling on profitability has been incorporated in the $Cost(.)$ function and a consistent representation should consider its positive effect on turbine's productivity. Again, equivalence laws between wind speed, turbine size and its rated power allow us to construct the yearly generated output as a function of turbine capacity. It is written:

$$Q^{\omega}_{c,t} = Q^{ref}_c \left(\frac{Cap^{\omega}_{c,t}}{Cap_{ref}}\right)^{\frac{3}{2}\alpha} \tag{2.11}$$

where Q_c^{ref} is the initial country-specific amount of annual output and α is the wind shear exponent. It represents the increase in wind speed velocity at higher altitude resulting from a lower effect of obstructions, e.g. buildings or trees. The wind shear exponent is assumed to be equal to one seventh as it corresponds to a smooth and grass-covered terrain. Deviations from these values are captured by the distribution around the level of profitability. To conclude, expected profitability $RoI^{\omega}_{c,t}$ is expressed as a function of turbine's rated power $Cap^{\omega}_{c,t}$ when incorporating (2.11) in $Revenue^{\omega}_{c,t}$ and $Cost^{\omega}_{c,t}$. It also depends on the cumulative installed capacity at $t-1$ because of the learning-by-doing. It is written

$$RoI^{\omega}_{c,t} = \frac{Revenue(Cap^{\omega}_{c,t}, k^{\omega}_{t-1}) - Cost(Cap^{\omega}_{c,t}, k^{\omega}_{t-1})}{Cost(Cap^{\omega}_{c,t}, k^{\omega}_{t-1})}. \tag{2.12}$$

In this expression, the key variable is $Cap^{\omega}_{c,t}$. Data on turbines average rated power are available per year and country in the IEA Wind reports (IEA Wind, (215)). However, in counter-factual scenarios the average rated power for a cohort t cannot be considered as exogenous as it depends from two factors:

- at the country level, the geographic and climatic peculiarities impact the optimal choice made by wind power plants designers about turbines rated power.

- at the European level, the progress made by manufacturers in producing larger wind turbines positively affects the value of $Cap^{\omega}_{c,t}$.

Consequently, the turbines rated power at time t can be represented by a country-specific function of k^{ω}_{t-1} that approximates the experience gathered by wind turbines manufacturers in building larger units. The European cumulative capacity is chosen instead of the global one in order to exclude the experience gathered by foreign manufacturers, in particular the US and Chinese. According to the European Wind Energy Association, the global market shares of European turbine manufacturers was 37% in 2010 (EWEA, 2012, (207)). However, at the European level it rises to 89%. Hence, the European market is a relevant measure of EU manufacturers experience and since k^{ω}_t is expressed relatively to the reference level k_{ref} the variation matters, not the absolute level. A functional form of the link between $Cap^{\omega}_{c,t}$ and k^{ω}_{t-1} that fits well the observed relations is

$$Cap^{\omega}_{c,t} = d_c(\frac{k^{\omega}_{t-1}}{k^{ref}})^{b_c}, \tag{2.13}$$

where $b_c < 1$ represents the elasticity of turbines rated power of country c to European cumulative installed capacities. For each country this relation is estimated and the results are presented in the section 2.A of the Appendix. The estimated coefficients are retained when simulating counter-factual scenarios. If suppressing demand-pull policies substantially reduces the diffusion of wind power in a country it will reduce the European cumulative installed capacity and, indirectly, it will reduce the average rated power of the newly built turbines. To summarize, the micro-founded model of diffusion determines the newly installed wind capacities per year for a particular country and consequently determines the value of k_t^{ω}, that has two impacts on the variation of the profitability : 1/ the learning effect that reduces the installed cost; 2/ the growing turbine rated power that increases both the turbine cost and the generated amount of kWh per year. Thus, relation (2.13) links a period to the next and endogenously determines the diffusion dynamics.

2.4.3 Sources of heterogeneity and national policies

In this subsection the several types of heterogeneity synthesized by the $RoI_{c,t}^{\omega}$ are detailed. When necessary, precisions are given about the assumptions made for its computation. A complete description of the assumptions and the data used for computing $RoI_{c,t}^{\omega}$ is given in Appendix 2.B.

The first source of heterogeneity is related to demand-pull policies. Among the six countries analyzed in this article, three types of demand-pull policies have been implemented:

- Feed-in tariff (FiT) is the most frequently policy instrument implemented for promoting renewable energy. It makes it compulsory for the system operator(s) to buy each kWh of renewable electricity at a fixed rate, independently of market signals. The tariffs are defined for a given period and thus make investments almost risk-less.
- Feed-in Premium (FiP) constitutes an alternative to the previous instrument. The principle is the same except that producers receive a fixed premium on top of the market price. Hence, the total payment varies with the price of electricity and investors bear some risk.
- Tradable Green Certificates (TGC) is a quantity-based instrument. It requires electricity suppliers to supply a certain amount of renewable electricity. In order to demonstrate that they have complied with quotas of renewable electricity, suppliers must present the corresponding quantity of certificates. For this purpose and for the

sake of flexibility, a green certificates market is established and its price constitutes the support to renewable electricity producers (in addition to the market revenue).

Table 2.1 presents the successive phases of the demand-pull support policies implemented in the analyzed countries. A more detailed version of this Table is given in Appendix 2.C. The $RoI^{\omega}_{c,t}$ takes into account the national support policies through the values taken by $P^{\omega}_{c,t,i}$ in $OD^{country}$ scenarios.

	Denmark (1985-2012)	France (2001-2012)	Italy (2000-2012)	Spain (2000-2012)	Portugal (2000-2012)	Germany (2000-2012)
FIT	Phase 1 (1985-1990) Phase 2 (1991-1999) Phase 3 (2000-2002)	Phase 1 (2001-2005) Phase 2 (2006-2012)	Phase 1 (2000-2001)	Phase 1 (2000-2003) Phase 2 (2004-2006) Phase 3 (2007-2012)	Phase 1 (2000-2001) Phase 2 (2002-2004) Phase 3 (2005-2012)	Phase 1 (2000-2008) Phase 2 (2009-2012)
FIP	Phase 4 (2003-2007) Phase 5 (2008-2012)			Phase 1 (2000-2003) Phase 2 (2004-2006) Phase 3 (2007-2012)		
TGC			Phase 2 (2002-2005) Phase 3 (2006-2012)			

Table 2.1: Evolutions of demand-pull policies for onshore wind power in the six European countries analyzed.

The second source of heterogeneity is technological. First, investment costs are initialized with country-specific values from the IEA Wind national reports (215). When the reports do not distinguish the turbine cost from other costs the following decomposition is applied: turbine cost is assumed to represent 71% of the investment cost and balance-of-system and soft costs 29 % (Blanco, 2009, (15)). Second, learning-by-doing rates are country specific and capture how the countries convert the experience gathered at the European and national levels into lower investment costs.

The third source of heterogeneity is geographic, which is of special importance for variable energies. First, it is taken into account by using national capacity factors. Capacity factors are the ratio between the produced output per year and the maximum theoretical production. Based on Boccard (2009, (16)), the capacity factors of a MW of wind power is computed for each country. These values are used to initialize the amount of generated output in each country. Then, capacity factors improve with turbines scaling as expressed by (2.11). Second, geographic peculiarities influence how power plants designers will adapt the optimal size of turbines. For instance, the increase of turbines size in Italy has been slower, compared to other countries such as Germany, in order to adapt the turbines to rough and hard-to-access terrain (215). Estimates of the link between the turbines rated power and the cumulative European installed capacities capture this second type of geographic heterogeneity.

The last source of heterogeneity is economic. The economic background influences several parameters such as average risk-free financial returns in the Euro zone (used in this paper as discount rates) and electricity spot prices. The latter fulfills three functions in the analysis:

- In the case of Feed-in-Premiums and Tradeable Green Certificates, a share of producers revenues comes from the electricity market.
- After the scheme ends, if it does before the decommissioning of the plant, the producer only receives the market price.
- In the counter-factual scenarios, the only source of revenue are sales on the spot market of electricity.This last point has been detailed in section 2.2.

2.5 Calibration and results

2.5.1 Calibration

The purpose of the quantification of the parameters involved in (2.6) is to conduct a counter-factual analysis of the development of new onshore capacities for wind power by investigating several scenarios. As already stressed when commenting equation (2.6), parameter κ is deduced from the other parameters so as to satisfy the initial condition (2.5). The parameters that must be calibrated are the initial level of average profitability μ_0, the standard deviation σ of the distribution of R, and the two learning exponents θ (European) and β (national). The peculiarity of the counter-factual analysis is that we want to solve the dynamics in open loop, not in closed loop. Indeed, we want to construct a counter-factual time path of the proportion of installed capacities, starting from the same initial conditions than those that have actually prevailed, but proceeding with fictitious values of the revenue earned from wind electricity. For this purpose, we have to make sure that the values used for the parameters enable us to correctly reproduce the time path of wind power deployment in accordance with the actual values of the revenues determined by demand-pull policies. The open loop approach requires to compute the predicted proportion of installed capacities at dates $t > 0$ on the basis of (2.6). If the dynamic equation (2.6) was linear, it could be done analytically and we would be able to estimate the parameters with standard econometric methods. The point is that (2.6) is highly non linear and that we are not able to find a simple and econometrically tractable analytical expression of Δk_t. Therefore, we calibrate the model rather than estimate it with econometric methods. Notwithstanding, we use a root mean square minimization method to calibrate the parameters. Indeed, a grid of possible values of the different parameters is first generated. For each set of parameters' values in the grid, we compute the time path of k_t over the whole period of the study, conditionally on the initial condition (2.5), and on the observed values of the payments received by producers under support schemes. The set of parameters' values that minimizes the root mean square error between the simulated diffusion and its actual profile is used as the solution. A new minimization, based on a narrower grid with smaller increments between the values of parameters, is implemented until the root mean square error (RMSE) obtained for the solution does not decrease more than a fixed relative value. Last but not least, prior to calibrating the parameters we need to specify a distribution function f for R. For the sake of limiting the number of parameters, while allowing enough flexibility, we restrain the analysis to distributions with two parameters, a position parameter μ_t and a dispersion parameter σ. A natural candidate is the Gaussian distribution with expected value μ_t and standard deviation σ. An alternative specification for the distribution of R is the Extreme Maximum Value distribution. This specification is an interesting alternative because it is initially defined for any real value of the return but, contrary to the Gaussian distribution, it is asymmetric. Parameters of the model are calibrated country by country. The results of calibration are given in Table 2.1.

Distribution function of the RoI		DE	FR	IT	PT	ES	DK
Gaussian	μ_0	-2.06	-5.22	-11.5	-8	-2.06	-0.9055
	σ	1.955	1.335	3.45	2.25	1.4	0.38
	β	0.94	0.1735	0.195	0.692	0.55	0.755
	θ	1.9	4.525	1.425	2.1475	1.9325	0.52
	RMSE	$1.24436 * 10^6$	**16240.6**	123431	147942	**419549**	118225
Extreme Values	μ_0	-1.145	-2.855	-13	-3.375	-1.74	-1.035
	σ	2.05	0.608	1.7	0.955	1.54	0.4
	β	1	0.38	0.2575	0.66	0.73	1.064
	θ	1.8	4.18	1.475	2.255	2.04	0.56
	RMSE	$\mathbf{1.18706 * 10^6}$	18784.1	**106855**	**140113**	488875	**87943.8**

Table 2.1: Estimation results by country, depending on the distribution function of the RoI[6].

[6]ISO 3166-2 codes are used instead of countries complete names.

2.5.2 Results

2.5.2.1 Observed Diffusion scenarios ($OD^{country}$).

As explained in section 2.2 the first step of our analysis is to replicate as good as possible the diffusion paths of wind power that have been observed. Figure 2.1 represents for each country the observed and the replicated time paths of diffusion that integrate demand-pull policies. In order to visualize the S-shaped curves of diffusion the time period considered for all the countries is 1985-2012. It is the longer period for which data on investment cost is available and correspond to Denmark. The simulated time path starts later for the other countries (in 2000 for Germany, Spain, Italy and Portugal and in 2001 for France).

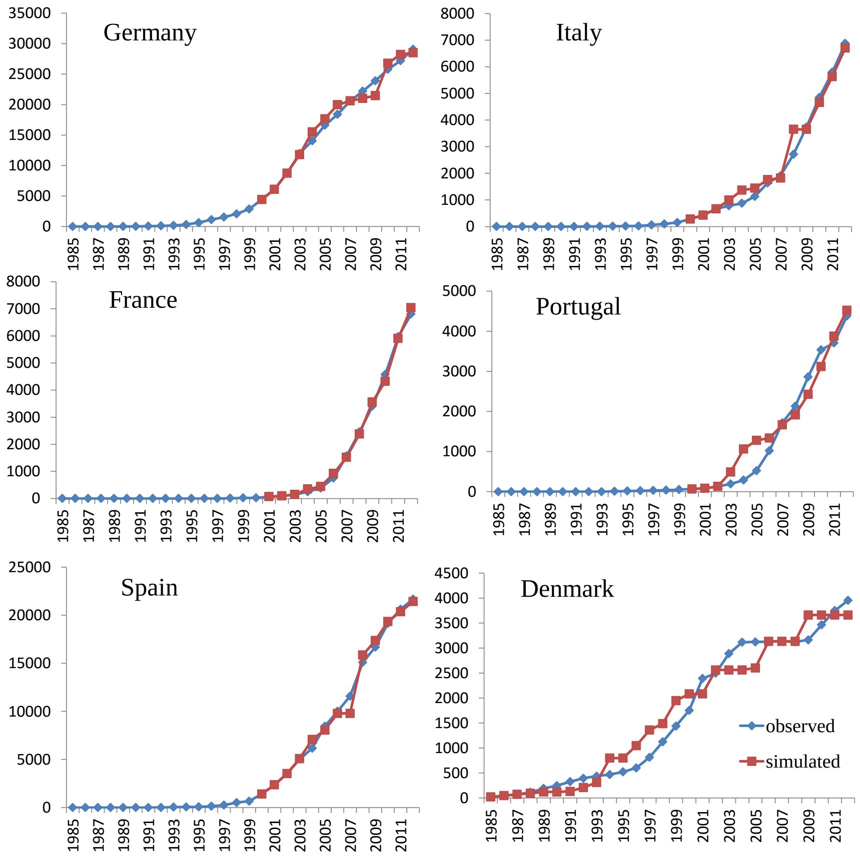

Figure 2.1: Observed versus replicated time paths of diffusion of wind power (in cumulative MW of installed capacity).

Several comments have to be made about the replicated diffusion paths of wind power, represented by the red lines of Figure 2.1. First, we can observe several jumps in the replicated diffusion time paths. This is the case for Germany (2010), Spain (2009), Italy (2008) and more generally for Denmark for which the replicated diffusion is subject to several jumps. For the three first countries two factors are responsible for these jumps.

The first factor is the rise of the prices of metals that began around 2006 and that sees its maximum, during the analyzed period, in 2009 for aluminum, copper and steel. The higher level was reached later, in 2012 for iron. Even if we use a three years moving average of the prices of metals, we are not able to perfectly represent how the manufacturers hedge themselves against the volatility of the cost of their inputs. Consequently, the negative effect of the rise of the metals prices indexes on profitability, and hence on diffusion, is exaggerated these years where a shock on metals prices occurred, until the replicated diffusion catches up the observed one. The second factor are the changes in national demand-pull policies. For these three countries the jumps in the replicated diffusion occur after a modification of the design of the demand-pull support, in each case it corresponds to an improvement of the conditions of support in terms of profitability, through higher payments or a longer support periods. In response to more attractive support policies the share of newly installed wind capacities rises within a year while in reality the administrative process associated with the installation of new renewable energy capacities tends to slow down the reaction to more advantageous policies in terms of newly installed capacities. The inability of the model to take into account the administrative process also explains the difference between the replicated and the observed diffusion in Portugal between 2003 and 2006. According to the IEA Wind reports, a critical effort has been made during these years, following the Dec.-Law no. 68/2002, to simplify the administrative process concerning the implementation of renewable energy power plants. As it is neglected by the model, all the projects that are considered as profitable are realized faster than in reality. Finally, for the Danish case the model is able to replicate the general trend of the diffusion but it presents a discontinuous dynamics that contrasts with the observed diffusion. However, the period of replication is much more longer than for the other countries and the replication of the general trend gives us confidence in the use of the model for the counter-factual analysis.

2.5.2.2 Unilateral Removal scenarios ($UR^{country}$)

The results of the counter-factual scenarios $UR^{country}$ and $MR^{low}\&MR^{high}$ are reported in Table 2.2. They are expressed as the percentage of difference between the amount of installed capacities of wind power in 2012 that the model replicates given the actual demand-pull policies and the amount of installed capacities induced by a suppression of the support. In other words, the absolute values of the percentages given in this Table are the shares of the national cumulative wind capacities that are imputable to demand-pull support policies, depending on the simulated scenario.

		DE	FR	IT	PT	SP	DK
$UR^{country}$	Country of removal	-32.39%	-95.31%	-84.49%	-71.47%	-43.32%	-34.61%
	Other countries	-16.12%	-2.96%	-3.65%	-2.78%	-9.34%	-1.4%
	MR^{high}	-41.1%	-95.92%	-86.27%	-83.11%	-54.33%	-42.11%
	MR^{low}	-41.32%	-96.01%	-86.01%	-84.44%	-53.98%	-39.9%

Table 2.2: Differences in % of the cumulative capacities in 2012 between the counter-factual scenarios and the simulated scenarios with demand-pull support (simulations starts in 2001 and end in 2012).

Our counter-factual analysis of the unilateral removal of demand-pull policies allows us to split the six countries into two groups. The first group are Denmark, Germany and Spain whereas the second group gathers Italy, France and Portugal. For the first group we observe that removing the national support policies would have had a negative but moderate impact on the cumulative installed capacities of wind power in 2012. For instance, the German cumulative capacity would have been 32.39% lower and the same orders of magnitude are found for Denmark and Spain: 34.61% and 43.32%, respectively. For these three countries the demand-pull policies contributed to accelerate the diffusion of wind technology. Nevertheless, simulated counter-factual time paths indicates that a slower diffusion would have had occur anyway and in this sense the dynamics of diffusion is, of course, stimulated by demand-pull supports but also self-sustained by the effect of a national learning. When computing the ratio between the national and the regional learning elasticities we obtain that they are the higher for this three countries, and for Portugal. The difference between these three countries and the Portugal is that their diffusion time paths of wind technology started earlier whereas Portugal can be considered as a laggard since its diffusion started around 2003. These results suggest the existence of a first mover advantage that follows from an important role to the national learning and reduces the dependency on foreign demand-pull policies. This last point is strengthened when simulating the multilateral removal scenarios, as detailed in the next part of the subsection.

The second group is composed by France, Portugal and Italy. The common denominator is the high negative impact of removing the demand-pull policies on the cumulative installed capacities. An unilateral removal of the demand-pull policies of these countries would have decreased the cumulative installed capacities by 95.31%, 84.49% and 71.47% for France, Italy and Portugal respectively. For France and to a less extent Italy, the diffusion is almost fully triggered by the policy support as only a very small amounts of wind capacities would have been installed in the absence of public support. For the three countries of this group the diffusion starts later compared to Germany, Denmark and Spain. Hence, they rely more on a regional, i.e. European, learning than the national one and this is particularly true for France when considering the value of the Table 2.1.

One interesting property of the model is to consider how the countries interact with each other in terms of learning. It allows to estimate the impact of an unilateral removal on the five other countries. As can be expected the higher impacts are found for Spain and Germany; two countries with high levels of wind power installed capacities. For Germany, the removal of the demand-pull support would have decrease the cumulative installed capacities at the end of the diffusion period in the five other countries by 16.12%. Spain also contributed to increase the European cumulative capacities as suppressing its demand-pull policy reduces by 9.34% the cumulative installed capacities in the five other countries. In this extent, Germany and Spain bear the cost of the scheme but create important spillovers toward their European neighbors.

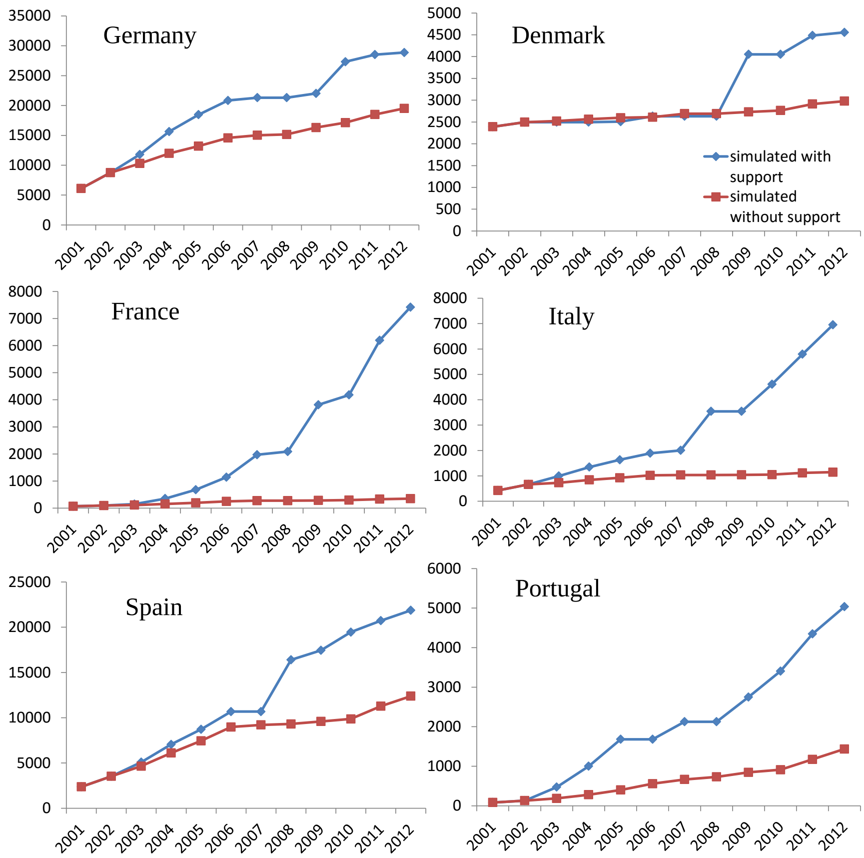

Figure 2.2: Simulated time paths of diffusion with and without demand-pull policies (in cumulative MW on installed power).

The detailed impact of unilateral removals through time are represented on Figure 2.2. The replicated diffusion time paths with demand-pull support are represented by the blue lines and the simulated diffusion without support by the red lines. Prior commenting this

Figure, it is worthwhile giving some precisions about how the diffusion time paths with demand-pull support are simulated. Compared to the diffusion time paths represented on figure 2.1, the blue lines on Figure 2.2 are slightly different. Since we take into account the interactions between the six countries when investigating the unilateral removal of their policies, we do the same when simulating the diffusion time paths with the actual demand-pull policies. Hence, when simulating the supported diffusion, the newly built capacities in each country are jointly determined at each year and impact, through the regional learning, the other countries. The Figure 2.2 allows for a finer analysis of the impact of demand-pull support removal. A first remark is that for Spain and Denmark the impact of demand-pull support changes over time. For Spain, the impact of the removal remains relatively small until 2007 as the diffusion simulated in the absence of demand-pull support is close to the diffusion obtained with support. The disconnection between the two diffusion paths occurs after 2007 when the feed-in premiums have been implemented as an option and chosen by 90 % of producers (Ragwitz et al., 2012, (225)). This modification has been criticized for creating windfall profits but it has also strongly accelerated the diffusion of wind power in Spain. The same phenomenon is observed for the Denmark as the demand-pull support impacts the diffusion after 2008. Again, it may be explained by a modification of the form of the policy support. In Denmark, wind power producers were supported by a system of premium added to the spot price of electricity until 2008. The total payment was capped to 48 €/MWh in order to reduce the windfall profits while reducing the volatility of the revenue. As we consider annual average values of the electricity spot price, this effect is excluded from our model. Since the average electricity price was close to the upper bound of the total payment the effect of the demand-pull support is underestimated.

2.5.2.3 Multilateral Removal scenarios (MR^{low}&MR^{high})

The impacts of a multilateral removal of demand-pull policies, expressed as the shares of the cumulative installed capacities in 2012 that would have not be installed, are given in the two lower rows of Table 2.2. The impact is detailed country by country. Consistent with the fact that an unilateral removal of their policies would have had a relatively small impact on their cumulative capacities compared to the three other countries, Denmark Germany and Spain would have been less impacted by a multilateral removal. Nonetheless, the impact is slightly higher. The multilateral removal of demand-pull policies would have induced a decrease of the amount of cumulative installed capacities by approximately 41% in Germany, 54% in Spain and 41% in Denmark in 2012 compared to the actual installed capacities. It should be kept in mind that our analysis focuses on six countries of the

European Union and consequently, even when jointly removing their support policies, they continue to benefit from the learning in the other countries. For Italy, France and Portugal a multilateral removal of demand-pull policies almost prevents the diffusion of wind power to start but the orders of magnitude stays comparable with the unilateral removal scenarios. More, an interesting result is the very low difference between MR^{low} and MR^{high} indicating that the merit order effect has a limited impact. Hence, a lower share of wind electricity fed into the grid would have not been sufficient to raise the profitability of wind projects through higher electricity prices to induce a significant proportion of additional installed capacities. The two scenarios are presented on Figure 2.3 for each country.

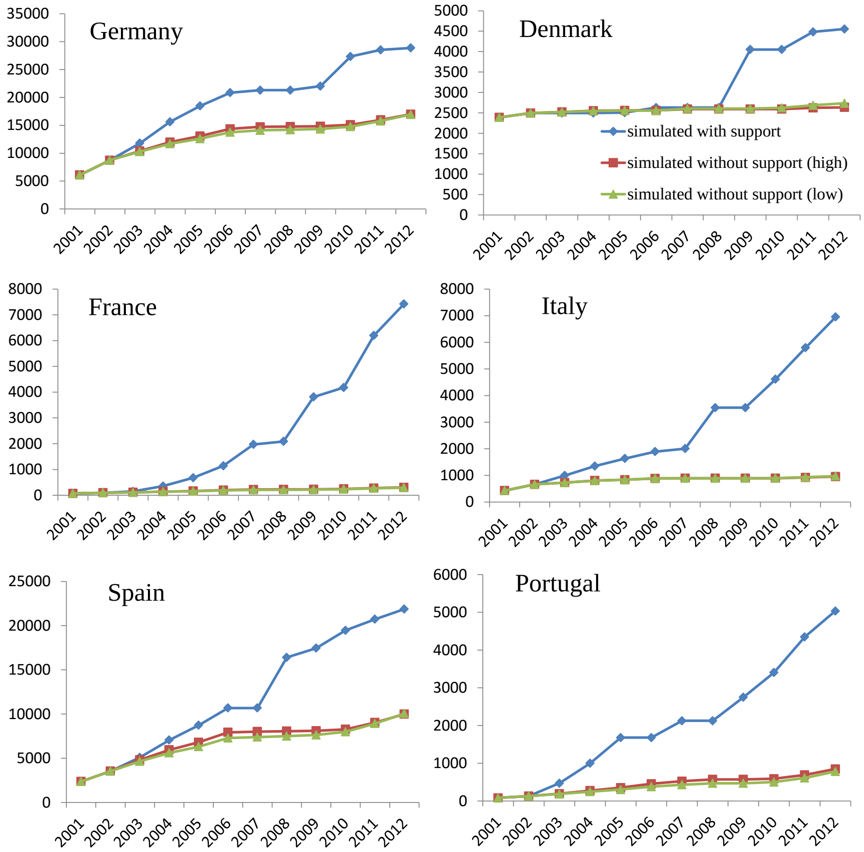

Figure 2.3: Simulated time paths of diffusion of the Multilateral Removal scenarios (in cumulative MW of installed power).

2.6 Conclusion

The counter-factual analysis allowed by the micro-founded diffusion model developed in this paper highlights some key points for the design of policies intended to promote renewable energies. The main point is that spillovers play an important role but can not allow a country to significantly develop its own installed capacities without implementing a national support policy. The case of France, Italy and to a lesser extent Portugal is illustrative of this point. If these countries had unilaterally removed their support policies they would have not been able to increase their wind power capacities in spite of important spillovers coming from Denmark, Germany and Spain. Another important point is that being a first mover for the development of wind power has conferred an advantage to Denmark, Germany and Spain in the sense that the dynamics of diffusion in these countries has been to a large extent autonomous and thus not contingent on policies implemented by other countries. By contrast, a removal of policy in these three countries would have negatively impacted diffusion in other countries. Put together, these two findings implies that the risk of free riding, i.e. the risk that countries prefer to be laggards in order to benefit from the support policies implemented by first mover countries, is low. This is confirmed by the results of the counter-factual analysis of a joint removal of support policies. Such a joint removal would have increased the slowdown of diffusion but would have not affected the first mover advantages of Germany, Denmark and Spain.

Appendix

2.A Appendix A: The return-on-investment function

The average Return-on-Investment, $RoI^{\omega}_{c,t}$, in country c for the cohort of wind plants commissioned at year t is expressed as

$$RoI^{\omega}_{c,t} = \frac{Revenue(k^{\omega}_{t-1}) - Cost(k^{\omega}_{t-1})}{Cost(k^{\omega}_{t-1})}, \tag{2.14}$$

where k_{t-1} is the cumulative installed capacity of wind power in Europe (EU-28) at $t-1$. ω indicates whether we are in the $OD^{country}$ or in a counter-factual scenario. This Appendix details how $Revenue(.)$ and $Cost(.)$ are constructed as functions of k^{ω}_{t-1}. Advantages of making $RoI^{\omega}_{c,t}$ a function of the European cumulative capacity are discussed further in subsection 2.4.2.

2.A.1 The Revenue Function.

$Revenue(k^{\omega}_{t-1})$ is the discounted sum of the yearly revenue of one MW of wind capacity installed at time t in country c. It is computed as

$$Revenue_{c,t}(k^{\omega}_{t-1}) = \sum_{i=0}^{T} \frac{P^{\omega}_{c,t,i} Q^{\omega}_{c,t}}{(1+a_t)^i}.$$

where T is the power plant lifetime, a_t the discount rate, $P^{\omega}_{c,t,i}$ the average annual price of electricity (in eurocents/kWh) during the year i for the cohort t in country c and $Q^{\omega}_{c,t}$ the annual amount of generated kWh. Prices are taken as exogenous by producers and they are impacted by the policy support. Yearly amounts of generated output depend on national

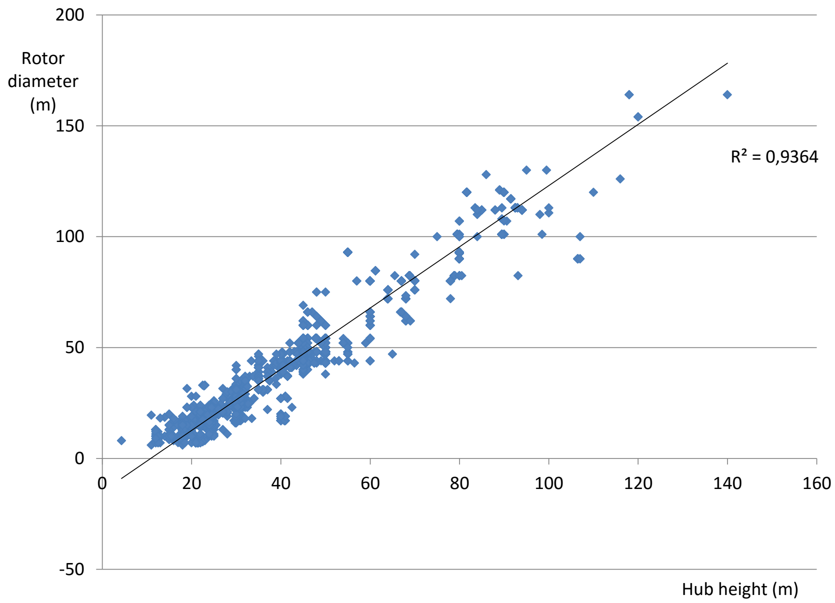

Figure 2.A.1: Correlation between turbine's height and rotor diameter, based on a sample of 8334 Danish turbines (from the *Master Data Register of Wind Power*).

wind resources and on turbines' diameter. The latter factor is a key element because a substantial increase in turbines' size has been observed since technology started to diffuse and it has strongly improved wind plants' productivity. It is known that, *ceteris paribus*, the energy captured by a wind turbine scales with the cube of the wind speed:

$$\frac{Q_i^\omega}{Q_{ref}} = (\frac{S^\omega}{S_{ref}})^3,$$

where S^ω measures the mean wind speed that depends on the tower's height. Q_{ref} and S_{ref} are the reference values of generated output and mean wind speed, respectively. As done in Burton et al. (2001, (175)) and Coulomb and Neuhoff (2006, (31)) and supported by the correlation represented on Figure 2.A.1, the proportionality between a turbine height and its diameter is assumed. Moreover, the relation between the mean wind speed and the turbine size is approximated by an exponential function.

The mean wind speed variation is a function of turbine's height (H), and thus of its diameter (D) given the proportionality:

$$\frac{S^\omega}{S_{ref}} = (\frac{H^\omega}{H_{ref}})^\alpha = (\frac{D^\omega}{D_{ref}})^\alpha \tag{2.15}$$

with D_{ref} and H_{ref} the reference values (Burton et al., 2001, (175); Coulomb and Neuhoff, 2006, (31)). α is the wind shear exponent measuring how mean wind speed increases with tower height. Given that energy scales with the cube of mean wind speed using (2.15) we can write how quantity scales with the diameter:

$$\frac{Q_i^{\omega}}{Q_{ref}} = (\frac{D^{\omega}}{D_{ref}})^{3\alpha}.$$

Finally, the link is made with the installed capacity of the turbine, denoted $Cap_{c,t}^{\omega}$, as it scales with the square of the diameter ((207)). Thus

$$Q_i^{\omega} = Q_{ref}(\frac{Cap_i^{\omega}}{Cap_{ref}})^{\frac{3}{2}\alpha}.$$

To conclude, $Revenue_{c,t}(k_{t-1}^{\omega})$ depends only on the average rated power Cap_i^{ω} of the representative wind turbine and some parameters. The link with k_{t-1} is made explicit below.

2.A.2 The Cost function

$Cost_{c,t}^{\omega}$ is the sum of the discounted costs and can be decomposed into two components: investment cost, denoted $IC_{c,t}^{\omega}$, and operation and maintenance cost per generated kWh denoted $O\&M$. The former is assumed to be paid entirely on the first period so that

$$Cost_{c,t}^{\omega} = IC_{c,t}^{\omega} + \sum_{i=0}^{T} \frac{O\&MQ_{c,t}^{\omega}}{(1+a_t)^i}. \tag{2.16}$$

As explained in the body of the article, operation and maintenance cost are assumed to be constant for every country and cohort. $IC_{c,t}$ is disaggregated into two components: the turbine cost ($TC_{c,t}$) and the balance-of-system and soft costs (BOS_c^{ref}). As made for the *Revenue* function, $TC_{c,t}$ is expressed as a function of turbine's installed power. *Ceteris paribus*, the turbine's cost scales with its mass. Nonetheless, the analysis takes place in a dynamic framework and the factors that contributed to the observed increase in turbine prices during the late 2000s have to be incorporated. According to Bolinger and Wiser (2012, (18)), the major factors are metal prices and turbine scaling. In order to include metal prices, the variation of $TC_{c,t}$ is decomposed as

$$\frac{TC_{c,t}}{TC_{ref}} = w_{steel}\frac{m^{\omega}}{m_{ref}}I_{steel,t}+w_{copper}\frac{m^{\omega}}{m_{ref}}I_{copper,t}+w_{iron}\frac{m^{\omega}}{m_{ref}}I_{iron,t}+w_{alu}\frac{m^{\omega}}{m_{ref}}I_{alu,t}+w_{other}\frac{m^{\omega}}{m_{ref}}$$

where the w_j denote the shares of the turbine mass (m^{ω}) of metals and other components. The weights are assumed to be constant over time. Metal prices indexes, denoted by $I_{j,t}$, are introduced to represent the evolutions of metal prices over time and they take unit values for the reference year. A common approximation of the relation between turbine mass and its diameter is known as the cube law (Burton et al., 2001, (175)) and stipulates that the mass scales with the cube of turbine's diameter, so that we can write

$$\frac{TC_{c,t}}{TC_{ref}} = \left(\sum_{j=1}^{4} w_j(\frac{D^{\omega}}{D_{ref}})^3 I_{j,t} + w_{other}(\frac{D^{\omega}}{D_{ref}})^3\right).$$

As done for the *Revenue* function, using the relation according to which installed power scales with the square of diameter, the turbine cost is expressed as a function of turbine installed capacity

$$TC_{c,t} = \left(\sum_{j=1}^{4} w_j(\frac{Cap^{\omega}}{Cap_{ref}})^{3/2} I_{j,t} + w_{other}(\frac{Cap^{\omega}}{Cap_{ref}})^{3/2}\right) TC_{ref}. \tag{2.17}$$

The second component, BOS_c^{ref} is difficult to model as its determinants are less documented. It is assumed that its values depend from both regional and national learning-by-doing effects impacting the whole investment cost. Hence, investment cost dynamics is initialized with observed reference values and formalized as

$$IC_{c,t} = (TC_{c,t}^{\omega} + BOS_c^{ref})(\frac{k^{\omega}_{national,t-1}}{k^{ref}_{national}})^{-\beta_c}(\frac{k^{\omega}_{regional,t-1}}{k^{ref}_{regional}})^{-\theta_c} \tag{2.18}$$

where β_c and θ_c are the learning-by-doing elasticities. Finally, the complete form of $Cost_{c,t}^{\omega}$ is obtained by incorporating (2.18) in (2.16). At this stage, $RoI_{c,t}^{\omega}$ is constructed as a function of $Cap_{c,t}^{\omega}$ the average capacity of wind turbines built at year t. National time series of $Cap_{c,t}^{\omega}$ are available and it would be possible to use it to estimate the parameters of the model. However, it could not be assumed that these values would have been the same when simulating the counter-factual scenarios because bigger wind turbines were available due to the technical progress made in manufacturing. In this sense, the average rated power of

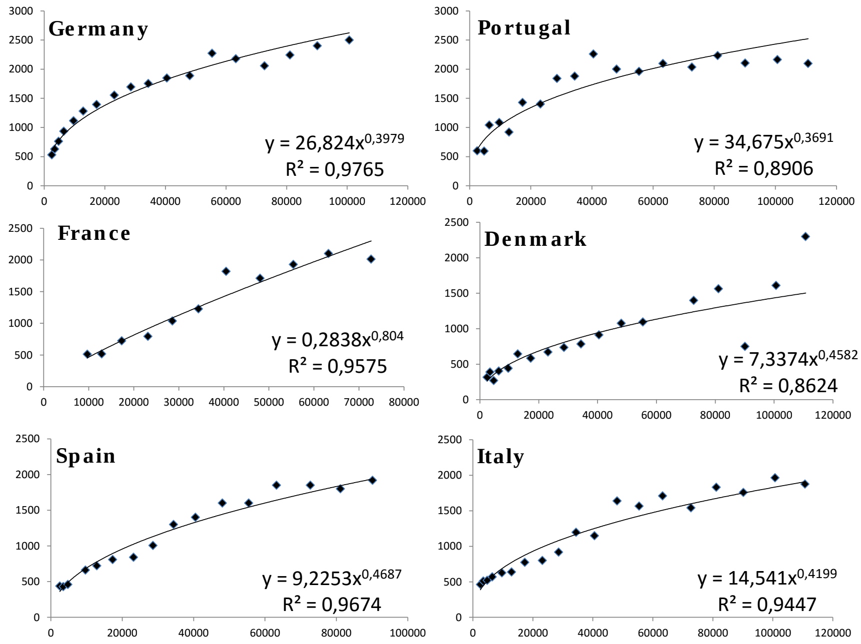

Figure 2.A.2: Estimations of the relation between average turbines rated power and lagged European cumulative capacity.

wind turbine at time t is modeled as a function of the European cumulative capacity, k^{ω}_{t-1}, and country-specific estimations are made on the basis of data on historical average wind turbine rated power, available in the IEAwind annual reports. Results of these estimates are given on Figure 2.A.2.

2.B Appendix B: Assumptions and data

2.B.1 Investment costs (IC)

According to the IPCC (2012, (218)), IC_t for an onshore wind plant encompasses the turbine cost, grid connection costs, civil work costs and other costs (transaction costs, land cost, etc.). The cost values used for initializing the dynamics of diffusion come from the IEAwind annual reports (215), except for France where it come from (Ademe, 2002, (194)). They are summarized in Table 2.B.1. Stars indicate the countries for which, in the absence of available data, a decomposition of the investment cost is applied following Blanco (2009, (15)): 71% for the turbine cost and 29% for the balance-of-system and soft costs.

	DK* (1985)	DE (2000)	FR* (2001)	IT* (2000)	ES (2000)	PT* (2000)
TC_c^{ref}	904.2	825	756.9	738.5	680.8	1004.65
BOS_c^{ref}	369.3	275	309.1	237.5	239.2	410.35

Table 2.B.1: Investment costs data (€/kW of installed power).

2.B.2 Operation and maintenance costs (O&M)

O&M costs gather insurance costs, management costs, repair and replacement costs. However, depending on studies, all or parts of these costs are taken into account. In order to avoid any bias when comparing countries, the choice is made to use the same value for the six countries. Based on the EWEA (2009, (206)), a value of 1.35 eurocents per kWh is chosen.

2.B.3 National capacity factors

The capacity factor of a power plant measures the ratio between the yearly quantity of generated output and the maximum theoretical generation in a year. Assumptions about the capacity factor of a wind turbine may vary significantly from a study to another. In this article, the retained values are from Boccard (2009, (16)) who computes the realized values of the wind power capacity factors for several European countries. They are reported in Table 2.B.2. The initial levels of generated output are computed on the basis of these capacity factors.

Country	France	Spain	Italy	Germany	Portugal	Denmark
Average realized capacity factors between 2003 and 2007	22.3%	24.8%	19.1%	18.3%	22.7%	22.8%

Table 2.B.2: National capacity factors for a typical wind power plant

2.B.4 Discount rates

The discount rate partially captures the influence of the macro-economic environment on the micro-economic investment behavior. To reflect this causality, yield curves may be used to discount cash-flows. These curves represent the yield from a bond depending on its maturity. The bond that is considered here is a zero-coupon from euro zone AAA rated governments bonds. As a result the discount rate is risk-free, making $RoI_{c,t}^{\omega}$ necessary overestimated. However, this is not a problem as it is the variations and not the absolute levels of $RoI^{\omega}_{c,t}$ that matters in the model. Yield curves data can be found on Eurostat; 20 years maturity bonds are chosen in order to fit with our assumption on wind farms lifetime. For the Danish case, since the study starts before the Euro implementation, Danish bonds yields are used from 1985 to 1999, the source being MPK100: *Government bond yields by country, Denmark statistics.*

2.B.5 Electricity prices

The liberalization of electricity markets in Europe that began in the 2000s produced an increasing amount of information. Data on the electricity spot price is used whenever it is available. Otherwise, assumptions on the electricity price are made. Sources and assumptions are detailed in Table 2.B.3.

Country	Data and assumptions
Denmark	The Danish system operator (dk.net) provides data for hourly spot price on DK-west and hourly wind generation since 2003. Prices used are the yearly average price weighted by the wind output. Before 2003 and after 2012 we assume a yearly spot price equals to 50 €/MWh.
Germany	Before 2005, we assume a spot price of 30 €/MWh. Based on data from EPEX between 2005 and 2011, yearly average spot prices are calculated. After 2011, we assume a spot price of 49 €/MWh.
France	In France, since 77% of the generated electricity come from nuclear technology the chosen value for the spot price is the price of the Regulated Access to the Historical Nuclear Electricity, i.e. 42 €/MWh. Even if this value was defined in 2010, it is a good approximation of the cost of nuclear electricity that represents the main competitor for wind power.
Italy	Before 2005, IEA Wind reports on Italy provided the yearly average market revenue of wind producers, a useful information for the RoI computation. Between 2005 and 2012 the system operator (Gestore Mercati Energetici) makes available data on hourly spot price. Yearly averages are used. After 2012, a spot price equals to 60 €/MWh is assumed.
Portugal	From 2000 to 2006 regulated tariffs are integrated in RoI. After 2006 yearly average spot prices are used, from the OMEL (Operador del mercado Energéticos). Then after 2012, an assumption of 50 €/MWh is made.
Spain	Since 2000 the OMEL communicates price data. Due to the strong convergence between Spanish and Portuguese markets, the same assumption is made about the future spot price of electricity.

Table 2.B.3: Data and assumptions on national electricity prices.

2.B.6 Metals weights and price

In this paper, it is assumed for simplicity that metals weights are constant over time. For calibration, the values we choose correspond to the average shares of metals for four types of wind turbines presented on Table 2.B.4.

	Steel	Iron/Cast Iron	Copper	Aluminium
Vestas V82	70	13	1	1
Gamesa G8X	74	15	2	0
Vestas V80	81	8	1	1
Vestas V112	66	18	1	1
Weights	72.75	13.5	1.25	0.75

Table 2.B.4: Metals weights, from Bolinger and Wiser, 2012, (18), (in % of turbines' masses).

2.C Appendix C: Evolution of the demand-pull schemes in the six European countries

[7] The sources for the Denmark are (215), (155), (124) and (221).

[8] According to the Royal Decree 2818/1998, the FiT is guaranteed for five years. However, it contains a provision guarantying unlimited availability of premiums and therefore, indirectly, automatic renewal of purchase contracts (Dinica, 2002, (177)). A survey conducted among 40 renewable energy producers demonstrated the minor role of the uncertainty on purchase contracts renewal (Dinica, 2002, (177)).

[9] The Average Electricity Tariff (AET) reflects the overall average cost of the electricity system. The level of the AET is decided each year by the government, values can be found in national reports on Spain (215).

[10] Royal Decree 2818/1998 gives the choice to producers between a FiT and a FiP. Since 'an overwhelming majority of RES plant owners chose the market-based price option', according to Dinica, 2002, (177), only the premium option is considered for the profitability variations computing.

[11] To compute profitability variations, the premium option is retained since '90% of wind producers have opted for the FIP-support' according to Ragwitz et al., 2012 (225).

[12] Cap and floor prices are indexed on the electricity retail price. In 2008, the values were 73.6 €/MWh and 87.8 €/MWh.

[13] According to the Royal Decree 1614/2010.

	Denmark[7] (1985-2012)	France (2001-2012)	Italy (2000-2012)
FIT	Phase 1 (1985-1990) 85% of the Local Retail Price (LRP), taxes excluded Phase 2 (1991-1999) 85% of the Local Retail Price (LRP), plus 36 €/MWh Phase 3 (2000-2002) 58 €/MWh for the first 22,000 full load hours. Then, a premium of 13 €/MWh is given (lifetime, total payment capped to 48 €/MWh)	Phase 1 (2001-2005) 83.8 €/MWh for the first 5 years, then from 30.5 to 83.8€/MWh for 10 years depending on the site productivity Phase 2 (2006-2012) 82 €/MWh for the first ten years, then from 28 to 82 €/MWh for 10 years (depending on site productivity)	Phase 1 (2000-2001) 100 €/MWh for 8 years, then 50 €/MWh (lifetime).Then, for cohort of 2001 the payment is 124 €/MWh for 8 years, then 69 €/MWh (lifetime)
FIP	Phase 4 (2003-2007) Premium of 13 €/MWh (lifetime, total capped to 48 €/MWh) Phase 5 (2008-2012) 34 €/MWh for the first 22,000 full load hours, then 3 €/MWh (lifetime)		
TGC			Phase 2 (2002-2005) Electricity price, plus the certificate price (for 8 years) Phase 3 (2006-2012) Support period increases from 8 to 12 years

Table 2.C.1: Instruments of support to onshore wind.

	Spain (2000-2012)	Portugal (2000-2012)	Germany (2000-2012)
FIT	Phase 1 (2000-2003) 62.6 €/MWh for 5 years[8] yearly adjusted depending on electricity price. Phase 2 (2004-2006) Phase 3 (2005-2012) AET[9] for 15 years, then 80% lifetime, Phase 3 (2007-2012) Tariffs are indexed on the retail price and guaranteed for 20 years. In 2008, the payment was 75.6 €/MWh	Phase 1 (2000-2001) 60 €/MWh for the first 12 years Phase 2 (2002-2004) 82 €/MWh for 20 years decreases annually by 76 €/MWh for 15 years, reduced to 74 €/MWh after 2007	Phase 1 (2000-2008) 91 €/MWh for 5 years. For the following 15 years the payment is adjusted depending on the site productivity. After 2002 the payment 1.5%. After 2004, it becomes 86 €/MWh for 20 years with an annual decrease of 2% Phase 2 (2009-2012) The payment is 92 €/MWh with an annual decrease of 1%. As in the first phase, producers receive the full payment during 5 years, it is then adjusted for the remaining 15 years
FIP	Phase 1[10] (2000-2003) 28.8 €/MWh for 5 years added to the AET Phase 2 (2004-2006) A premium equals to 40% of the AET, plus 10% if production is sold on the market Phase 3[11] (2007-2012) A premium of 30.2 €/MWh indexed on the electricity price. A cap on the total payment is introduced[12]. In 2011 the premium is reduced by 35% [13].		

Table 2.C.2: Instruments of support to onshore wind.

Chapter 3

Measuring innovation with patent data: an application to low-carbon energy technologies

3.1 Introduction

In 2010, the energy supply sector was responsible for 46% of energy-related greenhouse gas emissions (GHG) (IPCC, 2014, (219)). In order to achieve a reduction of GHG emissions consistent with a limitation of the planetary global warming to 2 degrees Celsius, a deep transformation of energy systems is required, with additional policies aiming at reducing the demand for energy. To decarbonise energy mixes, fossil technologies must be progressively phased out, as attested by the increase from approximately 30% in 2010 to more than 80% by 2050 of the share of low-carbon electricity supply in stringent mitigation scenarios (IPPC, 2014, (219)). For that purpose, several technological options exist, e.g. nuclear power, renewable energies or Carbon Capture and Storage (CCS). Except for the first one, these are not yet developed at a large scale. To remedy this, innovation is expected to improve the attractiveness of these technologies in comparison with fossil ones. To this end, environmental and technology policies should be jointly implemented to foster low-carbon innovation. As stated by the IPCC, "Technology support policies have promoted substantial innovation and diffusion of new technologies, but the cost-effectiveness of such policies is often difficult to assess" (IPCC, 2014, (220)). A robust measure of innovation in Low-Carbon Energy Technologies (LCETs) is a prerequisite for such an assessment. This is the subject of the article.

Two approaches are generally considered to measure innovation in particular technology fields: input-based measure built using R&D expenses data, and output-based measure that relies on patent data (Jaffe and Palmer, 1997, (76)). The first option accounts for the efforts made to foster innovation whereas the second one measures their results. As our aim is to quantify the effective knowledge accumulated in LCETs, patent data is preferred. Patents have been extensively used in the empirical literature on innovation. The count of patents was initially considered as a satisfactory measure of innovation (Scherer, 1965, (151)). However, this approach suffers from a major drawback as the distribution of the value of patented inventions is positively and highly skewed (Schankerman and Pakes, 1986, (150)). To take into account the heterogeneity of patented inventions, researchers have considered several indicators of the patent quality, such as the number of citations a patent receives after its publication, the number of citations made to other patents or the number of patent offices in which an invention is protected. Numerous articles have shown that these metrics are correlated with the economic value or the patent quality. In these studies, the value of a patent is generally either captured by: (1) surveying patent-owners or inventors about their valuation of the patented inventions (Harhoff et al., 1999, (67); Harhoff et al., 2002, (68)), (2) considering the decision of patent-owners to pay a renewal fee to extent patent duration (Schankerman and Pakes, 1986, (150); Harhoff and Wagner, 2009, (69)) , or (3) analyzing financial information such as the stock market or the profits of innovative firms (Lerner, 2004, (106) ; Hall et al., 2005, (65)). Although the links between patent metrics and the quality of protected inventions are well established, the relationship may be noisy when a single metric is used (Harhoff et al., 1999, (67)). In order to improve the accuracy of the measure of patent quality, Lanjouw and Schankerman propose a composite index built with several metrics (2004, (100)). The quality index accounts for both the technological and value dimensions of the inventions and synthesizes information on the different metrics associated to a single invention. We follow this approach and estimate a quality index for a data set of 28,951 LCET-related inventions patented in seven countries over the period 1980-2010. In line with the results of Lanjouw and Schankerman (2004, (100)), we find that using several metrics reduces the variance of our measure of the quality by 52.48%. Hence, based on the quality index, a more robust measure of innovation can be provided. Our quality index is used to compute the accumulated stock of knowledge in LCETs.

we discuss the relative roles of technologies and countries in the accumulation of knowledge over the period 1980-2010. Although our approach is mainly descriptive, several insights emerge. First, there are marked differences in the dynamics of patent quality between technologies. Older technologies such as nuclear, solar thermal or geothermal energy, have seen the average quality of their inventions decrease or stagnate. On the contrary, the average quality of inventions related to more recent technologies (e.g. solar PV power or wind power) have increased. Second, the potential of nuclear technology to reach high quality inventions has decreased over time. R&D investments in nuclear technology are thus on average, of lower values and have a lower chance to reach a higher quality. The fact that the number of patents is strongly correlated with R&D expenses suggests the existence of diminishing returns. Considering wind power and solar PV technologies we conclude that their potential for high value inventions have been higher during 2001-2010, compared to 1980-2000. Third, we investigate how innovation reacts to demand-pull and supply-push forces and compute two index that capture their intensities. Considering the case of wind power technology we compare the balance between the two approaches. Our results suggest that there is a strong complementarity between demand-pull and supply-push.

The paper is organized as follows: Subsection 3.2.1 identifies several needs in the modeling literature that a measure of innovation could fulfill. Subsection 3.2.2 reviews the empirical literature on innovation that uses patent data to measure innovation and Subsection 3.2.3 emphasizes the body pertaining to environmental economics. Subsection 3.3.1 presents the LFM used to estimate the quality index. Subsection 3.3.2 presents the data set. Subsection 3.3.3 examines the results of our estimates. Subsection 3.4.1 discusses the stock of accumulated knowledge in LCETs over the period 1980-2010 and examine the relative shares of technologies and countries in knowledge production. Subsections 3.4.2 and 3.4.3 conduct cross-technologies and cross-countries comparisons and provide for several insights. Section 3.5 concludes .

3.2 Measuring knowledge with patent data

3.2.1 The low-carbon innovation

Consistent with the hopes governments are placing in innovation to be a part of the solution to climate change (Article 10 of the Paris Agreement), efforts have been undertaken to enhance the representation of technological change in economic models. A body of the literature proposes an endogenous formulation of technical change based on the macro models of induced technological change (Löschel, 2002, (110)). An early contribution from Goulder and Mathai uses a partial equilibrium model where the stock of knowledge accumulated by a firm lowers its abatement cost (Goulder and Mathai, 2000, (58)). They assume that the stock of knowledge increases with the cumulative R&D expenditures directed toward the abatement technology. In the same vein, Nordhaus modifies the DICE model, renamed the R&DICE model, in which R&D expenditures improve the energy-efficiency of the energy sector (Nordhaus, 2002, (188)). The RICE model of integrated assessment, a variant of the DICE model, is modified to investigate how the knowledge stock affects the emission-output ratio (Buonanno et al., 2003, (22)). These works follow a top-down approach and provide for a theoretically consistent representation of the economy as a whole. These models however offer a poor level of details of the technological structure of the energy sector (Löschel, 2002, (110)). Bottom-up models answer this critic but are generally unable to take into account macroeconomic feedback. Hence, they may miss important crowding-out effects that result from the redirection of R&D investments toward environmental technologies. Berglund et al. discuss the introduction of learning in bottom-up energy models and its benefits (Berglund et al., 2006, (13)). They emphasize recent applications of the concept of learning that take into account learning-by-searching and its impact on technological change. To do so, modelers generally use two-factor-learning curves. Learning curves have been extensively used in bottom-up energy models. Learning occurred through one factor in the first versions of learning curve: the cumulative quantity of produced output. It is assumed to reduce the production cost by a constant fraction each time the cumulative output is doubling (learning-by-doing assumption). The origins of this hypothesis date back to the work of Wright (1936, (169)). He analyzes the production of airframe and observes that for each doubling of the cumulative production, the number of hours of direct labor by unity decreases by a constant share. A major step has been taken by including a second factor explaining cost decrease: learning-by-searching. Kouvaritakis et al. depart from the usual one-factor-learning curve and include the role of R&D activities (Kouvaritakis et al. 2000, (94)). They approximate the level of available technical knowledge by the cumulative R&D expenditures. They are included in a two-factor-learning curve. These authors implement this specification in the POLES model and investigate the effects of including learning-by-searching. However, they underline the difficulties encountered with data availability and regret having only short time series to estimate the learning rates. Criqui et al. also use the POLES model to investigate the relative roles of learning-by-doing and learning-by-searching in different scenario of GHG mitigation policies (Criqui et al., 2014, (32)).

In the empirical literature, two-factor-learning curves were estimated for several renewable energy technologies. Klaassen et al. estimate a two-factor-learning curve that explains the reductions of wind turbines production cost by the cumulative installed capacity of wind power and a R&D-based measure of knowledge stock (Klaassen et al., 2005, (90)). Jamasb estimates learning-by-doing and learning-by-searching rates for four stages of development of energy technologies. He concludes that the former is generally lower than the latter in the several stages of technological development (Jamasb, 2007, (79)). In his study, knowledge is approximated by the cumulative private and public R&D expenditures. Similarly, Kobos el al. estimate two-factor-learning curves for wind and solar PV technologies in the USA (Kobos et al., 2006, (92)). The knowledge stock is again constructed using cumulative R&D expenditures.

Constructing knowledge stocks with R&D expenses has been the most preferred option. However, the uncertain feature of research activities is left out when R&D expenses are used as a measure of the available knowledge. In this extent, patent data can be used to measure the effective creation of knowledge because patents are more closely related to the output of innovation activity whereas R&D activity is an input-based measure (Griliches, 1990, (61)) and that there are very few examples of major inventions that have not been patented (Dernis et al., 2001, (46)). Nonetheless, there is also an important proportion of low quality inventions that are patented. Popp et al. underline that there are strong levels of uncertainty about the returns to R&D and that they vary among technologies (Popp et al., 2013, (138)). The quality index developed in this article allows to distinguish inventions on the basis of their quality and to consider the distribution of the quality of inventions within a particular technological area in order to infer the uncertainty about the returns to inventions. Finally, there are other issues to deal with when using R&D expenditures: the role of the public sector can be overestimated as the data for the private sector is not very often available and for most countries it is aggregated and does not allow to focus on narrow technological fields such as low-carbon technologies (Dechezleprêtre et al., 2011, (37)).

3.2.2 Patent metrics as indicators of the quality of inventions

A patent confers to the applicant(s) the sole right, during a limited period of time, to exclude others from making, using or selling the patented invention. The protection is guaranteed only within the geographical area of the patent authority that delivers the patent. A patent family is defined as the set of patents granted by different patent authorities that protect the same invention. Since 1883, the Paris convention gives one year to patent owners from the priority date, i.e. the date at which the first application is filed in any office, to apply for patents in other Convention countries. After this period, the patentee does not benefit anymore from the priority right over her invention and other agents can apply for a protection for the same invention in the offices where it is not patented. The earliest patent of the family is called the priority filing and to avoid counting multiple patents for a single invention researchers usually consider only priority filings when they study patents from multiple patent authorities. Initially, the patent count was considered as an appropriate proxy of technological innovation (Scherer, 1965, (151)). This approach has proven to be limited as it gives to every patented inventions equal importance. This is a serious pitfall because empirical studies observe a highly skewed distribution of the value of protected inventions with a high share of low-value patents (Dernis et al., 2001, (46)). This heterogeneity calls to take into account the quality of inventions. Hence, researchers investigated several ways to provide for more realistic measures of innovation based on patent data (for an early survey of these studies, see Griliches, 1990, (61)). In this way, patent metrics were called to play an increasingly important role as they provide additional information on patented inventions. For a given invention, there are several metrics. We discuss the links between the quality of an invention and the most commonly used metrics.

As said above, an invention may be protected by a family of patents. Because protecting an invention with multiple patents is costly for the applicant who bears the additional cost of each applications, the size of the family partly reflects the invention expected value. This metric has been widely used in the literature. An early contribution by Putnam exploits data on patent families to estimate the distribution of patent quality across countries (Putnam, 1996). In the same vein, Harhoff et al. estimate the values of a set of patents by surveying patent holders and compare their results with several patent metrics among which family size (Harhoff et al., 2002, (68)). They conclude that it represents a good approximation of patent value. Nonetheless, family size is also influenced by other factors such as the strategy of the patentee with respect to its competitors or the peculiarities of the markets where the invention is protected.

Valuable information about patent quality is provided by citations. For a given patent, there are two types of citations. Citations made by a patent document to previous patents, as well as to non-patent literature when a broader definition is retained, are known as its *backward citations*. When innovators apply for a patent, they have to detail prior knowledge on which they have relied by citing older patent documents and scientific publications (OECD, 2009, (222)). These references are listed by applicant(s) and checked by examiners who can decide to remove or to add citations. Backward citations have been used to study knowledge spillovers (Jaffe et al., 1993, (77); Criscuolo and Verspagen, 2008, (33)) and have been found to be positively correlated to the patent value (Harhoff et al., 2002, (68)). The second type of citations are *forward citations*. These are the citations received by a patent after its publication. Counting the number of forward citations is an useful measure of quality as it indicates to what extent an invention contributes to future knowledge creation. Literature has emphasized a positive correlation between the number of forward citations received by a patent and its social value (Trajtenberg, 1990, (159)), or its private value when the analysis is coupled with renewal data (Schankerman and Pakes, 1986 (150); Harhoff and Wagner, 2009, (69)), survey of patent-holders (Harhoff et al., 1999, (67); Harhoff et al., 2002, (68)) or market stock valuation of the firms (Lerner, 2004, (106); Hall et al., 2005, (65)).

There are other metrics that contribute to our understanding of patent quality. For instance, the claims establish the scope of the protection granted by a patent. They represent the breadth of the temporary monopoly rights. This indicator is considered as a good proxy of an invention value as the patent fee generally depends on the number of claims. Thus, it reflects the applicant's willingness-to-pay for a protection and her expectations about the invention value. Several papers have considered the relation between patent claims and its value. Lanjouw and Schankerman show that patents with more claims are more likely to be involved in litigation which indicates that these are of higher value (Lanjouw and Schankerman, 2001, (99)). Another metric is the time lag between the application for a patent and, when successfully, its grant. It is considered as an indicator of patent quality as applicants try to accelerate the granting of a patent for their best inventions. Thus, they will bear an additional cost for providing a well-documented application and push forward the granting of the protection. This additional cost is expected to be justified by an invention of higher value. It is confirmed by Harhoff and Wagner who find evidence that application processing of most valuable patents are accelerated by applicants (Harhoff and Wagner, 2009, (69)). However, the positive correlation between this metric and the value of a patent is controversial. Indeed, Johnson and Popp (2003, (82)) find that the application process is longer for patents that are more cited. An explanation for these opposite results is given by Régibeau and Rockett (2010, (143)) who take into account the position of the patent in the innovation cycle when studying the relation between the application process length and the patent quality. They confirm the result of Harhoff and Wagner (2009, (69)) by finding a positive relation between these two features. Their paper enlightens the importance of having a detailed technological classification when investigating the length of granting applications. The technological scope of a patent has also been used as a measure of its quality. When a patent is granted it is classified following the International Patent Classification (IPC) depending on the function(s) of the invention or its field(s) of application (OECD, 2009, (222)). Hence, the number of technological classes has been considered as a good proxy of the patent scope and suspected to be representative of its quality. A first study by Lerner finds a positive correlation between the technological scope and the market value of a patent in the sector of biotechnology (Lerner, 2004, (106)). However, the link between this metric and the value of a patent remains questionable as it is refuted by several studies (Lanjouw and Schankerman, 1997, (98); Harhoff et al., 2002, (68)).

Over time, the empirical literature has emphasized that if the quality of a patent is unobservable by essence, metrics provide for different viewing angles from which researchers can partly capture it. Starting from this idea, a significant step in the measure of innovation using patent data has been made by Lanjouw and Schankerman (2004, (100)). They build a composite index of the quality of a patent. It is called 'composite' because it takes into account the information on the quality embodied in the different metrics of a patent document. The *quality* index represents both the technological and the economic dimensions of the invention. In their study, the quality of a patent corresponds to an unobservable factor that commonly influences the four metrics they consider (forward citations, backward citations, number of claims and family size). We use the same method to estimate the quality of inventions in LCETs for seven countries patented during 1980-2010. To our best knowledge, the only other studies that implement a LFM to estimate patents quality are Squicciarini et al., 2013, (157) and Dumont, 2014, (47).

3.2.3 Patent data and environmental technologies

In the field of environmental economics patent data has attracted an increasing attention over these last years. In this subsection we present a short review of the literature that uses patent data to study environmental technologies. An early study on environmental technologies has been realized by Lanjouw and Mody who estimate the international diffusion of environmental technologies using patent data (Lanjouw and Mody, 1996, (97)). They attempt to analyze how environmental innovation reacts to regulation and to do so they use pollution abatement expenditures as indicators of the effective demand for pollution control. They conclude that regulation and innovation are positively correlated. In order to measure environmental innovation they compute the share of environmental-related patents in the total amount of patents for 17 countries. Another early attempt to understand environmental innovation has been performed by Jaffe and Palmer who estimate the impact of abatement cost on two measures of innovation: R&D expenditures and patent counts (Jaffe and Palmer, 1997, (76)). Their results indicate that these two measures do not identically react to higher lagged abatement cost; the impact is strong and positive for R&D expenditures but little evidence is found about the link with the number of patents.

However, they focus on the impact of environmental regulation on the overall innovation as they use the total number of granted patents and the total amount of R&D expenditures. Brunnermeier and Cohen reduce the scope to strictly environment-related innovation and investigate how US manufacturing firms' abatement expenditures influence the amount of successful environmental patents (Brunnermeier and Cohen, 2003, (21)). They find a significant positive relationship between the two variables although they recognize the limits of a simple count of patents due to the asymmetric distribution of their quality.

The count of environmental patents generally remains the privileged way to measure environmental innovation. Haščič et al. use patent counts to question the theoretical assertion according to which a greater flexibility of policy instruments leads to more innovation and find that it is empirically supported (Haščič et al., 2009, (70)). Similar approaches, based on patent counts, are adopted to measure innovation by Bointner (2014, (17)), Noailly and Smeets (2015, (128)) and Lindman and Söherholm (2015, (109)). In order to avoid the pitfalls of counting patents, low value patents can be excluded to reduce the heterogeneity of inventions quality. In this vein, Johnstone et al. examine the effects on innovation of several policy instruments based on a panel of patents filed in 25 countries over the period 1978-2003 (Johnstone et al., 2010, (81)). They consider the patents filed at the European Patent Office (EPO) to ensure that the protected inventions meet a minimum level of quality that justify the higher patent fee paid at the European level. The bias of the count is reduced but the heterogeneity of the inventions in terms of quality remains above the minimum threshold of quality that implies the higher cost of an EPO application. A similar approach is chosen by Aghion et al. ((2)). In order to overcome the problem of low-value patents, only *triadic* inventions are included in their data set. Triadic inventions are inventions protected at the three main patent offices: the Japanese Patent Office (JPO), the EPO and the United States Patent and Trademark Office (USPTO). Due to the higher cost of filing a patent in these three offices, counting only triadic patents excludes less valuable inventions. The authors consider several alternatives to test for the robustness of their results by counting only *biadic* patents (filed at the EPO and the USPTO) and counting patents weighted by the number of forward citations they have received. Their results are robust to the types of count. An assessment of the impact of the European Union Emission Trading Scheme (EU ETS) on technological change is conducted by Calel and Dechezleprêtre (2016, (23)). The causal impact of the EU ETS on innovation is estimated by considering a sample of 5,500 EU ETS firms in 18 countries. Technological change is measured with EPO patents in order to avoid counting low value inventions. Two options are considered by the authors to test the robustness of their results: 1/ a count of patents weighted by the number of forward citations; 2/ a count of patents weighted by the size of their families. They conclude that approximately 1% of the increase of the innovative activity in environmental technologies in the European Union can be attributed to the EU ETS. Popp summarizes several lessons about environmental technologies drawn from his empirical work with patent data (Popp 2005, (136)). Among other results, he finds that technology fields experience diminishing returns over time when innovation is measured by a count of patents weighted by the number of citations they receive after their publication (i.e. forward citations).

In this paper, we follow the approach proposed by Lanjouw and Schankerman (2004, (100)) to estimate inventions quality. We build knowledge stocks for each country/technology field and investigate how the quality index may be used by researchers. To our best knowledge, this the first time this method is applied to environmental technologies.

3.3 A quality index for low-carbon energy technologies

3.3.1 The latent factor model (LFM)

For each invention of our data set we observe a vector of p metrics. The metrics included in the model are defined in 3.3.2.5. We assume they follow a multivariate log-normal distribution of dimension p with mean $\mu + \alpha Z$ and non-singular covariance matrix Σ. The first term of the mean, μ, is a $p \times 1$ vector of constants. The second term expresses the effects of the k dummy variables contained in Z, with α is a $p \times k$ matrix of coefficients. Dummy variables are included in the model to control for the effects of cohorts, technologies and delivering offices. For instance, the technological class of an invention may influence the size of the scope, regardless of the quality; more recent cohorts of inventions are susceptible to cite more than older ones due to the advances in information ad communication technology; and some offices ask for a more detailed patent's bibliography that increases the number of backward citations. We log-transform the patent metrics[1] and obtain what is called in the LFM terminology the manifest variables. The first ingredient of the model is simply the distribution of the set of manifest variables X:

$$X \sim N_p(\mu + \alpha Z, \Sigma). \tag{3.1}$$

[1] 1 is added to citations metrics as they can take null values.

Based on the empirical studies reviewed in subsection 3.2.2, we assume that the p metrics of each patent are influenced by a common factor representing the quality of the patented invention. As stated by Lanjouw and Schankerman, the common factor represents quality as no other characteristic is suspected to jointly influence the values of all the patent metrics (Lanjouw and Schankerman, 2004, (100)). Even if we do not use exactly the same set of manifest variables their demonstration applies to our study. As the quality of a patent cannot be observed we assume that it follows a log-normal distribution with zero mean and unit variance. The log-normal distribution is a good candidate that reflects the distribution asymmetry of patents quality. It is reasonable to consider that an invention quality and its reward are similarly distributed. Scherer et al. test several sets of data and find that a log-normal distribution provides for the best fit of the distribution of the rewards realized on technological innovations (Scherer et al. 2000, (152)). The quality index is log-transformed to be normally distributed. Once the model is estimated, the values of the log-transformed quality index are transformed back using the reciprocal. It should be noted that there is no loss of generality from assuming a zero mean and an unit variance, the key part of the assumption being about the type of distribution (Bartholomew et al. 2011, (174)). The second ingredient of the model is the distribution of the log-transformed index of quality denoted Y

$$Y \sim N(0,1). \tag{3.2}$$

Using basic results of the distribution theory we can derive the model we want to estimate by computing the distribution of the X conditional to the Y. It is written $X|Y \sim N(\mu + \alpha Z + \Lambda Y, \Sigma - \Lambda\Lambda')$, or equivalently

$$X = \mu + \alpha Z + \Lambda Y + e, \tag{3.3}$$

where Λ is $p \times 1$ vector of factor loadings and e is a normally distributed error term with zero mean and variance matrix $\Psi = \Sigma - \Lambda\Lambda'$. The vector of factor loadings Λ is the covariance between the manifest variables X and the latent factor Y. Similarly, we can write the distribution of the Y conditional to the X that allows us to make inferences about the value of Y on the basis of the observed variables. The posterior distribution of the Y is

$$Y|X \sim N\big(\Lambda(\Lambda\Lambda' + \Psi)^{-1}(X - \mu - \alpha Z), (\Lambda'\Psi^{-1}\Lambda + 1)^{-1}\big). \tag{3.4}$$

The mean term generates the most probable value of the latent factor given the observed metrics and the variance term indicates how precise is the inference. An interesting property of the model is that the variance of each manifest variable can be divided into two terms

$$var(X_j) = \Lambda\Lambda' + \psi_j, \quad (j = 1, 2, ..., p). \tag{3.5}$$

The first term of (3.5) represents **communality**, i.e. the parts of the variances accounted for by the common factor. The second term is the variance specific to the jth metric. This property will allow us to measure to what extent a metric is an accurate measure of the quality of a patent. The model is estimated by maximum likelihood using the E-M algorithm. The E-M is a powerful tool for estimating a model by maximum likelihood with missing data. It has been generalized by Dempster et al. (1977, (43)). We present here the successive steps of the algorithm and we provide for a complete description in Appendix 3.A. The first application of the E-M algorithm to latent factor modeling has been proposed by Rubin and Thayer (1982, (147)). We start by writing the joint log-likelihood function of the manifest variables and the latent factor. Its score functions are derived. Then, as its name indicates, the E-M proceeds in two steps:

(i) Expectation step: the expected values of the score functions, conditional to x_i where $i = 1, ..., p$, are computed for a given set of parameters taken from the previous iteration of the algorithm.

(ii) Maximization step: the score functions are set to zero to maximize the joint log-likelihood. They are solved and a new set of parameters is deduced.

For the next iteration, the new set of parameters estimates is integrated into the score functions and the operation is repeated. The convergence toward a global maximum is not guaranteed but Dempster et al. (1977, (43)) demonstrate that the marginal log-likelihood of the Xs is non-decreasing on each iteration. In order to control for the robustness of our results with respect to the initial conditions we proceed as follows. We estimate by maximum likelihood the model (3.1) and we use the results to initialize μ, α and Σ. For Λ we choose arbitrary non-zeroes components. A first estimation with the E-M is conducted. Then, we change the initial conditions with several sets of values and check whether the estimates vary or not. For each combination of initial values, the algorithm runs until a maximum is found. We find that the estimators are not sensitive to the initial conditions. The results of the estimation are presented in subsection 3.3.3.

3.3.2 Data presentation

3.3.2.1 The PATSTAT database

We use the data from the Worldwide Patent Statistical Database (PATSTAT) created and maintained by the European Patent Office (EPO). PATSTAT contains almost 75 millions of patent documents. Our dataset is extracted from the online 2015 Autumn version of PATSTAT. To avoid counting multiple patents that protect the same invention we extract patent families and their corresponding metrics. These are defined later in this subsection. The PATSTAT database proposes two definitions of a patent family: DOCDB family and INPADOC family. We use the former definition of family as the latter represents an extended definition of the family concept. In fact, an INPADOC family might covers several DOCDB families linked by prior applications, and also by technical links enlighten by patents examiners. The definition family we use, also called the DOCDB **simple** family, considers patents as belonging to the same family when they claim exactly the same prior application. Nonetheless, there are some exceptions to this general rule as the EPO reserves the right to classify an application that is not a priority filing into a simple family (PATSTAT Data Catalog, p.127, 2009, (224)). Hence, it is possible that several patent families have the same prior applications. In our initial dataset, we find that 12.7% of the families share the same priority filing with another family (or more). This is a problem as the protected inventions will be counted several times[2]. To address this issue, when multiple families claim the same priority filing we retain the largest one and exclude the other from the data set. Our final data set comprises 28,951 patents families, or inventions, of seven nationalities belonging to 15 different technological fields and granted between 1980 and 2010. Only families with a granted priority filing are extracted as we let apart the applications that did not succeed in obtaining a patent right. We detail further how nationality, technological classification and year of count are determined before giving precise definitions of the patent metrics included in the model. The distribution of the inventions between technologies is given in Table 3.1.

3.3.2.2 Classification of inventions per technology

The technological classification of inventions is of critical importance when one works with patent data. This is particularly true when the focus is on narrow technological fields such as

[2] For instance, the application identified in Patstat as 315604701 is the prior application of 16 different DOCDB families. This (extreme) example illustrates the importance of a data treatment aiming at suppressing patent families claiming the same prior filings.

Bio-fuels 1019	CCS 1065	Sea energy 655	Energy storage 3955
Fuel from waste 1186	Geothermal energy 394	Hydro energy 1243	Hydrogen 1416
Nuclear 3656	PV energy 3748	Smart grids 1567	Solar thermal 4050
Wind energy 3162	Combustion efficiency 630	Combustion mitigation 1205	Total 28951

Table 3.1: Number of inventions per technology (all countries, 1980-2010).

LCETs. Indeed, there are risks to: (i) extract inventions that do not pertain to the targeted technological class (ii) exclude relevant inventions by narrowing too much the technological scope. In PATSTAT, each patent document is referenced following two classifications: the International Patent Classification (IPC) and the Cooperative Patent Classification (CPC). From now, the IPC has been preferred by researchers working on environmental technologies and several papers provide for the classification codes that should be used and explain how to combine them to extract the relevant patents depending on the targeted technological fields (see Johnstone et al., 2010, (81); Lanzi et al. 2011, (102); Popp et al., 2011, (137) and Dechezleprêtre et al., 2011, (37)). Patents related to LCETs can be found in many areas of technology and it increases the risks evoked above. According to Veefkind et al., using the IPC classification generally creates too much 'noise' and the extracted data sets are frequently incomplete (Veefkind et al., 2012, (164)). The EPO has completed in December 2015 the CPC system that now covers environmental technologies to address this issue. This new scheme improves the classification quality by including technologies that were difficult to extract in the IPC. Hence, it strongly enhances the quality of our data. For a presentation of the CPC scheme of classification of environmental technologies and its advantages, see Veefkind et al. (2012, (164)). The technologies we analyze and the corresponding CPC codes are detailed in Table 3.2. To our best knowledge, only few papers have already use this classification in the literature (Calel and Dechezleprêtre, 2016, (23); Haščič and Migotto, 2015, (71)).

3.3.2.3 The cohort of an invention

As we aim to estimate the time path of innovation we must determine a year at which the newly created knowledge embodied in a patented invention adds to the existing stock. For each invention (i.e. patent family), several options are possible: to choose the year at which the priority filing is filed, or the year at which it is published. The first possibility is considered as being the closest to the invention date and the second one as being the date

Technology	Description	CPC codes
Biofuels	Combined Heat and Power turbines for biofeed, gas turbines for biofeed, bio-diesel, bio-pyrolysis, torrefaction of biomass, bio-ethanol.	Y02E 50/1
CCS	Capture by biological separation, chemical separation, by absorption, by adsorption. Subterranean or submarine CO_2 storage.	Y02C 10/
Sea Energy	Oscillating water column, ocean thermal energy conversion, salinity gradient, wave energy.	Y02E 10/3
Energy Storage	Battery technologies, ultracapacitors, supercapacitors, pressurized fluid storage, mechanical energy storage, pumped storage.	Y02E 60/1
Fuel From Waste	Synthesis of alcohol or diesel from waste, production of methane (fermentation, landfill gas).	Y02E 50/3
Geothermal Energy	Earth coil heat exchangers, systems injecting medium into ground or into a closed well. Systems exchanging fluids in pipes.	Y02E 10/1
Hydro Energy	Conventional (dams, turbines or waterwheels), tidal stream or damless hydropower.	Y02E 10/2
Hydrogen	Hydrogen storage, distribution, production from non-carbon sources.	Y02E 60/3
Nuclear	Fusion reactors (Magnetic Plasma Confinement (MPC), inertial plasma confinement), nuclear fission reactors (reactors, fuel, control of nuclear reactions).	Y02E 30/
PV Energy	PV systems with concentrators, materials technologies, power conversion electric or electronic aspects.	Y02E 10/5
Smart Grids	Systems integrating technologies related to power network operation, communication or information technologies for improving the electrical power generation, transmission, distribution, management or usage.	Y04S
Solar Thermal	Tower concentrators, dish collectors, fresnel lenses, heat exchange systems, through concentrators, conversion into mechanical power.	Y02E 10/4
Wind Power	Wind turbines (rotation axis in wind direction and perpendicular to the wind direction), power conversion electric or electronic aspects.	Y02E 10/7
Combustion Efficiency	Heat utilization in combustion or incineration of waste, Combined Heat and Power generation, Combined Cycle Power Plant, Combined Cycle Gas Turbine.	Y02E 20/1
Combustion Mitigation	Direct (use of synair or reactants before or during combustion, segregation from fumes) and indirect(cold flame, oxyfuel and unmixed combustion) CO_2 mitigation, heat recovery other than air pre-heating.	Y02E 20/3

Table 3.2: Description of the technologies and their classification codes (CPC).

at which the knowledge embodied in the patent becomes publicly available (OECD, 2009, (222)). The second option is retained to measure the evolution of common knowledge in particular technology fields. Thus, a cohort of inventions brings together all the inventions that received their first patent the same year.

3.3.2.4 Nationality of inventions

Finally, we have to sort inventions depending on their nationality. There are two types of agents involved in patenting process: applicants and inventors. The nationality(ies) of applicant(s) represent(s) the ownership of the protected knowledge, independently of the location of research laboratories. Hence, the best option when one wants to measure the new knowledge discovered within a country is to sort inventions by inventors' country of residence (OECD, 2009, (222)).

If there are multiple inventors residing in different countries, a fractional count is applied (De Rassenfosse et al., 2014, (45)). For instance, when two Danish inventors and one French inventor have taken part in an invention we consider that two-thirds of the invention belong to Denmark and one-third to France. In some cases, the inventor's country of residence is not referenced in PATSTAT. By default we consider the priority office nationality as the inventors' nationality. There is only a minor risk of doing so for two reasons:

- when information on inventor's nationality is available, 96.3% of the inventions of our dataset are first protected in the office of the same nationality (share computed after excluding inventions first filed at the EPO).
- In the case the invention is first filed at the EPO (1.547 % of the inventions), the country of residence of inventors is available in almost every cases. For the few for which it is not, an online research on *Espacenet.com* provides for the nationality of inventors.

Our choice of the countries that are included in the study is motivated by the availability of information on metrics. In PATSTAT, a default value of variables when information is not available is zero[3]. Consequently there is a risk to include countries with low data coverages and to bias the analysis. Based on several extractions and after cautious examination of the data we choose to include France, the United States of America (USA), Spain, Germany, the United Kingdom (UK), Denmark and the Netherlands.

[3]For instance a vast majority of the patents filed at the SIPO, the Chinese patent authority, show zero backward citations. Obviously, it does not mean that Chinese inventions do not rely on past knowledge but rather that PATSTAT does not contain the information.

3.3.2.5 Invention metrics

We come now to patent metrics. As discussed above, literature has emphasized the links between the quality of a patent and its metrics. In this study we run several estimates of the LFM on the basis of:

- The size of the patent family (family size). As new patents may be added to the priority filing's family after its publication, this metric might increase over time. Hence, we consider as belonging to an unique family the patents published during the five years that follow the priority filing's publication.
- The number of citations received by a priority filing before five years have elapsed after its publication (forward citations). In order to suppress the bias of the family size, we only count the citations made by patents from other families.
- The number of citations made to other patent families (backward citations).
- The number of IPC classes of the priority filing (technological scope)[4].
- the normalized difference between the granting date and the application date of the priority filing (grant lag). The metric is normalized because the conditions of examination vary depending on granting authorities and years of examination. It is divided by the average examination time took for patents delivered by the same office to the same cohort and technological class .

These are the metrics containing information about the quality of an invention. In the next subsection we detail how the optimal set of metrics is chosen.

3.3.3 Metrics choice and estimation results

3.3.3.1 Number of metrics included in the LFM

Choosing what metrics to include in the model is of major importance. Indeed, depending on the set of metrics considered the correlation structure of the data could reveal the existence of more than one latent factor. In our case, it would be problematic to conclude

[4]Contrary to the Y02 scheme that focuses on the use which might be made from the invention, the IPC scheme provides for a more technologically-oriented system of classification and is closer to the technological scope of a patent.

that the optimal number of latent factors is larger than one as our aim is to capture an unique measure of quality. Hence, we choose the set of metrics that corresponds to a unique latent factor. We start by considering the largest set of available patent metrics (forward citations, backward citations, family size, normalized grant lag and technological scope) and search for the number of latent factors that are common to these variables. To do so we use the Kaiser-Guttman criterion. The principle is that the number of latent factors must be equal to the number of eigenvalues of the correlation matrix greater than one. Including the five manifest variables, the criteria points to two latent factors. To solve this issue, we exclude each manifest variable from the data set and we question the number of latent factors within the five combinations. Computing the eigenvalues of the correlation matrix of each combination of normalized we find that the number of latent factor decreases from two to one when we exclude the grant lag, in the four other cases the criteria indicates two latent factors. It appears that the need for a second latent factor is generated by the inclusion of the grant lag.

Harhoff and Wagner (2009, (69)) show evidence that applicants accelerate examination processing when patents are valuable. Excluding the normalized grant lag from our set of manifest variables could be suspected to invalidate this result. This is not the case. Indeed, their study examines patents filed at the EPO whether or not these are priority filings. When computing the share of priority filings in the total amount of patents filed at the EPO we obtain that it is equal to 4.8%, all technological classes taken together. Hence, the study of Harhoff et al. refers almost exclusively to patents protecting inventions that were already filed in another office(s) before being granted by the EPO. Due to the 1883 Paris Convention, applicants have up to 12 months from the first filing to apply for subsequent applications in other offices. This limited time period has a positive effect on the incentive to accelerate the granting procedure. This incentive is further strengthened if the invention is of high value. In our case, the normalized grant lag may not respond to the same economic fundamentals as it measures the delay of examination of the first patent that protects the invention. Hence, the incentive to accelerate the process may be weaker and it explains why we exclude this metric from our set of manifest variables. Another study that finds a relationship between the grant lag and the value of a patent is Régibeau and Rockett (2010, (143)). The authors also use a data set of patents containing not only priority filings.

To conclude, we estimate a LFM with one latent factor to build an index measuring the quality of 28,951 patents granted between 1980 and 2010 to seven countries in fifteen LCETs. The manifest variables included in the model are the number of forward citations received

	Family size	Forward citations	Technological scope	Backward citations
μ_i	1.13	1.83	1.21	2.93
λ_i	0.25	0.17	0.16	0.45
ψ_i	0.17	0.55	0.17	0.37

Table 3.3: Estimated coefficients in the Latent Factor Model.

within five years from the publication date, the number of backward citations, the number of technological classes of the patent and the size of its family. We present below the estimation results.

3.3.3.2 Estimation results

The estimation results of the model 3.3 are presented in Table 3.3. The second row contains the factor loadings λ_i of the p metrics. Their variances are presented in the third row. The estimation of the modem with the E-M algorithm generates no heteroskedasticity. We test the existence of a common factor. As the previous subsection discusses the existence of more than one common latent factor, we must consider the case of no common factor. Considering that there is no common factor means that the observed variables are mutually independent. Under this hypothesis the estimator of Σ would be the diagonal elements of the data set covariance matrix. It is tested with a likelihood ratio test. The test statistic increases as the estimator of Σ diverges from the observed covariance matrix. In the particular case of zero common factor the test statistic reduces to $-nln|R|$ where R is the correlation matrix of X (Mardia et al., 1979, (185), pp. 267-268). The statistic follows a chi-square distribution with $p(p-1)/2$ degrees of freedom. The null hypothesis of zero common factor is rejected at the 1% level of confidence. We test the significance of parameters by conducting a sequence of likelihood ratio test of nested models. The principle is to test the significance of the difference between the maximized log-likelihoods of two competing models: M_0 and M_1. The former is a more restricted model setting parameters to a null vector, while the latter includes all the parameters. Under the null hypothesis the two models are equivalent and we conclude that the parameters that are not free in M_0 are not significant (Bentler and Bonett, 1980, (12)). The test statistic is $-2(L^*(M_0) - L^*(M_1))$, where $L^*(.)$ is the maximized log-likelihood of a model. The statistic test follows a chi-square distribution. The degrees of freedom are the number of parameters that are not free in M_0 compared to M_1. We test the significance of μ and find that it is highly significant at the 1% level. We question the relevancy of introducing dummies in the model. They take into account the effects of the technological class, the cohort and the office on the values taken by manifest

	Family size	Forward citations	Technological scope	Backward citations
Weights	0,68	0,14	0,42	0,58
Share of communality in the variance (%)	26.65	4.82	12.3	35.48

Table 3.4: Factor loadings and share of metrics' variances attributable to the common factor.

variables. We find that all the dummies of the model are statistically significant at the 1% level. Hence, they are maintained.

We now discuss the inverted relation between the observed variables and the common factor described by the model (3.4). The weights of manifest variables in the common factor are presented in Table 3.4. They are now demeaned to control for cohort, technology and office[5]. These weights represent how the metrics influence the level of the latent factor. We find that the two metrics with the larger weights are the size of the family and the number of backward citations. The small weights of forward citations is explained by several factors. First, we only consider the citations received by an invention within the five years after its publication. This truncation introduces a bias in the metric as high-quality inventions can be identify by other inventors after a longer period. Second, forward citation is a noisy indicator of quality. The essence of LFMs is to reduce dimensionality without loss of information. As explained in subsection 3.3.1, the two terms of equation (3.5) are the communality and the specific variance of each metric. The weights of communality in the total variance of the metrics are given in the second row of Table 3.4. They represent how much the variance of each metric is affected by the common factor. Hence the lower it is, the more noisy is a metric with respect to the common factor. We observe that forward citation is the metric with the smaller share of variance explained by commonality. The communality represents only 4.8% of forward citations variance whereas the size of the family and the count of backward citations have the highest shares with respectively 26.63% and 35.48% of their variances attributable to communality. Hence, once the specific variance of forward citations is deducted, there remains little information about the quality. When using only one metric to measure patent quality, one should consider the high variance of forward citations that is not linked to communality. This feature of forward citations metric has been already emphasized[6] by Harhoff et al. (1999, (67)). The small weight of forward

[5]To control for all the effects that are not linked to the quality of the patent, the new set of manifest variables is computed as $x_i - \mu - \alpha z_i$ for $i = 1, ..., n$.

[6]It can be illustrated by an example taken from their study. Based on a survey realized among patent owners, the authors estimate a model predicting that patents valued at \$ 100 million will receive 13.7 forward citations with a two standard error range from 1.2 to 156.

citations contrasts with Lanjouw and Schankerman (2004, (100)) who find that forward citations are the less noisy indicator among the four they consider in their model. In their study they log-transform the metrics they use and set to zero the observations that received no forward citations. They explain that their results are the same when excluding patents with no forward citations from their data set. Hence, their data treatment is equivalent to ignore non-cited inventions and may overestimate the influence of forward citations on quality.

We measure the gain of information from using simultaneously several patent metrics to capture quality. To do so, the percentage difference between the normalized latent factor variance and the conditional variance is computed. We find that it decreases by 52.48% when using our set of manifest variables. This result is in line with Lanjouw and Schankerman (2004, (100)) who find variance reductions of 47.6% and 53.5% in electronics and mechanical; the two technological classes they investigate that are the closer to LCETs. As explained at the beginning of subsection 3.3.1, the estimated values of the latent factor are exp-transformed in order to find back a log-normal distribution. Hence, inventions with a latent factor on the negative side of the normal distribution will have, after being transformed back, a weight lower than one and at the contrary inventions with a positive latent factor will have a quality index higher than one. This is an advantage as we want to emphasize the contrast between a simple count of inventions and a quality-weighted one.

3.4 A quality-adjusted measure of knowledge in low-carbon energy technologies

3.4.1 Knowledge stocks

On the basis of the observed metrics, a quality index is estimated for each invention of our data set. The annual inventions flows weighted by their quality indexes are represented on Figure 3.1, all technologies and countries taken together. As explained above a fractional count is applied so that we do not overestimate the 'share' of an invention belonging to one of our country. On Figure 3.1, the dashed line represents the annual average Brent crude oil spot prices, in $2014/bbl, taken from the BP statistical review of world energy 2015.

The similar shape of the two curves illustrates the response of LCET invention production to oil price and supports the assumption of price-induced innovation[7].

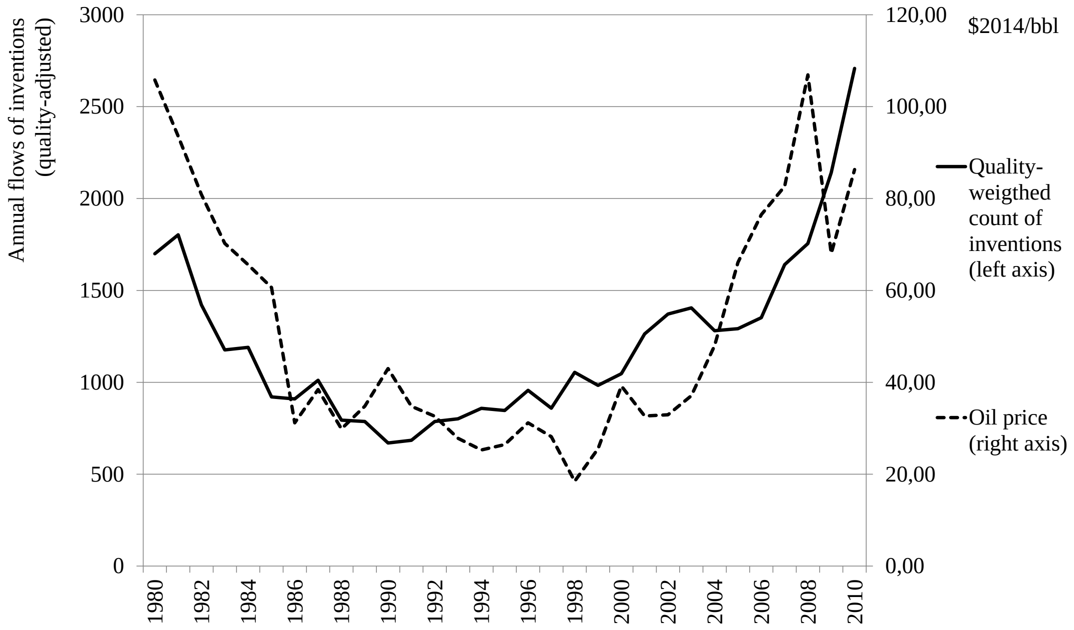

Figure 3.1: Quality-weighted flows of inventions, all countries and technologies taken together.

It is interesting to observe that the level of produced knowledge related to LCET reached in 1981 will not be achieved before 2008. In order to capture the cumulative feature of invention production we compute the stocks of knowledge accumulated in LCETs. The expression of the stock of knowledge KS_t^τ at time t in technology τ is

$$KS_t^\tau = (1-\delta)KS_{t-1}^\tau + Q_t^\tau \tag{3.6}$$

with Q_t^τ denoting the annual flows of quality-weighted inventions. Parameter δ is a depreciation rate that takes into account the depreciation of knowledge. Following Popp, a value of 10% is retained (Popp et al., 2013, (138); Boitner, 2014, (17)). For a discussion on the depreciation rate of knowledge in energy technologies, see Bointner (2014, (17)). The knowledge stocks are represented on Figure 3.2 all countries taken together and the country-specific knowledge stocks are given in Appendix 3.B. On each figure, a dashed line represents an alternative measure of knowledge stock (all technologies taken together) built

[7] The 'induced innovation' hypothesis has been first proposed by Sir John Hicks (Hicks, 1932, (183), pp 124-125). It states that technical change is directed by the relative prices of production factors. Innovators will find new production processes and products to substitute more expensive factors by cheaper ones. As fossil fuel price rises, innovation in energy low-carbon technologies should increase.

using only a fractional count of inventions, i.e. unweighted by their quality. The same depreciation rate is retained. The comparison between the upper frontier of the quality-weighted knowledge stock and the dashed line offers an illustration of the role of quality in the measure of knowledge dynamics.

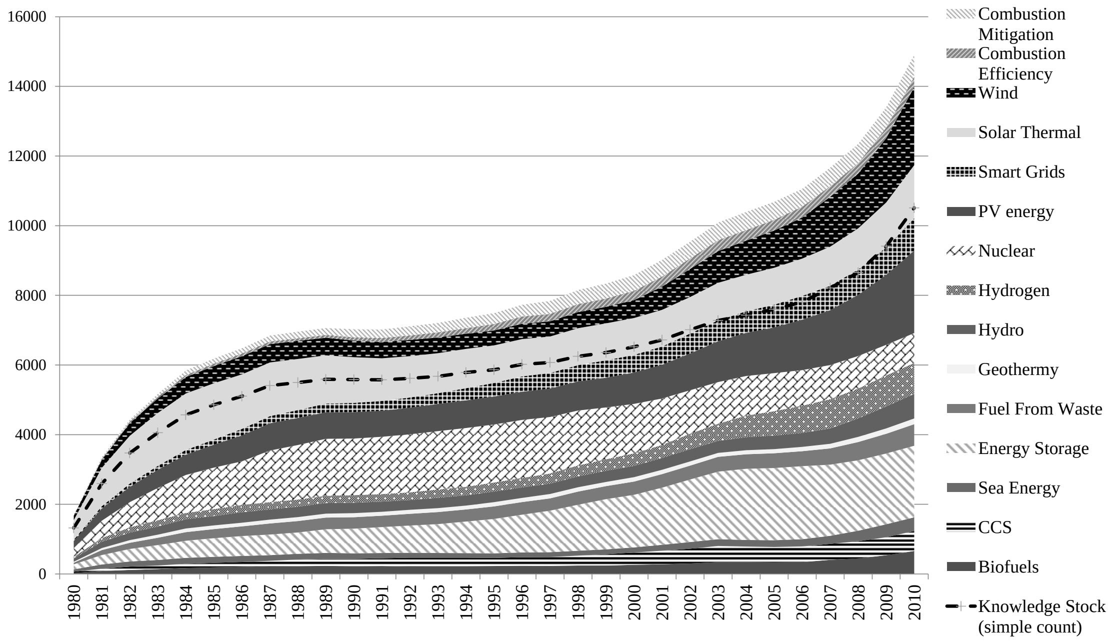

Figure 3.2: Quality-weighted stocks of knowledge, all countries taken together.

At the end of 2010, the three leading technologies are solar PV energy, wind power and energy storage. They represent 15.75%, 14.8% and 13.8% of the total stock of knowledge, respectively. They are followed by solar thermal power (10.40%), smart grid technology (6.3%),nuclear power (5.95%) and hydrogen (5.91%).

The USA have the larger share of the knowledge stock: at the end of 2010, 50.67% of it belong to this country. It is followed by Germany and France that possess 18.42% and 13.67% of the patented stock of knowledge, respectively. Smaller countries, despite lower innovative activities, present some peculiarities. Spain and the Netherlands represent 6.84% and 3.63% of the total knowledge stock in 2010. However, they have undertaken considerable efforts during the 2000s to foster LCET innovation as show the strong increases of their knowledge stocks during the last decade (see Figures 3.B.4 and 3.B.5 in Appendix 3.B).

We compute the ratio between the quality-weighted knowledge stock and the unweighted one and find that it is rather stable over time as it varies between 1.22 and 1.48. Hence, the value-added of the quality index is quite small compared to a measure based on a simple count when countries and technologies are all considered together. Nonetheless, a deeper analysis is carried out to compare the evolutions of invention production between technologies (subsection 3.4.2) and countries (subsection 3.4.3). The comparison of the quality of inventions between technologies, cohorts and countries is made possible by the introduction of dummy variables in the LFM, as explained above. Because the effects of these three features of an invention on the level of the patent metrics are neutralized the quality index can be compared across cohorts, countries and technologies. Our results put forward the advantages of a neutral measure of the quality of an invention.

3.4.2 Cross-technology comparison

3.4.2.1 Relative shares of technologies in the annual flows of knowledge

Over 1980-2010 the shares of technologies in the yearly flows of quality-weighted inventions have changed considerably. Their annual values are represented on Figure 3.3. To make the graph more readable, fuel from waste, geothermal energy, smart grids, CCS, bio-fuels, sea energy, hydro energy, combustion mitigation and combustion efficiency are isolated in the group called 'other technologies'. When necessary, additional information is given in the text.

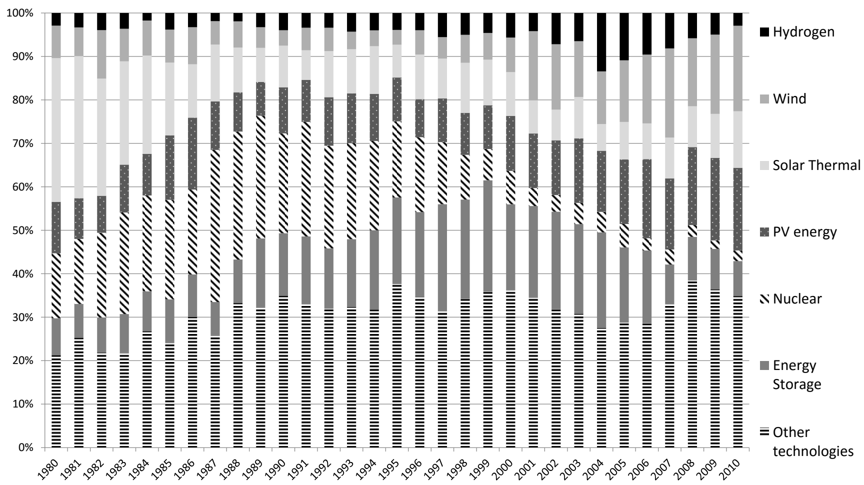

Figure 3.3: Technologies shares in the annual quality-weighted flows of inventions, 1980-2010.

Three groups of technologies distinguish themselves depending on how their shares in the overall quality-weighted count have evolved.

- The first group contains the technologies on which there has been much less emphasis over time: nuclear power and solar thermal power. Taken together, these two technologies represented 48% of the quality-weighted count of LCETs inventions in 1980. The share of solar thermal declined rapidly after 1980. However it has stabilized after 1990 and maintained an important role in the dynamics of newly created knowledge. Nuclear power share in the overall knowledge flow knew its maximum in 1987 and then has steadily decreased. Nuclear knowledge is almost exclusively driven by the USA, France and Germany that possess 55.22%, 23.34% and 18.48% of nuclear-related inventions. After the Chernobyl disaster in April 1986, there has been an important one-off increase in the US patenting activity in nuclear technology. This is much less marked for France and Germany. After 1987, the innovative activities of these three countries have decreased. The decrease of invention production is the strongest in Germany as the country has decided to phase out from nuclear after Chernobyl disaster. Indeed, between 1980 and 1987 the share of the German inventions in the total amount of quality-weighted nuclear inventions was 26.76% and decreased to 14.53% in 2010.

- A second group puts together technologies that took a growing share in the annual flow of knowledge related to LCETs. Unsurprisingly, this is the case of solar PV power and wind power - two LCETs that are expected to take the lion share in our future energy mixes. A complementary technology, energy storage, has also maintained an important place in the creation of new knowledge and has experienced a substantial increase of the production of inventions. It represented 8.45% of the knowledge stock in 1980 and has reached 25.62% in 1999. Nonetheless, during the 2000-2010 decade the share of energy storage in the knowledge stock has slowly decreased to 8.05% in 2010. More recently, new technological opportunities came up. Hydrogen has a growing share in the knowledge stock after 2000 despite the small number of commercial applications as an energy vector. In a less extent, this is also true for sea energy, hydro energy and bio-fuels.

- For the remaining technologies there have not been any major changes over time. Indeed, their shares in the total knowledge stock remain almost stable over the three decades. This is not surprising for older and/or niche technologies such as geothermic energy, fuel from waste and hydro energy (this class does not contains sea energy inventions). However, this is more surprising for smart grids and carbon capture and storage (CCS). Despite the major roles these two technologies have in the scenario of

GHG mitigation they do not seem to be a priority for innovative firms compared to the technologies of the second group.

Over the period 1980-2010, knowledge in LCET has been driven mostly by nuclear power, solar thermal, energy storage, solar PV and wind power. The two former have been progressively abandoned although the two latter have gained increased importance. To explain the substitutions between technologies we investigate further the dynamics of their quality.

3.4.2.2 Quality versus quantity of Low-Carbon Energy Technologies inventions

Two factors drive the importance of technologies in the overall knowledge: the quantity of inventions and their quality. What we are concerned with here is the additional information provided by quality. We have observed in subsection 3.4.1 that the ratio between the quality-weighted stock and the unweighted one has remained fairly stable. Although the average quality of inventions remained almost stable when all technologies are taken together, there have been major substitutions between technologies. The question arises whether technologies exhibit similar average level of quality or not. To this end, we compute the annual average level of quality in each technological field and represent the evolutions of the simple count of inventions versus the quality-weighted one. It is represented on Figure 3.4 for nuclear power. The evolutions of the two types of counts for the 14 other technologies are given in Appendix 3.C. We focus on nuclear technology as it is illustrative of a decoupling between the quality and the quantity of inventions.

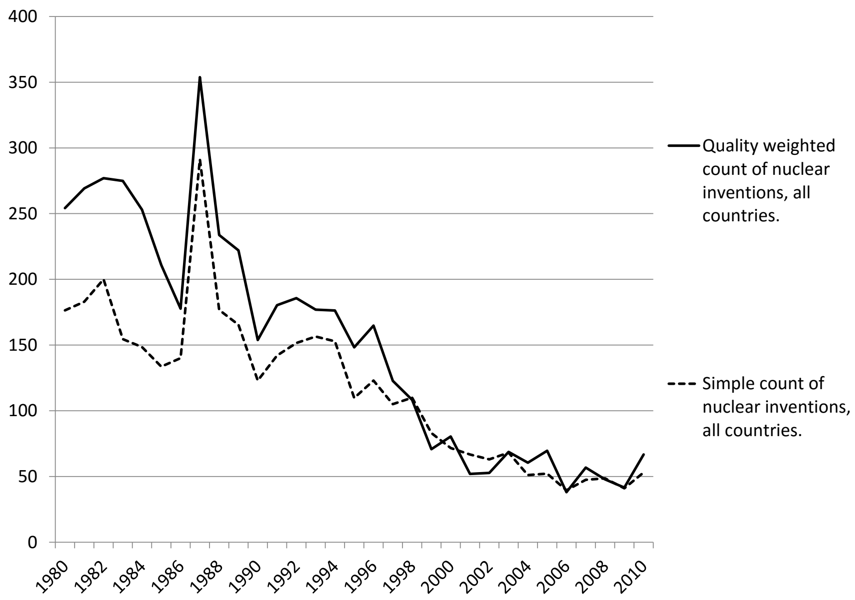

Figure 3.4: Evolutions of quality-weighted flow versus unweighted flow of nuclear-related inventions, all countries taken together.

Between 1980 and 1987, before the number of inventions in nuclear technology has dropped, the quality-weighted count has stayed above the simple count indicating that inventions were on average of relatively high quality. During 1980-1986, there have been on average 162.28 nuclear inventions per year. In 1987, 291.25 nuclear inventions were patented. The average quality of the inventions patented in 1987 was 1.21 while it was equal to 1.51 over 1980-1986. After 1987, a slow convergence between the two counts began before their overlap started around 1999. It illustrates the decrease of the quality of nuclear-related inventions, relative to other technologies, and indicates that knowledge in this technology is overestimated when approximated by a simple count of inventions. It should be noted that it is the only technology among the fifteen studied in this article for which a decreasing average quality is so striking.

Considering solar thermal power and geothermal power we observe no clear signs of a decrease (or an increase) of the annual average quality. For geothermal energy there have been some jumps in the quality-weighted count and this is explained by few inventions of high quality that are weighting heavily in the low amount of inventions. Still, geothermal energy is used and commercially viable for more than a century using mature techniques, the main obstacle to its development being the scarcity of exploitable sites (IPCC, 2012, (218)). This barrier could explain the low amount of inventions patented in this technological field. The technological paradigm of solar thermal energy has remained fairly unchanged over the analyzed period. For instance, most of the installed capacities at the end of the 2000s have a similar design compared to the first operating commercial plants installed in California in the 1980s (IEA, Technological report on solar thermal). In the mid-late 2000s, concentrated solar power has opened a new area for innovation and it has contributed to a growing number of patented inventions. Nonetheless, there is no clear sign that these new inventions were, on average, of better quality.

Contrary to solar thermal and geothermal energies, a clear decoupling between the quality and the quantity occurred for more recent technologies since there has been an increase of the average quality of patented inventions. The most vivid examples are wind power, solar PV power and energy storage. In the energy storage technological area, patented inventions have seen their annual average quality substantially increased at the beginning of the 1990s. It came later for solar PV power and wind power for which patented inventions have gained in quality since the beginning of the 2000s. Consequently, the knowledge related to these three technological fields is underestimated if the role of quality is let apart.

The technologies' relative shares in the annual flows of quality-weighted inventions have changed considerably over 1980-2010. One can expect the dynamics of substitution between older and newer technologies to be led by the evolutions of the returns to R&D. As they decrease in a particular technological field the investment will be redirected towards technologies with higher returns[8]. This assertion is supported by the decreasing number of nuclear patents that goes hand in hand with a decreasing average quality. At the contrary solar PV power and wind power technologies have experienced a growing average quality per cohort and have seen their shares in the annual flows of quality-weighted inventions considerably increasing over time.

3.4.2.3 Distribution of inventions quality

The previous part investigates how the average quality of technologies has evolved. Reasoning on average levels hides however an important feature of innovation: the uncertainty of research outcomes. According to Popp et al., models may suffer from two major limits: 1/ to consider a composite low-carbon technology neglects the differences between technologies in terms of outcomes ; 2/ to reason on the basis of average returns omits the uncertainty associated to R&D and may underestimate the potential innovation of high value (Popp et

[8]As Popp et al. (2013, (138)) underline, as the returns to research in a particular technology decrease over time and make the technology obsolete, research efforts will move to more productive technologies. Hence, increasing returns to research may be observed at the macroeconomic level despite there are decreasing returns in particular research areas.

	Biofuels	CCS	Sea Energy	Energy Storage	Fuel from waste	Geothermal Energy	Hydro	Hydrogen
Mean	1.38	1.31	1.38	1.375	1.39	1.27	1.34	1.38
Max	12.64	8.725	14.37	29.98	40.3	13.7	18.2	11.24
Min	0.12	0.1	0.185	0.1	0.16	0.2	0.15	0.12
Standard error	1.36	1.06	1.56	1.4	1.78	1.18	1.45	1.36
Mode	0.84	0.71	0.43	0.67	0.83	0.96	0.82	1.11
1^{st} quartile	0.59	0.58	0.59	0.58	0.58	0.65	0.64	0.57
Median	0.95	0.98	0.91	0.94	0.93	0.97	0.9	0.945
3^{st} quartile	1.60	1.70	1.52	1.67	1.55	1.44	1.46	1.64
Coefficients of Variations	0.91	0.85	0.85	0.90	0.86	0.74	0.79	0.90
Kurtosis	14.17	6.43	25.47	56.01	198.43	36.65	34.54	11.60
Skewness	3.13	2.11	4.33	4.9	10.49	4.70	4.78	2.95
Count	1019	1065	655	3955	1186	394	1243	1416
	Nuclear	Solar PV	Smart Grids	Solar Thermal	Wind	Combustion Efficiency	Combustion Mitigation	Total
Mean	1.28	1.36	1.33	1.27	1.33	1.3	1.31	1.33
Max	11.45	20.24	18.43	25.24	22.56	9.11	11.47	40.3
Min	0.1	0.1	0.15	0.12	0.13	0.12	0.14	0.1
Standard error	1	1.28	1.31	1.16	1.34	1.07	1.12	1.29
Mode	0.99	0.53	1.11	0.99	0.58	0.93	0.78	0.82
1^{st} quartile	0.61	0.58	0.60	0.65	0.62	0.57	0.60	0.60
Median	0.99	0.93	0.96	0.96	0.94	1	0.94	0.95
3^{st} quartile	1.61	1.65	1.54	1.42	1.48	1.68	1.65	1.57
Coefficients of Variations	0.80	0.88	0.82	0.72	0.81	0.83	0.83	0.83
Kurtosis	8.67	21.54	32.67	59.87	34.85	7.82	10.72	61.9
Skewness	2.25	3.29	4.30	5.17	4.38	2.24	2.57	4.86
Count	3656	3748	1567	4050	3162	630	1205	28951

Table 3.1: Descriptive statistics of the quality index per technology.

al., 2013, (138)). In order to obtain a patent protection an invention must meet a minimum level of quality and adds new knowledge to the existing stock. Above this minimum level, the distribution of inventions in terms of quality reflects the breadth of the new technological opportunities that open up through new knowledge. Descriptive statistics are presented in the Table 3.1 and indicate rather stable values of the average level of quality among technologies. The higher value being 1.39 (fuel from waste) and the lower 1.27 (solar thermal and geothermal energy). However, differences are more marked when comparing the shapes of distribution among technologies. The propensity of a technology to reach high values of quality is reflected by the skewness and the kurtosis of the distribution. The larger they are, the more the distribution is skewed to the right and the thicker are the distribution tails. On this basis, the technologies with the higher potential for high quality inventions are fuel from waste, solar thermal and energy storage. At the contrary, nuclear power, combustion efficiency and CCS exhibit the less skewed distributions with a stronger concentration of inventions around the distributions modes. It reflects that there are less uncertainties in terms of research outcomes for this last group of technologies.

The distributions of the quality index for a given technology have evolved over time and it supports the idea that the uncertainty on the R&D outcomes depends on the current technological state. Computing the distributions of the quality index for three time periods: 1980-1990, 1991-2000 and 2001-2010, we find contrasted results between technologies. They are computed for the seven technologies that have the larger stocks of knowledge at the end of 2010: namely solar PV, wind power, energy storage, hydrogen, solar thermal, smart grids and nuclear technologies. They are shown on Figure 3.5 for wind and nuclear technologies; the other can be found in Appendix 3.D [9].

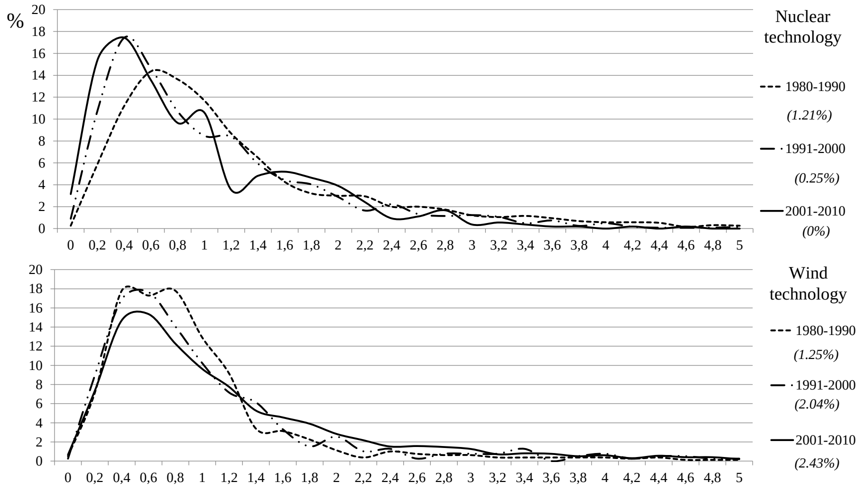

Figure 3.5: Distributions of the quality of inventions for three decades (Nuclear technology and Wind technology).

Wind power, solar PV and hydrogen constitute a group of technologies that presents a common feature: the shapes of quality distributions have changed over the three decades but it has only impacted the distribution of high quality inventions. Indeed, the left side of the distributions stayed rather similar whereas the right-side tail has became longer and thicker. A growing uncertainty is associated with a higher number of high-quality inventions, compared to older inventions.

The shape of the distributions of wind-related inventions is getting flatter over the three decades suggesting that the potential for significant inventions has grown: chances to reach higher quality levels have increased with the cumulative number of inventions. This is illustrated on the graph at the bottom of the Figure 3.5. This result is in line with the cumulative of wind power innovation: technical change in this field occurs through a series of successful innovations rather than some breakthrough inventions (Popp et al., 2013, (138)). This is not what we observe for solar PV and hydrogen technologies. For the latter, the

[9]All the distributions are truncated to the right for a value of the quality index of 5. The shares of inventions that exceed this value are given between brackets on the figures under the names of the technologies.

decade experiencing the larger share of high value inventions is 1991-2000. It has decreased during the last decade but stayed above the levels of 1980-1990. In the case of solar PV technology, the concentration around low quality was the larger during 1991-2000. Then, the right-tail of the distribution has grown longer during 2000-2010. This is the decade during which innovative activity in solar PV technology has been the more successful.

Consistent with the decreasing average quality of the inventions, the distribution of nuclear technology inventions has been progressively shifted to the left as shows the Figure 3.5. The variance of the outcomes was higher during 1980-1990 compared to the last two decades and their has been more inventions reaching high values of the quality index. During the last two decades, in addition to the shift of the distributions toward the left, nuclear technology has experienced an higher concentration of the inventions around low values of the quality index. Considering smart grid[10] and solar thermal technologies, the distribution of the quality during the last decade exhibits a higher number of low value inventions as well as a thicker right tail of distribution, compared to 1980-2000. Hence, despite the fact that the bulk of inventions are of lower values a subset of inventions is able to reach high levels of quality.

Analyzing the evolutions of the quality index distributions provides for several insights. When comparing nuclear power with other technologies, we observer that it has seen its potential for inventions of high quality decreased over time. On the one hand, the average quality of nuclear-related inventions has decreased (see 3.4.2.2). On the other hand, the distribution of research outcomes around a lower quality has been broadened so that the chances to reach high quality levels is reduced. At the contrary, new technologies such as wind power and solar PV experience higher potentials for high quality inventions during 2000-2010, as indicate the higher proportions of high-values inventions.

3.4.3 Cross-country comparison

3.4.3.1 Overview of the average quality among countries

An accurate measure of countries' innovative activities takes into account their size. On Figure 3.6, the relation between the cumulative Gross Domestic Product (GDP) and the

[10] The term 'smart grid' is fairly new in our vocabulary but the idea of making the grid more efficient has emerged with the electricity grid. As shown by Table 3.2 all the inventions that contribute to improve the network operation and the management of the generation, transmission and generation of electricity fall in the smart grids category. For instance, the first known electric meter patented in 1872 by Samuel Gardiner would be considered as a smart grid technology.

number of inventions over the period 2001-2010 is represented on a logarithmic scale. Additional information are provided by the size of the bubbles that represents the average quality of countries' inventions. Only the inventions of cohorts 2001-2010 are considered[11].

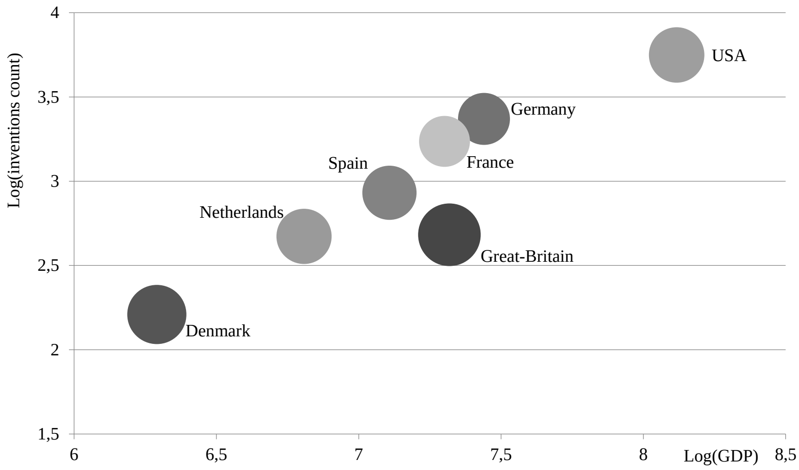

Figure 3.6: GDP, quantity and average quality of inventions over 2001-2010.

The relation between the cumulative GDP and the fractional count of inventions is almost linear. What is of interest for us is whether the average quality is linked to one of the two or both variables, or not. This is not the case. Nonetheless, this figure calls for two remarks. First, the lower amount of the UK's patents in comparison with countries with similar levels of cumulative GDP indicates that its propensity-to-patent is lower. Counting patents would lead to underestimate the UK's innovative activity but its lower propensity-to-patent is compensated by an higher average quality of patented inventions as shown on the figure. Second, Denmark exhibits a similar propensity-to-patent in LCETs compared to other countries, with the exception of the UK, and also an higher average quality of its inventions.

3.4.3.2 High quality inventions

As we have seen the propensity-to-patent varies among countries. This is due to several factors such as the patent fee or the ease of the application process. However, these factors are not expected to play a role on the patenting of high-quality inventions, their expected

[11] For each country, we compute the share of LCETs in the total amount of priority filings and observe that it has stayed rather stable between 1985 and 2000. Then, the growth of LCETs shares in the overall patenting activity has started around 2000 in all the analyzed countries, except in Denmark and Spain where one-off increases were observed previously. Here, we focus on the growth phase rather than the business-as-usual patenting activity.

values compensating the total cost of a patent. An advantage of the quality index is to identify these most valuable inventions. To do so, we consider the patented inventions over 1980-2010 of the higher decile, called hereafter High Quality Inventions (HQIs). 66.94% of the HQIs belong to the USA (46.84%) and Germany (20.1%). The leading roles of these countries are partly explained by their high patenting activities. German HQIs account for 10.3% of the total amount of German inventions and the corresponding ratio of the US HQIs falls to 8.8%. As a comparison, 1.6% of the HQIs belong to Denmark but it represents 17.4% of the total Danish portfolio of inventions. Despite its small size, Denmark has a leading role in LCET. The leading technologies, all countries taken together, are energy storage (15.4% of the HQIs subset), solar PV energy (14.7%), nuclear power (11.8%), wind energy (10.7%) and solar thermal (10.6%).

Now, considering the best inventions within a country helps to identify how the innovative efforts are spread among technologies. To do so, we select the ten percents domestic inventions with the higher quality index values, called hereafter Domestic High Quality Inventions (DHQIs). The results are presented in Table 3.2. It also contains measures of the technological concentration of a country's inventions portfolio[12].

As indicated by Table 3.2 no single technology is favored by the seven countries. Nonetheless, solar technologies (PV and thermal energies), energy storage and wind power are the most recurrent technologies among countries' DHQIs. In this extent, the low competence of France in wind power energy constitutes an exception (3% of French DHQIs). This is also true for the USA, albeit to a lesser extent, as wind power weights 5.53% of the DHQIs. As expected, the Danish portfolio exhibits an high technological concentration: its specialization in wind power is fairly reflected by the fact that 44.44% of its DHQIs belong to this technology.

From a policy perspective, the comparison between Spain and Germany suggests the insufficiency of strong demand-pull policies when not coupled with supply-push policies. These two countries have implemented generous demand-pull policies to stimulate the deployment of solar PV power (del Rio and Mir-Artigues, 2012, (41); Frondel et al. 2008, (52); Jacobsson and Lauber, 2006, (75)). Obviously, the results in terms of knowledge creation are contrasted. Germany possesses 19.7% of the ten percents higher quality solar PV inventions whereas 1.06% belong to Spain. This imbalance can be attributed to the fact that the German cumulative RD&D expenses dedicated to solar PV technology over the

[12]The technological concentration index is inspired by the Hirschman-Herfindalh index and computed as the sum of the shares' squares of each technology. Consequently, the higher the concentration index is the more the inventions portfolio is concentrated. We compute its values for the subset of DHQIs and the whole domestic inventions.

	Denmark	Germany	France	United Kingdom	Spain	USA	Netherlands
Bio-fuels	18.52	2.13	4.4	3.22	4.25	4.15	13.23
CCS	0	1.41	3.48	5.64	2.83	4.48	0
Sea energy	14.81	1.06	1.16	8.06	7.09	1.81	0
Energy storage	0	10.44	13.92	10.48	5.67	21.23	5.88
Fuel from waste	14.81	4.78	4.41	1.61	3.55	3.76	8.82
Geothermal Energy	0	0.53	0.69	3.22	0	1.10	1.47
Hydro Energy	0	4.6	5.10	9.68	2.84	2.72	7.35
Hydrogen	3.7	5.66	5.57	5.64	1.42	6.36	0
Nuclear	0	14.86	33.41	3.22	0.7	6.04	0
PV energy	0	15.04	8.12	16.13	6.38	18.38	20.58
Smart grids	0	1.95	2.78	5.64	2.84	7.79	0
Solar thermal	3.7	11.68	9.74	8.87	29.79	8.38	22.06
Wind	44.44	19.11	3.02	14.52	29.79	5.52	16.18
Combustion efficiency	0	1.95	1.62	0	0	3.18	0
Combustion mitigation	0	4.78	2.55	4.03	2.84	5.06	4.41
Concentration Index (top 10 %)	2784.63	1172.7	1606.85	963.84	1963.18	1126.16	1535.45
Concentration Index (all inventions)	3818.15	995.12	1050.29	902.63	1463.32	1030.28	1441.13

Table 3.2: Distribution of Domestic High Quality Inventions (1980-2010).

period 1980-2009 were 9 times higher than the Spanish ones[13]. It is costly for Spain as the deployment of solar PV power plants did not succeed in creating a leadership in solar PV technology. The question of the policy mix between demand-pull and supply-push approaches is investigated in greater details in the next part, taking as a case study the wind power technology during 1990-2010. The complementarity of these two approaches is emphasized.

3.4.3.3 Supply-push, demand-pull and technical knowledge

We explore the links between quality-adjusted invention production in wind power technology and two of its driving forces: demand-pull and supply-push. On the one hand,

[13]Shares computed using the data from the Energy Technologies RD&D database of the International Energy Agency

demand-pull represents the influence of the market size and its conditions on the rate and direction of invention. The existence of a profitable market for renewable energy increases the payoff expected by innovators and it is supposed to stimulate knowledge production in renewable energy technologies. On the other hand, supply-push fosters innovation by strengthening the scientific understanding of new technologies and reducing the cost of knowledge production (Nemet, 2009, (127)). The balance between these two approaches and their corresponding support policies is of major importance and widely discussed in the literature (Nemet, 2009, (127); Albrecht et al., 2015, (3); Laleman and Albrecht, 2014, (101); Horbach et al., 2012, (74); Peters et al., 2012, (134); Kemp and Pontoglio, 2011, (87); del Rio and Bleda, 2012, (40); Taylor, 2008, (160); see Zachmann et al., (193) for a comparison of the cost of support policies in Europe). Wind power technology has been one of the first renewable energy technology, with solar PV, to be supported by public authorities though both demand-pull and supply-push policies. To this extent, it constitutes a relevant case study to explore the relations between demand-pull, supply-push and knowledge production. For that purpose, we define three measures:

- A **demand-pull intensity** index is computed as the share of wind power in the total electricity generation capacity, each country from 1990 to 2010. It reflects the results of demand-pull policies, in terms of market expansion, not their efficiencies.

- A **supply-push intensity** index measures the efforts of RD&D directed toward wind power technology. As an input of the innovation process, RD&D expenses are a good proxy of the supply-push given to the industry to stimulate innovation. Due to the heterogeneity of the countries included in our study we need a relative measure. It is obtained by expressing the supply-push intensity as the share of RD&D expenses dedicated to wind in the total RD&D toward renewable energy and nuclear technologies[14]. Moreover, because research has a cumulative nature we consider a stock instead of annual flows. Hence, the supply-push intensity index is computed as the share of the stock of RD&D expenses dedicated to wind in the total stock of expenses related to nuclear and renewable energy technologies. The national stocks are computed using a depreciation rate of 10 %.

- A **knowledge intensity** index represents the annual share of wind power technology in the knowledge stock of a country. In order to compare this measure with

[14] The renewable energies included are those that correspond to the GROUP 3 of the IEA detailed country RD&D budgets.

supply-push intensity we compute the stocks of knowledge by taking into account only renewable energy and nuclear technologies.

The first two indexes are constructed with several data sources. The RD&D expenses are from the Energy Technologies RD&D database of the International Energy Agency. We use the annual total RD&D expenses of groups 3 (renewable energies) and 4 (nuclear power) from the detailed country RD&D budgets. The expenses directed toward wind power are available for almost every year from 1990 to 2010. When there are missing values they are replaced by a linear interpolation [15]. Total installed capacities per country are from the US Energy Information Administration.The installed capacity of wind power is taken from the IEA Wind annual reports, except for Denmark for which the installed capacities are computed based on the Master Data Register of Wind Turbines.

The relations between demand-pull, supply-push and knowledge are represented on Figure 3.7. Supply-push intensity and demand-pull intensity indexes are represented on the horizontal and the vertical axes, respectively. The diameter of the bubbles takes the value of the knowledge intensity index. We take into account a time lag of two years between supply-push and its expected effects on knowledge. The speed at which RD&D expenses are converted into new knowledge varies among technologies and depends both on the development stage of the technology and on the success of R&D projects. Researchers generally consider time lags between RD&D expenses and cost reductions varying from 2 to 5 years (Wiesenthal el al., 2012, (227); Watanabe et al., 2000, (166); Kobos et al., 2006, (92); Söderholm and Klaassen, 2007, (156)). Klaassen et al. (2005, (90)) survey several studies on renewable energy technologies and suggest to use a time lag of two years between R&D expenditures and their addition to knowledge stock.

[15] This is the case for the Netherlands in 2004 and the UK in 2008.

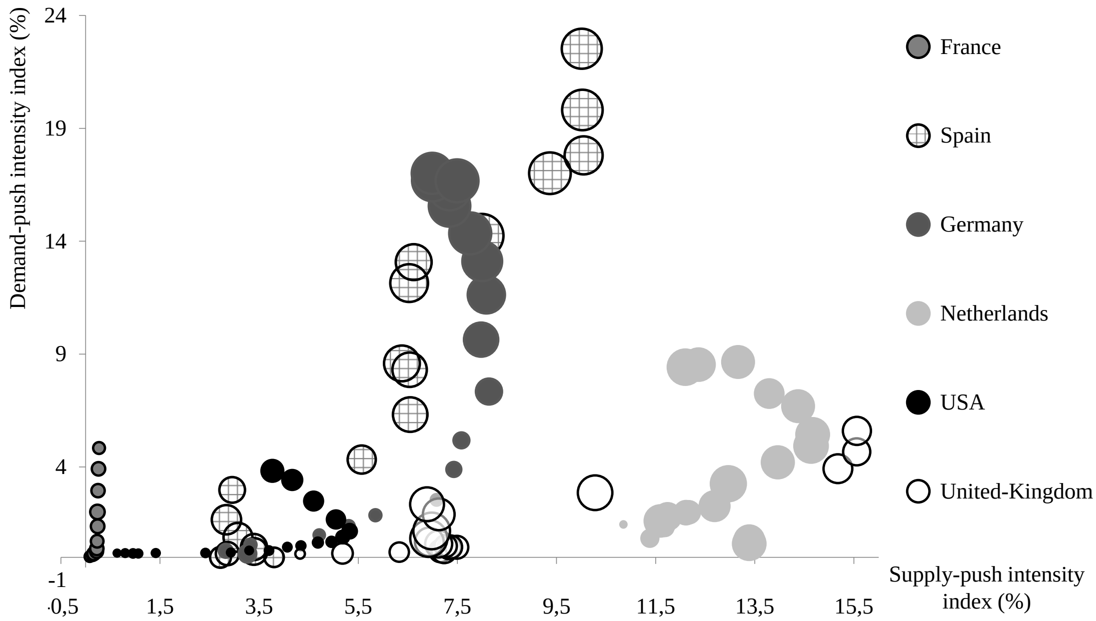

Figure 3.7: Relation between demand-pull, supply-push and knowledge (diameter) intensity indexes in wind power during 1990-2010.

To improve the readability of the figure Denmark is not represented because it has high intensity levels of demand-pull, supply-push and knowledge. However, it is discussed in the comments below and a similar figure including Denmark is given in Appendix 3.E. Figure 3.7 illustrates that knowledge production has positively reacted to a balanced mix of supply-push and demand-pull; supporting the hypothesis that they are complementary.

The most striking examples are those of Denmark, Spain and Germany. In Denmark, large and stable supply-push efforts have been maintained during the whole time period: the average level of the supply-push intensity index was equal to 36.12% and its average annual growth rate was 1.48%. In Germany, a major supply-push has occurred during the 1990s before the supply-push intensity index remained rather stable, hovering at around 7%. Spain has seen the supply-push intensity index increased at the bend of the 1990s, stabilizing in 2005 around 10%. Judging from figure 3.7 the knowledge intensity in these countries is led by market expansion, i.e. demand-pull, more than supply-push: our measure of knowledge intensity in wind power increases with the share of wind power in the electricity mix. These observations should not underestimate the role that plays a significant supply-push in triggering knowledge production. For instance, the French case is illustrative of the shortcomings of demand-pull policies implemented without being combined with a sufficient support on the supply side. The share of wind power in the French electricity mix has steadily increased during the 2000s but the intensity of the knowledge production has stagnated at a very low level. The near non-existence of a supply-push support toward wind power technology, as reflected by the low value of the supply-push intensity index in France, suggests that a minimum threshold of supply-push efforts should be met to let knowledge production takes off with market expansion. This idea is further supported by the comparison of the French case with the USA. Unlike France, the USA has impulsed an important RD&D effort after 1993 and for higher levels of the supply-push intensity index the knowledge intensity in wind power started to grow with the size of the market. At the contrary, supply-push alone does not seem to be able to positively influence knowledge intensity after a certain level. Indeed, despite a major supply-push given to wind industry after 2005, the United-Kingdom did not increase the share of knowledge related to wind power. It could be explained by the small size of the domestic market, reflected by the low values of the demand-pull intensity index.

3.5 Conclusion

We estimate a one LFM that explains the four patent metrics by some fixed effects and by a common and unobservable factor. Previous empirical studies on patent metrics assure that a factor affecting simultaneously the four metrics is an accurate measure of the quality of a patent. Based on the parameters estimates we can reify an index of the quality of 28,951 inventions pertaining to seven countries and patented in fifteen Low-Carbon Energy Technologies between 1980 and 2010. The variance of each patent metric can be subdivided into its specific variance and a part that is imputable to a commonality term representing the role of quality. We find that the number of backward citations and the size of the family are the metrics with the higher shares of their variances imputable to quality. At the contrary, only 4.8% of the variance of the count of forward citations received by a patent within the five years after its publication are imputable to patent quality. In line with the results of Lanjouw and Schankerman (2004, (100)), we find that using several metrics reduces the variance of the quality index by 52.48%. We compute the stock of knowledge over the period 1980-2010 in the fifteen energy technologies included in our data set. In 2010, the leading technologies were solar PV power, wind power and energy storage technologies. Comparing the weights of the seven countries included in the analysis we find that 50.68% the knowledge stock pertain to the USA, followed by Germany (18.42%) and France (13.68%). The evolutions of the shares of technologies in the knowledge stock indicate major substitution effects. Nuclear technology and solar thermal have the higher shares of the knowledge stock during 1980-1990. Between 1990 and 2010, the amounts of inventions in these two technological fields have decreased over time and new technologies, mainly solar PV and wind power, took up the baton.

This transition is analyzed through the quality index and several insights emerge. First, the average levels of inventions' quality have evolved very differently from technology to technology. In particular, nuclear technology is the only one to exhibit a clear decrease of the average quality of inventions over time. At the contrary, the average quality of inventions has increased for solar PV, wind power and energy storage technologies. This is also the case for hydrogen and sea energy technologies but the smaller amounts of inventions patented in these two technological fields call for some prudence. Research is an highly uncertain activity and one could think that a lower quality, on average, may be compensated by a small subset of inventions of very high quality. To investigate this issue we compare how the distributions of the inventions in terms of quality have evolved within a particular technology. The length and the thickness of the distribution tail toward high values of the quality index capture technologies' potential for significant inventions. A second insight is that this potential has been the higher during 2001-2010, compared to 1980-2000, for solar PV and wind energy technologies. At the contrary, the decreasing average quality of nuclear over time is not compensated by few inventions of great quality: from a decade to the next inventions tend to be more and more concentrated around small value of the quality index suggesting that best opportunities have been depleted.

The quality index also provides a wealth of information on countries' positions, relative to each other. It appears that Denmark has a rather similar propensity-to-patent, measured by the ratio of inventions on the GDP, and exhibits a higher average quality per invention. Considering the top 10% inventions of each country, wind power technology represents a significant share of the best inventions of Denmark, Spain, Germany, the Netherlands and Great-Britain. The place this technology has in the domestic best inventions is lower in the USA (5.52% of the top 10% patents) and France (3%). Generally, in addition to wind power, the other technologies that have a strong share in the best inventions of each country are solar technologies (thermal or PV). Based on the quality index, we represent the relation between the knowledge production and two forces that drive it: demand-pull and supply-push. A simple graphical comparison suggests that they are strongly complementary. On the basis of this intuition further research will be needed to quantify the impact of supply-push and demand-pull policies on innovation.

Appendix

3.A Appendix A: The E-M algorithm

This appendix presents the E-M algorithm. Although it is close to the presentation given in Bartholomew et al. (2011, (174)), we include in the model a set of dummy variables that requires a modification of the algorithm. We start by writing the joint log-likelihood of (x_i, y_i) for $i = 1, ..., n$,

$$\begin{aligned} constant - \frac{n}{2} log|\Psi| - \frac{1}{2}\sum_{i=1}^{n}(x_i - \mu - \alpha z_i - \Lambda y_i)'\Psi^{-1}(x_i - \mu - \alpha z_i - \Lambda y_i) \\ - \frac{1}{2}\sum_{i=1}^{n} y_i' y_i. \end{aligned}$$

Using the trace trick[16], the joint log-likelihood can be written:

$$\begin{aligned} constant &- \frac{n}{2} log|\Psi| \\ &- \frac{n}{2} trace\left(\Psi^{-1}\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu - \alpha z_i - \Lambda y_i)(x_i - \mu - \alpha z_i - \Lambda y_i)'\right) \\ &- \frac{n}{2} trace \frac{1}{n}\sum_{i=1}^{n}(y_i y_i'). \end{aligned}$$

The score functions of the joint log-likelihood for μ, Λ, α and Ψ, are

$$n\Psi^{-1}(\bar{x} - \mu - \alpha\bar{z} - \Lambda\bar{y}), \tag{3.7}$$

[16] When a matrix multiplication results in a scalar we can use trace to rearrange its arguments.

$$n\Psi^{-1}(S'_{xy} - \mu\bar{y}' - \alpha S'_{zy} - \Lambda S'_{yy}), \tag{3.8}$$

$$n\Psi^{-1}(S'_{xz} - \mu\bar{z}' - \alpha S'_{zz} - \Lambda S'_{yz}) \tag{3.9}$$

and the diagonal elements of

$$-\frac{n}{2}\Psi^{-1} + \frac{n}{2}\Psi^{-1}\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu - \alpha z_i - \Lambda y_i)(x_i - \mu - \alpha z_i - \Lambda y_i)'\right)\Psi^{-1}. \tag{3.10}$$

These score functions contain several sufficient statistics of the model, listed below

$$\begin{aligned}
&\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \quad \bar{z} = \frac{1}{n}\sum_{i=1}^{n} z_i, \quad \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i,\\
&S'_{xx} = \frac{1}{n}\sum_{i=1}^{n} x_i x'_i, \quad S'_{xy} = \frac{1}{n}\sum_{i=1}^{n} x_i y'_i, \quad S'_{xz} = \frac{1}{n}\sum_{i=1}^{n} x_i z'_i,\\
&S'_{zz} = \frac{1}{n}\sum_{i=1}^{n} z_i z'_i, \quad S'_{zx} = \frac{1}{n}\sum_{i=1}^{n} z_i x'_i, \quad S'_{zy} = \frac{1}{n}\sum_{i=1}^{n} z_i y'_i,\\
&S'_{yy} = \frac{1}{n}\sum_{i=1}^{n} y_i y'_i, \quad S'_{yx} = \frac{1}{n}\sum_{i=1}^{n} y_i x'_i, \quad S'_{yz} = \frac{1}{n}\sum_{i=1}^{n} y_i z'_i.
\end{aligned}$$

If all these sufficient statistics could be observed, we would set the score functions to zero and deduce the estimators. However this is not the case. Six sufficient statistics listed above, those that depend on the latent factor, are unknown. To cope with this problem we use the Expectation-Maximization algorithm that, as its name indicates, follows two successive steps at each iteration.

First step: Expectation step

The conditional expected values of the score functions are computed. To do so, it is enough to compute the conditional expected values of the unknown sufficient statistics. Their expressions are

$$E[\bar{y}|x_i] = \Lambda'\Sigma^{-1}(\bar{x} - \mu - \alpha\bar{z}), \tag{3.11}$$

$$E[S'_{yy}|x_i] = (1 + \Lambda'\Psi^{-1}\Lambda)^{-1} + \Lambda'\Sigma^{-1}[\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu - \alpha z_i)(x_i - \mu - \alpha z_i)']\Sigma^{-1}\Lambda, \tag{3.12}$$

$$E[S'_{xy}|x_i] = [S'_{xx} - \bar{x}\mu' - S'_{xz}\alpha']\Sigma^{-1}\Lambda, \tag{3.13}$$

$$E[S'_{yx}|x_i] = E[S'_{xy}|x_i]', \tag{3.14}$$

$$E[S'_{yz}|x_i] = \Lambda'\Sigma^{-1}[S'_{xz} - \mu\bar{z}' - \alpha S'_{zz}] \tag{3.15}$$

and

$$E[S'_{zy}|x_i] = E[S'_{yz}|x_i]'. \tag{3.16}$$

Second step: Maximization step

In the second step of the E-M, the unknown sufficient statistics are replaced by their conditional expected values, (3.11)-(3.16), in the score functions. Then, the score functions are set to zero in order to maximize the joint log-likelihood. It gives a matrix equations system that, once solved, allows to deduce new values of the parameters:

$$\begin{aligned}\widehat{\Lambda} = &\left(S'_{xy} - \bar{x}\bar{y}' - (S'_{xz} - \bar{x}\bar{z}')(S'_{zz} - \bar{z}\bar{z}')^{-1}(S'_{zy} - \bar{z}\bar{y}')\right) \\ &\times \left((S'_{yy} - \bar{y}\bar{y}') - (S'_{yz} - \bar{y}\bar{z}')(S'_{zz} - \bar{z}\bar{z}')^{-1}(S'_{zy} - \bar{z}\bar{y}')\right)^{-1},\end{aligned} \tag{3.17}$$

$$\widehat{\alpha} = \left(S'_{xz} - \bar{x}\bar{z}' + \widehat{\Lambda}(\bar{y}\bar{z}' - S'_{yz})\right)(S'_{zz} - \bar{z}\bar{z}')^{-1}, \tag{3.18}$$

$$\widehat{\mu} = \bar{x} - \widehat{\alpha}\bar{z} - \widehat{\Lambda}\bar{y} \tag{3.19}$$

and

$$\widehat{\Psi} = diag(\frac{1}{n}\sum_{i=1}^{n}(x_i - \widehat{\mu} - \widehat{\alpha}z_i - \widehat{\Lambda}y_i)(x_i - \widehat{\mu} - \widehat{\alpha}z_i - \widehat{\Lambda}y_i)'). \tag{3.20}$$

Using this new set of parameters value, the whole operation is reiterated by incorporating them in the score functions (3.7), (3.8), (3.9) and (3.10). The conditional expectancies of the unknown sufficient statistics are computed, then incorporated in the score functions that are finally set to zero; providing a new set of parameters values and so on. The final output of the algorithm are the parameters of the model and they are combined with the observed values of X in the mean term of relation 3.4 to infer the values of the latent factor.

3.B Appendix B: Knowledge stocks

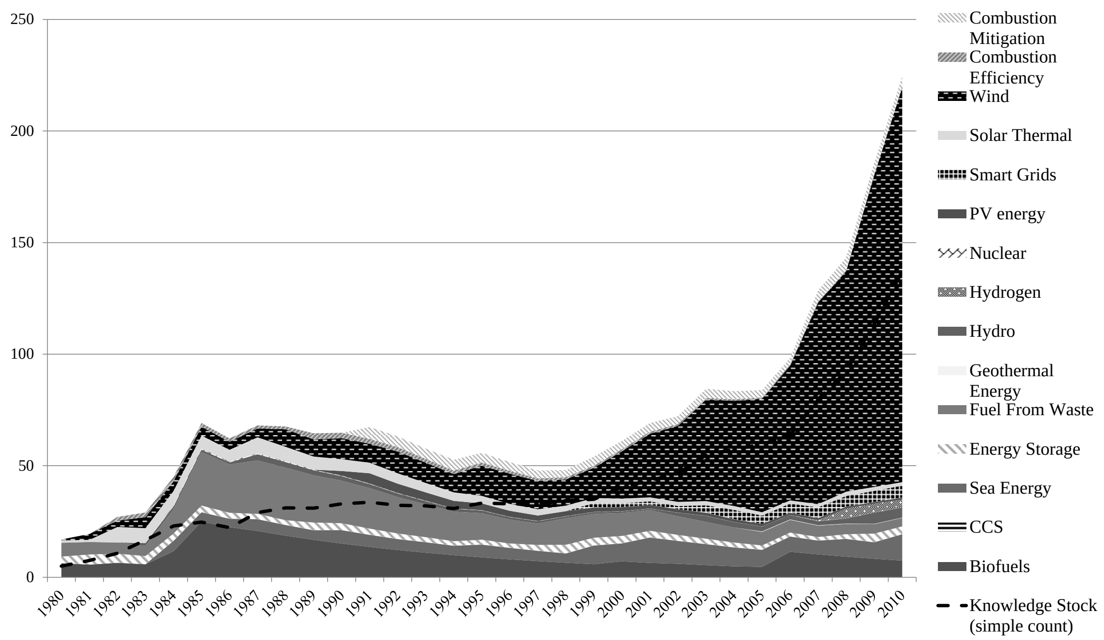

Figure 3.B.1: Quality-weighted stocks of knowledge, Denmark.

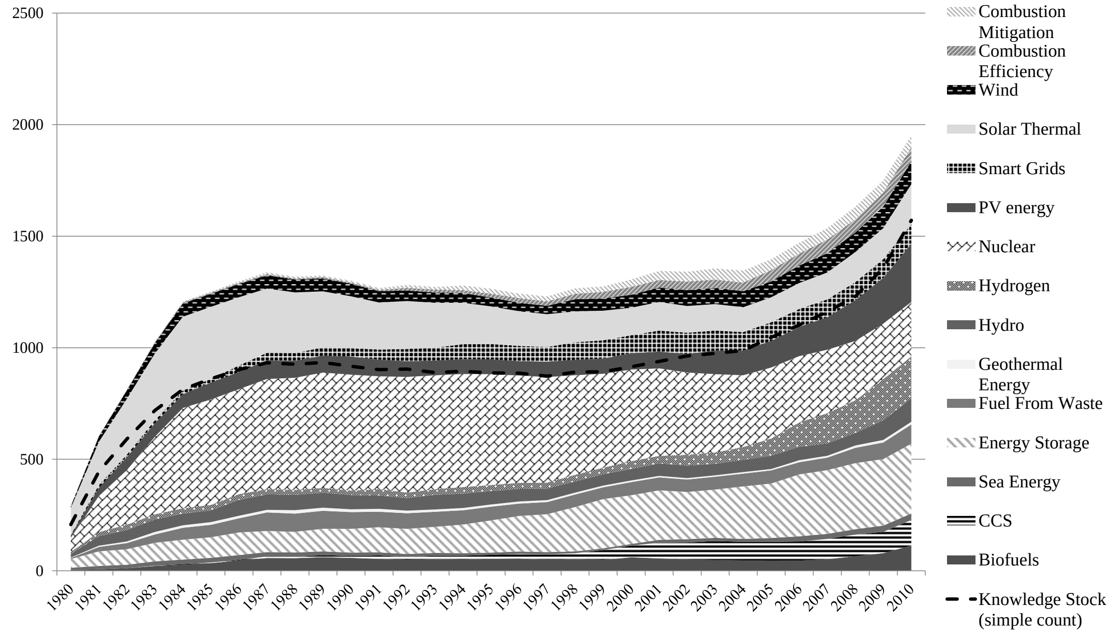

Figure 3.B.2: Quality-weighted stocks of knowledge, France.

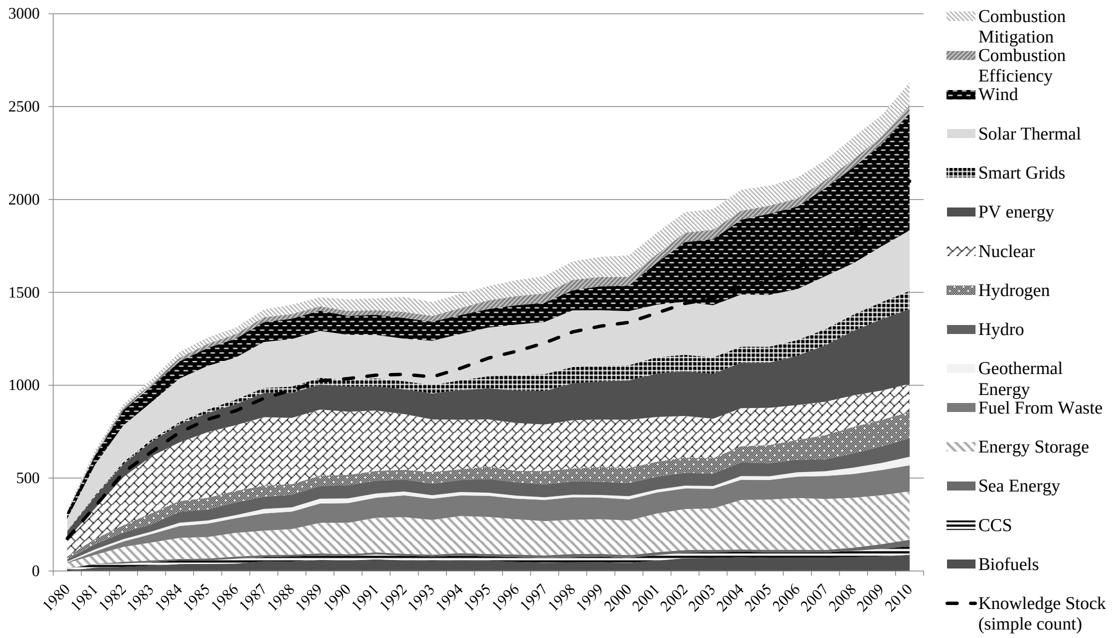

Figure 3.B.3: Quality-weighted stocks of knowledge, Germany.

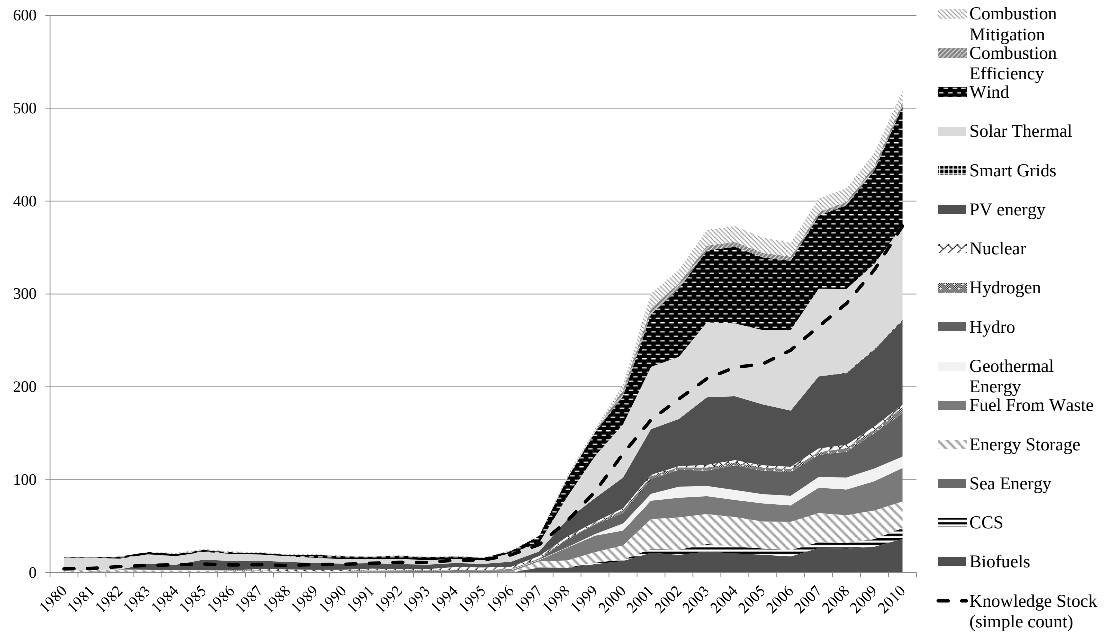

Figure 3.B.4: Quality-weighted stocks of knowledge, Netherlands.

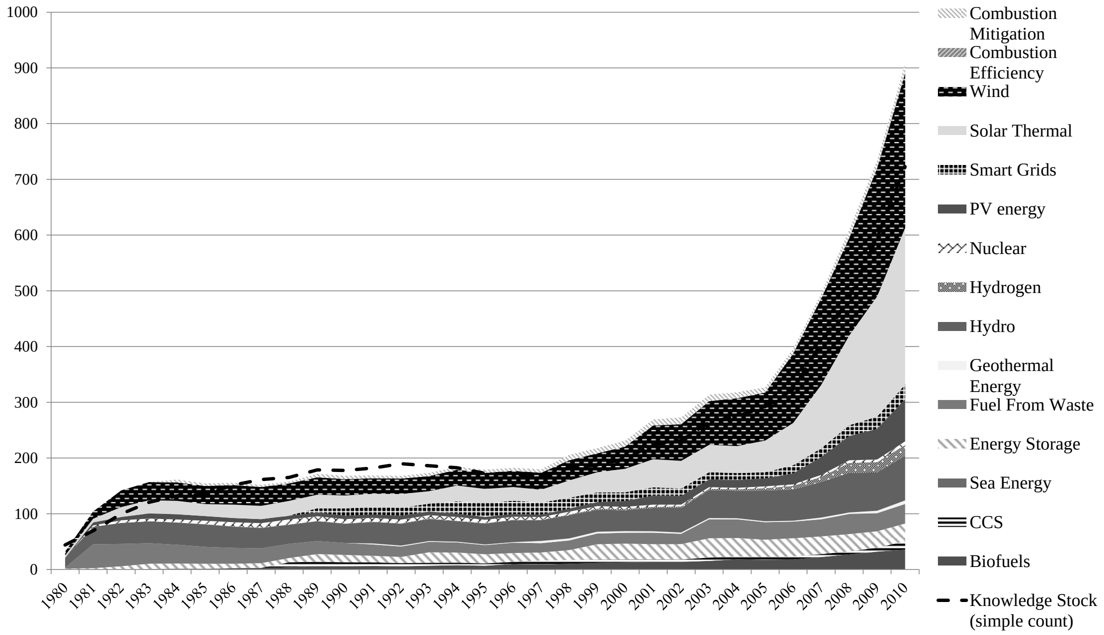

Figure 3.B.5: Quality-weighted stocks of knowledge, Spain.

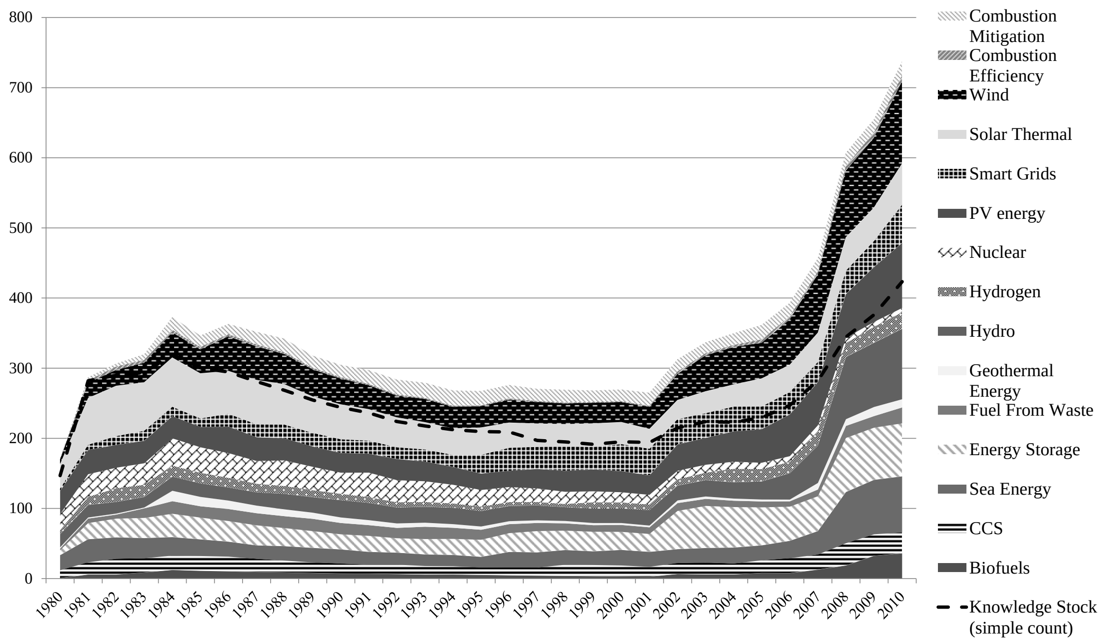

Figure 3.B.6: Quality-weighted stocks of knowledge, United Kingdom.

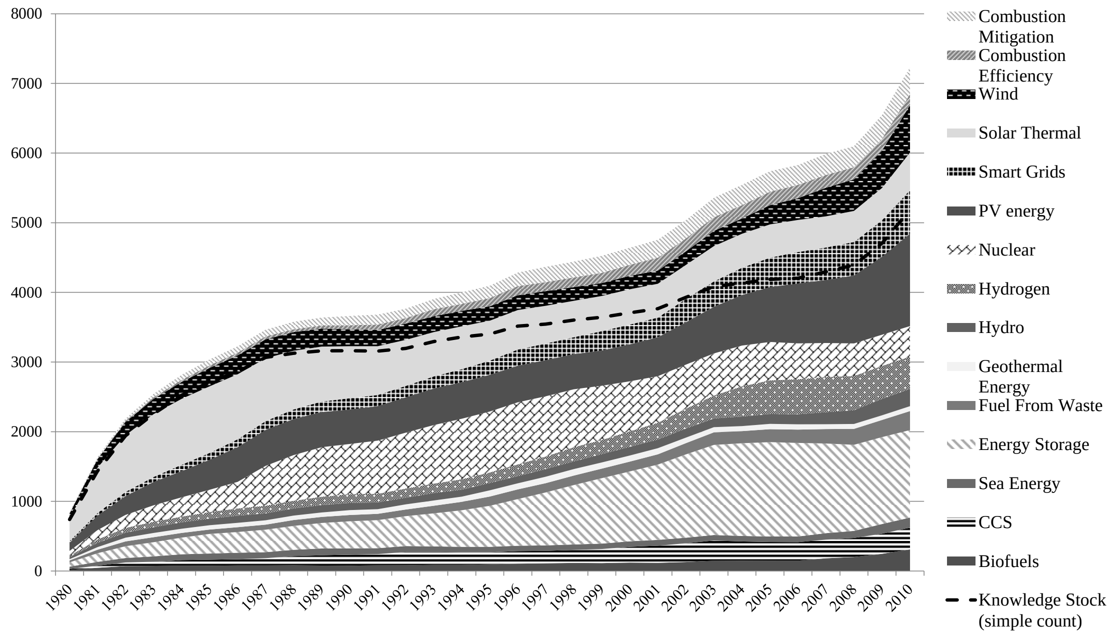

Figure 3.B.7: Quality-weighted stocks of knowledge, United States of America.

3.C Appendix C: Knowledge flows.

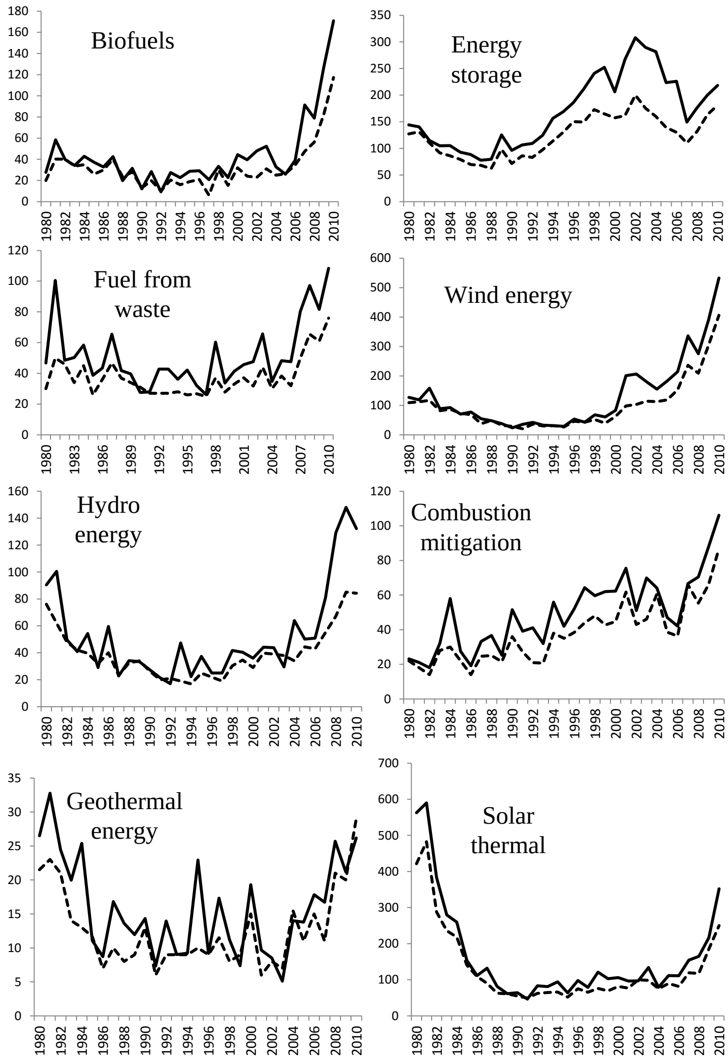

Figure 3.C.1: Evolutions of quality-weighted flow versus unweighted flow of inventions, all countries taken together (part 1).

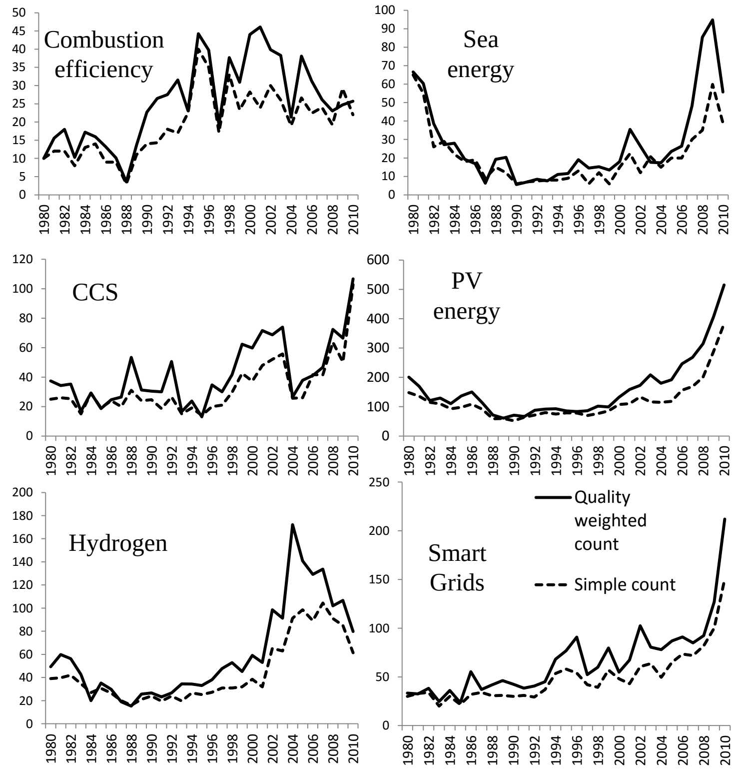

Figure 3.C.2: Evolutions of quality-weighted flow versus unweighted flow of inventions, all countries taken together (part 2).

3.D Appendix D: Distributions of the quality of inventions for three decades

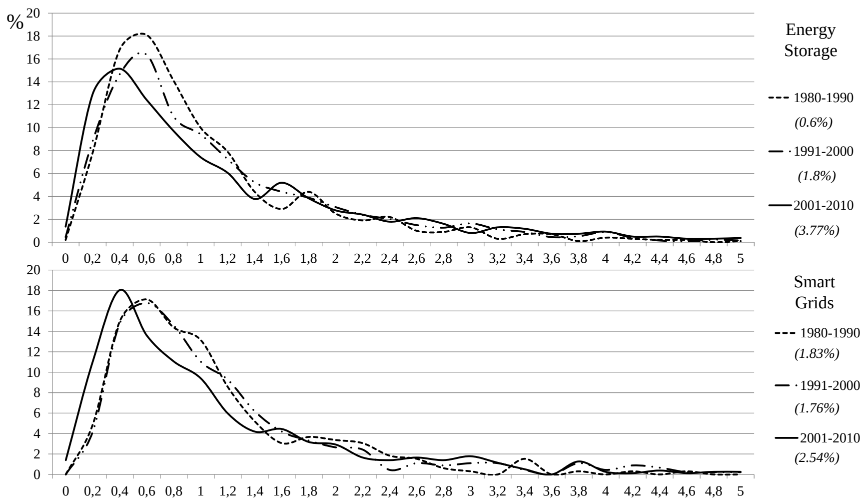

Figure 3.D.1: Distributions of the quality of inventions for three decades (Energy Storage and Smart Grids).

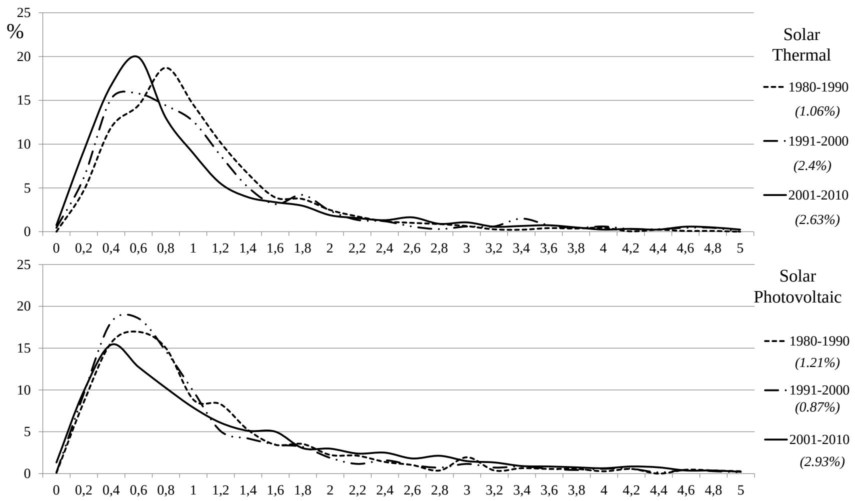

Figure 3.D.2: Distributions of the quality of inventions for three decades (Solar Thermal and Solar PV).

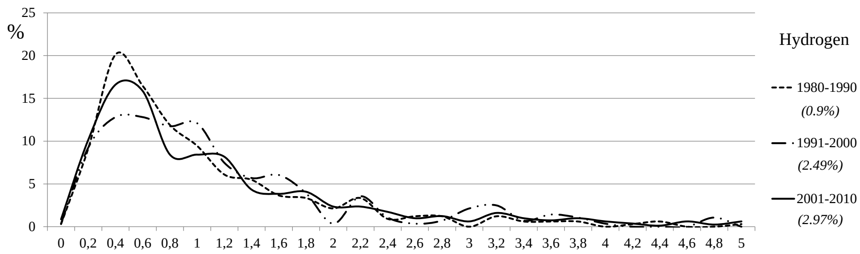

Figure 3.D.3: Distributions of the quality of inventions for three decades (Hydrogen).

3.E Appendix E: Demand-pull, supply-push and knowledge

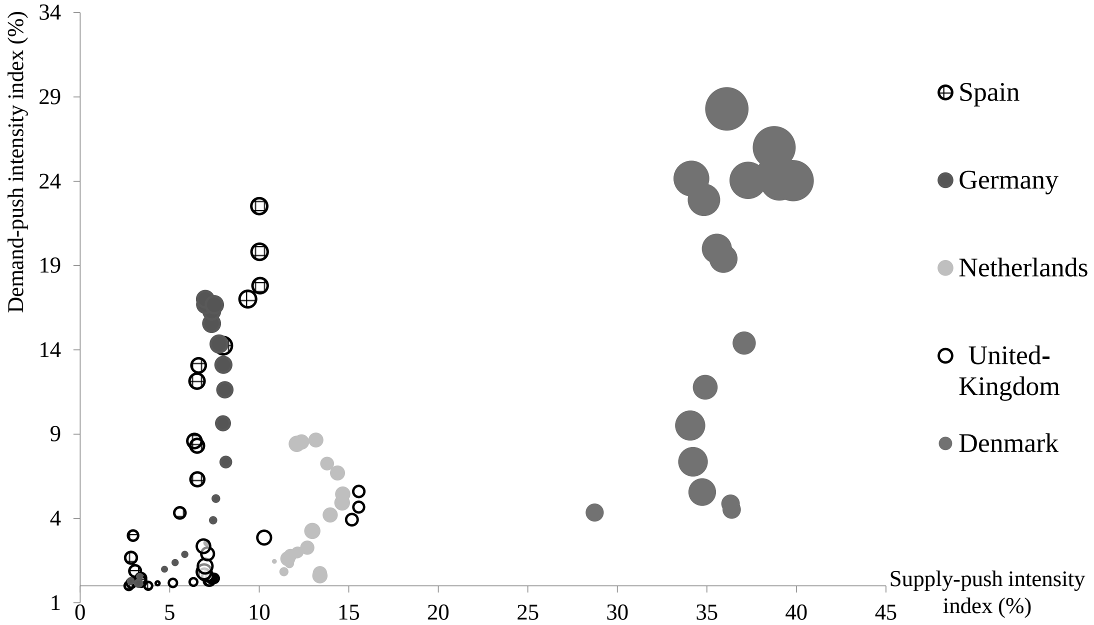

Figure 3.E.1: Relations between demand-pull, supply-push and knowledge (diameter) intensity indexes in wind power, (1990-2010).

Chapter 4

Revisiting the optimal patent policy tradeoff for environmental technologies: the role of the double externality problem

4.1 Introduction

Environmental technologies will be called to play a major role in the transition toward sustainable societies. A growing concern among economists is whether or not environmental technologies should be supported through dedicated policies, in opposition to neutral policies that equally support all inventions independently of their environmental features (Rennings, 2000, (145); Jaffe et al., 2005, (78); Weyant, 2011, (167); Nordhaus, 2011, (130)). In this paper we focus on a major instrument of support to innovation: the patent system. Our analysis explores the optimal patent system for environmental process inventions defined as process inventions that reduce the environmental damage associated with the production of a consumption good.

Letting apart the market failure due to an environmental externality, when a patent system is established to support regular inventions, the regulator deals with the tradeoff between the dead weight loss associated with the exclusivity right conferred by the patent system and the welfare improvement induced by the new technology.

When a market failure due to an environmental externality is included in the problem of an optimal patent policy, both the patent system and the environmental taxation have to be designed by the regulator. The interest of the analysis is then to determine whether or not environmental technologies are efficiently supported by an environmentally neutral patent system, i.e. a patent system that does not discriminate between environmental and regular inventions. Inventions in this article are said to be regular when they do not generate any environmental benefits. To answer this question we build a bridge between the literature on optimal patent policy and the literature on optimal environmental taxation. Assuming that the regulator can choose both the patent policy and the environmental taxation we conclude that the two market failures interact with each other through the patent system. Indeed, the distortive effect induced by the patent system impacts the optimal environmental taxation that in turn influences the strength of the protection that the regulator has to concede to profit-seeking innovators to foster investment in knowledge creation. More precisely, the environmental taxation is influenced by the patent protection that alters the competition regime. In turn, the environmental taxation policy, adjusted to the competition regime, impacts the profit of the patentee and changes the incentive to innovate, thus making the optimal patent policy different for environmental technologies compared to regular inventions. We conclude that a more efficient patent system for environmental technologies is coupled with a discriminating environmental taxation, i.e. different for the patentee and its competitors.

This paper is constructed as follows. Section 4.2 provides for the theoretical context. Section 4.3 presents a model of optimal environmental patent policy. First, the race for the patent is presented in 4.3.1. Second, the general principles of the environmental patent problem are detailed in 4.3.2 and the interactions between the patent system and the environmental taxation are discussed. Then, two illustrations of the general principles are given in subsections 4.3.4 and 4.3.3. Finally, section 4.4 discusses our results and concludes.

4.2 Environmental innovation and the double externality

Two strategies can be adopted by policymakers to stimulate environmental innovation. A first strategy is to correct the negative externalities on the environment on one hand and to provide for an environmentally neutral support to innovation on the other hand, i.e. a support to innovation that does not discriminate between R&D projects with respect to their environmental impacts. A second strategy is to implement an innovation policy that targets environmental technologies by discriminating the inventions reducing environmental damages. In subsection 4.2.1, we present the arguments that support the first strategy. In subsection 4.2.2 we demonstrate that it is inconsistent with a patent system, laying the ground for a patent policy dedicated to environmental technologies.

4.2.1 *Price fundamentalism*, Pigouvian taxation and perfect competition

According to Nordhaus (2011, (130)), when negative externalities on the environment are internalized, for instance with a tax or a quota market, environmental technologies are put on a leveled playing field with regular technologies. In addition to the environmental policy, the regulator must implement environmentally neutral innovation policies aiming at increasing the private rate of return from an invention in order to spur investments in new technologies. The rationale for this support to innovation lies in the public good feature of knowledge, discussed in the next subsection. Following this logic, it is sufficient to price the negative externalities on the environment to support environmental innovation, if innovative activities in general are efficiently bolstered. Nordhaus calls this approach the *price fundamentalism* and states that it can serve as a policy blueprint for policymakers who are committing to support environmental innovation. As Nordhaus acknowledges, it holds true under several conditions among which the perfect internalization of all product and market externalities, that constitutes the most important one.

In our view, the reason why this condition is the most important lies in the nexus between environmental taxation and market structure. Consider, for example, one of the favorite tool of economists to correct environmental externalities: the Pigouvian taxation (Pigou, 1932, (189)). The goal of a Pigouvian tax is to equalize the marginal private cost of production with the marginal social cost that includes the impact of the environmental damage of production on social welfare. To achieve this, the tax must be equal to the Marginal Environmental Damage (MED) of production and consequently the market price will reflect the marginal social cost of production. Hence, Pigouvian taxation corrects the environmental externality and market forces can then achieve the social optimum. This reasoning holds under the assumption that the polluting good market is perfectly competitive. As producers are price takers the tax is perfectly passed through the price. When it comes to innovation this assumption of perfect competition might not hold because of innovation policies. It questions the relevancy of using *price fundamentalism* to guide environmental innovation policies. Indeed, several articles have emphasized the influence of the market structure on the optimal environmental taxation (Buchanan, 1969, (20); Lee, 1975, (103) and Barnett, 1980, (8)).

4.2.2 The limits of *price fundamentalism* in a patent system

As evoked above, implementing an innovation policy might create competition distorsions. Innovation results from the accumulation of knowledge which is a public good: it is non-rival (the consumption of knowledge by an agent does not reduce the consumption available to other agents) and non-exclusive (it is too costly to completely prevent someone from consuming knowledge). Therefore, the socially optimal level of knowledge price is equal to zero because non-rivalry implies a marginal cost of reproduction of knowledge that is nill, if transmission cost are excluded. In other words, society's welfare is maximized when knowledge diffusion is the largest. This corresponds, as Arrow wrote (1962, (172)), to

> an ideal socialist economy, [where] the reward of the invention would be completely separated from any charge to the users

In a free market economy however a substantial part of research activities is undertaken by profit-maximizing firms. In the absence of a public intervention the market leads to an underinvestment in knowledge creation compared to its socially optimal level. In this extent innovation policies must increase the private yield the firms can expect from an invention. For this purpose, the regulator could either reduce the cost of R&D or increase the benefit from an invention. The latter lever mainly relies on Intellectual Property Rules (IPR) aiming at increasing the appropriability of an invention defined as the share of the new knowledge the inventor can internalized. In this paper we focus on one of the most used IPR instruments: the patent system. A patent system is an incentive mechanism that gives the inventor a temporary exclusivity right over the patented invention that prevents, or at least inhibits, other agents to produce use or sell the invention during the period of protection. The duration of the patent is its *length* and the degree of exclusivity over the invention with respect to competitors is its *breadth*. Thus, a patent system increases the incentive to innovate and contributes to common knowledge growth because of the requirement to disclose knowledge once the patent is published. The reasons why a patent protection is offered is to ensure such disclosure of the new invention (Matutes et al., 1996, (118)) and to eliminate the free-riding problem that arises from knowledge spillovers (De Brock, 1985; (36)). To this extent, a patent system constitutes a form of social control over knowledge that prevents firms to keep their knowledge advances for themselves while providing an incentive to engage R&D activities (Nordhaus, 1967, (129)). Such effect cannot be achieved through R&D subsidies only; this is the rationale this paper focuses on patent systems. The downside of a patent is that it confers a temporary market power to the patentee and therefore generates a temporary dead weight loss. The market power of the patentee invalidates the assumption of perfect competition on which relies *price fundamentalism*.

It should be noted that alternative theories on environmental innovation that derogate from 'price fundamentalism' have been proposed; albeit they do not explicitly discuss the design of a patent system. Weyant (2011, (167)) recommends a stronger government R&D budget dedicated to environmental technologies. Its argumentation is based on the existence of several barriers that stifle environmental innovation: the underpricing of environmental damages, the important role of not-for-profit research that does not respond to price signals and the difficult appropriation of energy technologies. Another critic can be found in Jaffe et al. (2005, (78)). These authors also discuss the issue of an imperfect internalization of environmental damages that limits investment in environmental technologies. In this second-best setting, they state that the two types of externalities, on the knowledge creation and on the environment, interact with each other making the implementation of support instruments dedicated to environmental innovation an efficient strategy.

To our view, the perfect internalization of environmental damages is not a sufficient condition to spur efficiently environmental innovation. To this extent, the aim of this paper is not to define the optimal patent policy when the environmental externalities are underpriced. Our focus is rather on the nexus of the patent system and the environmental taxation. We investigate this issue in a model of optimal patent policy for environmental inventions. It is demonstrated that the optimal tax paid by the patentee depends on the social cost of the patent system. To this extent, the regulator intervenes efficiently when the environmental taxation and the patent system are jointly designed. We conclude that environmental technologies should be promoted through a dedicated patent system.

4.3 The model

4.3.1 The race for the patent

In order to derive the optimal patent and environmental taxation policies, we have to represent how profit-seeking firms react to the economic incentive induced by the patent system. To do so, the race for the patent is modeled. It is based to a large extent on Loury (1979, (111)) and Lee and Wilde (1980, (104)). To our best knowledge these approaches, initially applied to invention races, were extended to optimal patent policy design by Denicolò (1996, (44)). Representing the patent race is necessary to deduct the incentive constraint the regulator has to take into account when she aims at inducing the desired amount of total R&D expenses denoted $\overline{X}$, that is assumed to be known and predetermined by the regulator. How $\overline{X}$ is chosen would raise the question of the socially optimal level of R&D expenses and it lies beyond the scope of the current paper.

Let consider n symmetric firms. They are all seeking to discover a new production process that reduces the MED associated with the production of a consumption good. We thus consider a 'purely' environmental invention since it only reduces environmental damages[1]. Each firm i, with $i = 1, ..., n$, chooses a level of R&D expenses denoted x_i. It will be paid at each period until the invention is discovered by one of the n competing firms. The racer who is the first to discover the invention wins the patent and obtains the corresponding payoff denoted B, defined later on. The losers do not earn any extra-profit from their R&D expenses. Firm i chooses x_i to maximize its expected profit that depends on: (1) the probability to win the race; (2) the payoff B. The former depends on two types of uncertainty: the intrinsic uncertainty of a R&D project (technological uncertainty) and the probability that a competitor wins the patent race by being the first to discover the invention (market uncertainty). The payoff B is, from the point of view of the competing firms, considered to be exogenous. Indeed, their R&D expenses only increase their chances to win the patent.

Technological uncertainty relates to the probability to discover an invention. The firm i knows that independently of its competitors the probability to discover the invention at a given period of time, denoted τ_i, increases with both the R&D expenses x_i and the time

[1]It does not influence, for instance, the marginal cost of production as it is often considered in the literature on the optimal patent policy dedicated to what we have called regular inventions (e.g. Nordhaus, 1967, (129); Denicolò, 1996, (44)).

t that has passed since the beginning of the research period. The probability law of the discovery time τ_i is

$$Pr(\tau_i \leq t) = 1 - e^{-h(x_i)t}.$$

The expected time of the discovery is then $E(\tau_i) = 1/h(x_i)$. It is assumed that there are decreasing returns on R&D, thus $h(.)$ is twice continuously differentiable, strictly increasing and concave. In the absence of any competitors the firm would choose x_i with respect to technological uncertainty only. However, the market uncertainty also influences the probability to win the race. It implies that the firm i takes into account the probability for a competitor to be the first to discover the invention. We denote $\overline{\tau}_i$ the earliest date at which one of the competitors of the racer i discovers the invention, hence we have $\overline{\tau}_i = Min(\tau_j, \forall j \neq i)$. Because firms are symmetric, they all face the same technological uncertainty and the probability law of $\overline{\tau}_i$ is

$$Pr(\overline{\tau}_i \leq t) = 1 - Pr(\tau_j > t, \forall j \neq i).$$

Denoting $H_i = \sum_{j \neq i} h(x_j)$, it can be rewritten

$$Pr(\overline{\tau}_i \leq t) = 1 - e^{-H_i t}.$$

When choosing its level of R&D expenses, the firm i will take into account these two sources of uncertainty and it is assumed it knows both the distributions of τ_i and $\overline{\tau}_i$. The probability to win the patent race thus becomes the probability to discover the invention before the discovery is made by a competitor. Considering that the firms are risk neutral and have perfect foresight, the expected profit from the patent race is the discounted value of the payoff from winning the patent, being B, weighted by the probability to win the patent race and minored by the discounted R&D cost paid until the discovery is realized by one of the racers. It is written

$$E(\Pi_i) = \int_0^{\infty} \left\{ \int_0^t Pr(\tau_i = s) B e^{-s\rho} \mathrm{d}s \right\} \mathrm{Pr}(\overline{\tau}_i = t) dt - \int_0^{\infty} \left\{ \int_0^t x_i e^{-s\rho} \mathrm{d}s \right\} Pr(\overline{\tau}_i = t \text{ or } \tau_i = t) \mathrm{d}t,$$

with ρ the discount rate. Integrating this expression gives

$$E(\Pi_i) = \frac{h(x_i)B - x_i}{H_i + h(x_i) + \rho}. \tag{4.1}$$

The level of R&D expenses only influences the probability to win the patent; The inventor maximizes (4.1) w.r.t x_i so that we can write

$$(H_i + \rho)(h'B - 1) - \Big(h(x_i^*) - x_i h'\Big) = 0$$

with h' the first derivative of h and x_i^* being now the private optimum of R&D expenses of the firm i. Obviously, the choice of x^* depends on B, among other parameters. The regulator, through the environmental taxation implemented and the level of protection guaranteed by the patent policy, will set B to induce the desired level of R&D expenses $\overline{X}$. Because the number of firms is fixed and that they are symmetric, it is equivalent for the regulator to equalize x_i^* to $\overline{x}$, denoting the desired level of individual R&D expenses. Inserting $\overline{x}$ in the previous expression and rearranging to isolate B, we have the following equality

$$B = \frac{h'(n - \overline{x}) + \rho}{h'[(n-1)h + \rho]}. \tag{4.2}$$

This expression represents the link between the payoff from winning the patent (B) and the individual R&D expenses $\overline{x}$. As the latter is known the r.h.s of equation (4.2) is a constant. What interests us is how the patent policy and the environmental taxation must be chosen to induce $\overline{x}$. To do so, we have to decompose B. Firms expect the winner's payoff B to be composed of two parts: the profit raised during the period of patent protection, denoted Π, and the profit raised after the patent has expired, denoted $\overline{\Pi}$. Hence we have

$$B = \int_0^T \Pi e^{-t\rho} \mathrm{d}t + \int_T^\infty \overline{\Pi} e^{-t\rho} \mathrm{d}t,$$

where T denotes the patent's length. Incorporating the developed form of B in equality (4.2) gives

$$\frac{\phi}{\rho}(\Pi - \overline{\Pi}) = K, \tag{4.3}$$

where $K = \frac{nh' - x^* h' + \rho}{h'[(n-1)h + \rho]} - \frac{\overline{\Pi}}{\rho}$ and $\phi = 1 - e^{-\rho T}$. The L.H.S of equation (4.3) depends on the strength of the patent protection (its breadth that influences Π and its length embodied in ϕ) and from the environmental taxes raised during the patent period that influence Π. The R.H.S of equation (4.3) is a constant including the profit realized after the patent period. This profit is considered to be exogenous as it does not depend from the patent system. After the patent has expired the remaining environmental externality is nonetheless assumed to be corrected by the first best taxation policy. The regulator has to find the optimal mix between the length of the patent, that determines the time during which the patentee will enjoy an extra-profit, and the amount of extra-profit $(\Pi - \overline{\Pi})$. This last term depends both on the patent's breadth and on the environmental taxation, as defined below.

4.3.2 General principles of the environmental patent policy

In this subsection we present the environmental patent problem and derive several general principles. The problem of the regulator is to maximize the total social welfare from the invention. This social welfare is written

$$\int_0^T W(\alpha, t_p, t_c) e^{-t\rho} \mathrm{d}t + \int_T^\infty \overline{W} e^{-t\rho} \mathrm{d}t,$$

where $W(\alpha, t_p, t_c)$ is the social welfare during the patent period and $\overline{W}$ is the social welfare after its expiry. The former depends from the patent breadt α, the tax paid by the patentee t_p and the tax paid by the competitors t_c. This expression can be written more simply as $(\phi/\rho)(W - \overline{W}) + \overline{W}/\rho$. Obtaining this improvement of social welfare is subject to the constraint that the private sector engages the desired amount of R&D, as stated by (4.3). Hence, the regulator's problem can be expressed as the following minimization problem

$$\underset{\phi,\alpha,t_p,t_c}{Min} \quad \frac{\phi}{\rho}(\overline{W} - W(\alpha, t_p, t_c)) - \frac{\overline{W}}{\rho}$$
$$s.t.c \quad \frac{\phi}{\rho}(\Pi(\alpha, t_p, t_c) - \overline{\Pi}) = K.$$

Both $\overline{\Pi}$ and $\overline{W}$ are constants because after the patent expires the regulator corrects the environmental externality by enforcing the first best environmental tax to firms. The problem of the regulator is to minimize the temporary dead weight loss of the patent system while inducing the right amount of R&D to achieve the discovery of the invention. Her intervention relies on four policy instruments:

- The patent's length T, embodied in ϕ, that has a positive influence on the patentee's reward. Obviously, both the temporary dead weight loss resulting from the patent and the incentive to increase individual R&D expenses increase with T.

- The patent breadth, denoted α, represents the strength of the protection guaranteed to the patent holder with respect to its competitors during the period of validity of the patent. The broader is the patent the harder it is for the competitors to use the new technology at its full potential. In this extent, when the breadth is minimum the new technology is in free access. At the other extreme of the protection spectrum, when α is maximum, there are no spillovers and the competitors are constrained to use the old technology.

- The environmental tax paid by the patentee per unit of produced output denoted t_p. Because having a patent identifies the firm as enjoying a technological advantage over its competitors the regulator is able to adjust the environmental tax paid by the patent holder.

- The environmental tax paid by competitors per unit of produced output, denoted t_c.

Substituting the constraint in the objective function and neglecting the constants K and $\frac{\overline{W}}{\rho}$, we can simplify the regulator's program as

$$\underset{\alpha, t_p, t_c}{Min} \; \frac{\overline{W} - W(\alpha, t_p, t_c)}{\Pi(\alpha, t_p, t_c) - \overline{\Pi}}. \tag{4.4}$$

The length of the patent, on which ϕ depends, can be deducted after solving (4.4) by using the incentive constraint (4.3). Deriving the FOCs of the program gives

$$W'_{t_p}(\Pi - \overline{\Pi}) + \Big(\overline{W} - W(\alpha, t_p, t_c)\Big)\Pi'_{t_p} = 0, \tag{4.5}$$

$$W'_{t_c}(\Pi - \overline{\Pi}) + \Big(\overline{W} - W(\alpha, t_p, t_c)\Big)\Pi'_{t_c} = 0 \tag{4.6}$$

and

$$W'_{\alpha}(\Pi - \overline{\Pi}) + \Big(\overline{W} - W(\alpha, t_p, t_c)\Big)\Pi'_{\alpha} = 0. \tag{4.7}$$

The novelty of our paper lies in the fact that the environmental feature of the patented invention puts forward a link between the environmental taxation and the patent. To solve analytically this problem we must know the social welfare expression and it implies to specify the competition regime, the demand and the production cost functions. This is done in the two applications presented in subsection 4.3.4 and 4.3.3. Nonetheless, this is not necessary if we want to derive several general principles that only rely on two realistic assumptions: $(\Pi - \overline{\Pi})$ and Π'_{t_p} are respectively non-negative and non-positive. The first proposition stipulates that the level of profit of the patentee is higher during the patent protection than after. This is a trivial assumption as the goal of a patent system is to guarantee an extra-profit that the inventor would not earn without a patent protection. The second one means that the patentee's profit cannot increases with the tax she has to pay; a straightforward intuition. When these two assumptions hold, two situations may arise from equation (4.5):

- First case: the dominant market position of the patent holder generates a dead weight loss during the patent period. Hence, all other things being equal, the social welfare is lower during the period of patent protection; we have $\overline{W} - W(\alpha, t_p, t_c) > 0$. Consider the benchmark case of the environmental taxation that maximizes W, i.e. $W'_{t_p} = 0$, denoted t^*. We can deduce from (4.5) that $W'_{t_p} > 0$, that implies that the optimal taxation paid by the patentee differs from t^*, that would have prevailed as the optimal tax in the absence of any patent system. Moreover, assuming that the social welfare is a strictly concave function of t_p and has an unique maximum t^* we conclude that the optimal level of environmental taxation of the patentee during the patent protection is below t^*. The patent system influences the environmental taxation policy, and we can expect this effect to be reciprocal because the reward from winning the patent depends from the tax paid by the patent holder.

- Second case: the patent system implies no dead weight loss during the patent period, hence $\overline{W} - W(\alpha, t_p, t_c)$ is nill. This case contrasts with the usual feature that a patent system, as a second best instrument, creates a temporary dead weight loss. The suppression of the temporary dead weight loss is achieved through the combination of the patent system and the environmental taxation. In this situation, the tax paid by the patentee maximizes the social welfare during the patent such that $W'_{t_p} = 0$. Here, implementing the optimal taxation suppresses the social cost of patent protection.

To synthesize, the double externality impacts the environmental patent policy in both cases. In the first case it prevents the regulator from deriving the environmental taxation paid by the patentee *as if* there was no patent system, that is by maximizing the welfare w.r.t the tax. In the second one, the double externality leads to an unusual situation where the patent system is not socially costly during its validity. Both situations are illustrated in the two following subsections.

4.3.3 Application 1: Optimal discriminatory taxation and patent policy in a Stackelberg competition

We consider the market for a polluting good and denote the produced quantity Q. The demand for this good is assumed to be linear and represented by the function $Q = a - dP$, where P is the price of the good. Producers, both the patentee and its competitors, have the same production cost function $C(q) = \frac{1}{2}q^2$ with q the quantity produced by a firm. The technological advantage of the patentee comes from the invention, being a less polluting production process. The magnitude of the spillovers towards its competitors is determined by the patent's breadth. Because the breadth of a patent depends from the claims made by the applicant(s). The content of the claims, and thus the protection scope of the patent, results from the negotiation between the applicant(s) and the patent examiner(s). In this extent the breadth can be regarded as the share of the new technology that is accessible to competitors without making them guilty of patent infringement. Drawing on this, we retain the following definition of the breadth: when the new invention allows for a decrease of the MED from e_0 to e with $e = e_0 - b$, the share of the technology that is lawfully accessible to the patentee's competitors allows them to reduce the MED of their production to $e_0 - (1-\alpha)b$. As in the previous subsection, the breadth is maximum when $\alpha = 1$ (no spillovers toward competitors) and minimum when $\alpha = 0$ (full spillovers toward competitors).

Once the winner of the race obtains the patent, she starts to produce. She knows that potential entrants will observe her decisions and because she has discovered first the new invention, we consider that she is able to anticipate the decisions of the potential entrants. Therefore, it is considered that the patent gives to its owner a Stackelberg leadership that competes in quantity with a competitive fringe of m firms. Since competitors must assess the share of the new technology they can copy without infringing the patent, additional research must be carried out and it generates an sunk cost denoted S, paid to enter the market. The quantity of output produced by the leader and the environmental tax she pays are respectively denoted q_l and t_l. The subscript f indicates the equivalents for each follower of the competitive fringe.

Subject to the incentive constraint, the regulator minimizes the temporary dead weight loss associated with the patent w.r.t. environmental taxes t_l and t_p, and the patent's breadth α. The F.O.Cs are

$$W'_\alpha = 0, \tag{4.8}$$

$$W'_{t_l}\Pi + (W(\alpha, t_l, t_f) - \overline{W})\Pi'_{t_l} = 0, \tag{4.9}$$

$$W'_{t_f}\Pi + (W(\alpha, t_l, t_f) - \overline{W})\Pi'_{t_f} = 0 \tag{4.10}$$

Combining (4.9) and (4.10), we obtain the following equality

$$W'_{t_f}\Pi'_{t_l} = W'_{t_l}\Pi'_{t_f}. \tag{4.11}$$

In this market setup the expression of the social welfare during the patent period is

$$W(\alpha, t_l, t_f) = \frac{1}{2d}Q^2 + (P - t_l - \frac{1}{2}q_l)q_l + m(P - t_f - \frac{1}{2}q_f)q_f - mS - eq_l - m(e_0 - (1-\alpha)b)q_f,$$

where $Q = q_l + mq_f$ the total quantity of produced output. The social welfare after the patent expires is equal to $\overline{W} = \frac{1}{2d}(a - de)^2$, as the patent holder loses the Stackelberg leadership and the market becomes perfectly competitive [2]. A corner solution is easily deducted for the optimal breadth which is minimum (the marginal loss in terms of welfare from increasing the patent breadth is positive and equal to mbq_f).

Developing and rewriting expression (4.11) give the optimal price $P = q_f + e$. As the firms of the competitive fringe are price takers they produce until their marginal cost of production ($q_f + t_f$, tax included) equals the market price and consequently the optimal tax paid by the competitive fringe denoted t_f^* is a Pigouvian tax: $t_f^* = e$. Inserting it into

[2] It should be kept in mind that under perfect competition firms enter the market until their profits fall to zero. This situation corresponds to a theoretically infinite division of production between producers since there are no fixed cost anymore after the patent expiry. Each firm will produce an infinitesimally small quantity and the marginal social cost of production (being the equilibrium price) will tend to e as the externality is corrected with a Pigouvian taxation.

(4.9) emphasizes the link between the temporary dead weight loss from the patent and the quantity of produced output:

$$(q_l - q_f)\frac{q_l}{2} = \overline{W} - W(t_l). \tag{4.12}$$

Developing this expression and simplifying, we obtain

$$\frac{1}{2d}(a - de)Q - m(\frac{q_f^2}{2}) = \frac{1}{2d}(a - de)^2.$$

Note that $m(\frac{q_f^2}{2})$ represents the total revenue earn by the competitive fringe that compensates the total sunk cost mS. Therefore, the difference between the level of produced output during the patent period, Q, and afterward, $(a - de)$, depends on the total amount of sunk cost. At this point we can derive the optimal level of tax t_l^*, being

$$t_l^* = e - (\frac{d+m+1}{d+m})(a - de) - (\frac{d+m+2}{d+m})Z \tag{4.13}$$

with $Z = \frac{mS}{(1/2d)(a-de)}$. The market price[3] can be deducted from the two environmental taxes and gives $P = e - (Z/d)$. As Z is positive this price is low enough to exclude the competitive fringe from the market since their profits are negative for every level of production. Hence, the expression t_l^* can be simplified to $t_l^* = e - (\frac{d+1}{d})(a - de)$. The optimal tax is lower than the MED in order to mitigate the patentee's market power. It remains nonetheless a temporary loss in terms of social welfare measured by the difference between W and $\overline{W}$. As q_f is nill, the equality (4.12) can be rewritten as

$$W = \overline{W} - \frac{q_l^2}{2}.$$

The temporary dead weight loss of the patent results from delegating the whole production to the same firm, being the patentee, because of the convexity of the cost function. The existence of a temporary dead weight loss provides for an illustration of the first case presented in subsection 4.3.2. In this extent the patentee must pay an environmental tax during the patent period that is lower than the level that would maximize the social welfare. Finally, the optimal length of the patent is derived by incorporating the patentee's profit $\Pi(t_l^*, t_c^*, \alpha^*)$ in the incentive constraint (4.3). We obtain

[3] The pricing equation resulting from the competition regime is $P = \frac{(d+m+1)(a+mt_f)+(d+m)t_l}{(d+m)(d+m+2)}$.

$$T^* = \frac{1}{\rho} ln(\frac{\Pi(t_l^*)}{\Pi(t_l^*) - \rho K}). \tag{4.14}$$

Because the optimal taxation policy excludes the competitive fringe, the profit of the patentee during the patent increases and it reduces the length of the protection duration.

4.3.4 Application 2: Patent length and environmental taxation with maximum breadth

In the previous application the optimal breadth of the patent is minimum. This arises from the fact that the discriminatory taxation can more efficiently control the difference of profits between the patentee and its competitors than the breadth does. In a simple case we now consider *ex ante* that the patent breadth is maximum. The advantage of such an assumption is to isolate the interaction between the environmental taxation of the patent holder and a patent system reduced to the period of protection, i.e. the length. Moreover, it offers the possibility for a straight comparison of our results with those of Nordhaus (1967, (129)) as this application is an extension to environmental inventions of his model of optimal patent length. As said before, the patented invention reduces the MED of production. We consider that this less polluting process of production generates a MED denoted e. A patent protection with a maximum breadth excludes any potential competitors to use the new process. As a result the patentee benefits from a temporary monopoly situation over the new technology.

Again, consider that the new technology is used to produce a polluting good and denote the produced quantity Q. The same demand function as in the previous application is retained. The marginal cost of production of the good is equal to c. For simplicity, we assume that e and c are both constant. Once the patent expires, all firms can use the patented invention and the market becomes perfectly competitive. The remaining externality on environment is internalized with a Pigouvian tax denoted t and equal to e. The social welfare after the patent has expired $\overline{W}$ is thus maximized and written $\overline{W} = \frac{1}{2d}\big(a - (c+e)\big)^2$. Moreover, the profit realized by the patent holder after the patent system has expired is zero and the incentive constraint (4.3) that can be written

$$\frac{\phi}{\rho}\Pi = K. \tag{4.15}$$

Substituting (4.15) in the regulator's program gives the following problem

$$\underset{t_p}{Min} \ \frac{\overline{W} - W(t_p)}{\Pi}.$$

Where $W = (1/2d)Q_p^2 + P_pQ_p - (c+e)Q_p$. With Q_p and P_p denoting respectively the quantity of output produced by the patentee and the corresponding price [4]. They both depend on the environmental tax t_p chosen by the regulator and paid by the patent holder. Differentiating w.r.t t_p, we have the following condition

$$W'_{t_p}\Pi = \Pi'_{t_p}(W - \overline{W}). \tag{4.16}$$

Replacing $\overline{W}$ by its expression in (4.16) and solving for t_p we derive the optimal tax paid by the patent holder denoted t_p^*:

$$t_p^* = e - \frac{1}{d}\left(a - d(c+e)\right). \tag{4.17}$$

The optimal level of environmental taxation kills two birds with one stone. First, it internalizes the environmental damage. Second, it corrects the market distortion caused by the monopolistic position of the patentee. This result is consistent with the literature on the optimal taxation of a pollutant monopoly (see Buchanan, 1969, (20); Lee, 1975, (103) and Barnett, 1980, (8)). The effect of the environmental taxation on the monopoly price and the resulting rent granted to the patent holder are represented on Figure 4.1. The rent is represented by the grey area.

The tax t_p^*, lower than the MED, makes the marginal production cost curve crosses the marginal revenue curve at a point that equalizes the monopoly price to the marginal social cost of production, being $c+e$. As a consequence the market equilibrium is the first best situation and the patent system generates no temporary dead weight loss. We can derive the implications of the environmental taxation t_p^* on the optimal patent length denoted T^*. Replacing the patentee's profit $\Pi(t_p^*)$ in the incentive constraint we obtain the optimal length

$$T^* = \frac{1}{\rho}ln(\frac{\Pi(t_p^*)}{\Pi(t_p^*) - \rho K}). \tag{4.18}$$

[4]Equalizing the marginal revenue and the marginal cost of the patent holder we obtain the usual expressions $Q_p = \frac{1}{2}(a - d(c+t_p))$ and $P_p = \frac{1}{2d}(a + d(c+t_p))$.

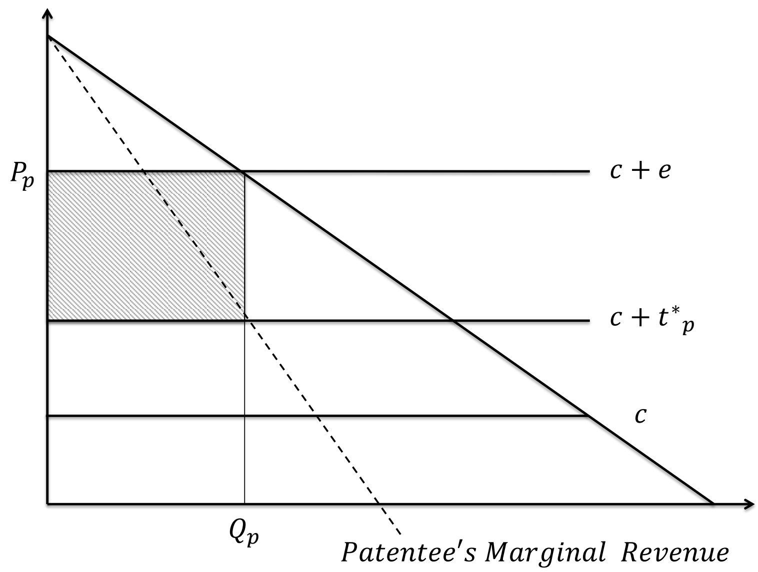

Figure 4.1: Optimal environmental taxation of the patent holder when breadth is infinite.

Several remarks must be made. First, compared to an invention that decreases the marginal cost of production c (a classic case widely covered by the literature; *e.g.* (129), (144) and (44)) the patent length for a environmental invention is shorter [5]. It results from the fact that the environmental taxation t_p^*, lower than e, induces a higher profit for the patentee that allows the regulator to shorten the patent length. Second, in this setup the patent system does not induce any dead weight loss for society during the patent protection as the monopoly power of the patentee is corrected. Hence, coupling a lower environmental taxation with a dedicated patent system provides for a more efficient policy than to separately correct each externality with help of an environmentally neutral patent system and an environmental tax disconnected from the competition regime associated with the patent protection. The application proposed in this subsection illustrates the second case evoked in subsection 4.3.2. However, it must be noted that the optimal tax t_p^* might become negative depending on the market conditions and it raises additional issues on the social acceptability and the funding of this subsidy.

[5]This comparison holds *ceteris paribus* for two inventions (a decrease of the MED versus a decrease of the marginal cost of production) with equal social yields. See proof in Appendix A.

4.4 Discussion and concluding remarks

This paper serves two purposes. The first is to detail the impact of the interactions between the two market failures on the environmental innovation within a patent system and to derive its general principles. The second is to provide for a narrower scope by investigating the optimal policies in two applications.

The first level of analysis can be called general as it includes as few assumptions as possible. They are mainly contained in the innovation race that generates the incentive constraint of the regulator' s problem. The value added of taking into account the patent race is to understand the determinants of the payoff from winning the patent that the regulator has to equalize to a constant K if she aims at inducing a predetermined level of R&D expenses. Another modeling strategy is to let this payoff unknown as in Klemperer (1990, (91)). The incentive constraint allows to formulate the problem of the regulator : to minimize the temporary dead weight loss generated by the patent system subject to the constraint that the private sector undertakes the desired level of R&D. Deriving the FOCs of the problem allows to deduct the general principles of the environmental patent problem by making two realistic assumptions. First, the level of the patentee' s profit is higher during the patent protection period than after its expiry. It is consistent with the principle of a patent system. Second, the profit of the patentee decreases with the environmental tax she pays as can be expected in reality. These assumptions are sufficient to demonstrate the existence of an interaction between a patent system and an environmental taxation policy. Two cases may arise:

- First, the optimal patent system has a social cost during the patent period. The condition of optimality (4.5) stipulates that the sign of the derivative of the social welfare during the patent period with respect to the environmental tax paid by the patentee should be positive. If the two externalities do not interact within the patent system the environmental tax paid by the patent holder would maximize the social welfare. Assuming that the social welfare is a concave function of the environmental tax paid by the patentee, we can conclude that the level of the tax paid by the patent holder is lower than the one that would have prevailed in the absence of a patent system.

- Another case may arise when the optimal patent system does not generate a dead weight loss during its validity. In this setting, the environmental tax paid by the

> patentee maximizes the social welfare during the patent period. Again, the introduction of an environmental externality in the patent system influences the optimal policy. Indeed, the regulator could jointly implement a patent system and an environmental taxation policy that are not socially costly during the patent period. This conclusion strongly contrasts with the literature on optimal patent policy built on the tradeoff between the temporary dead weight loss resulting from the market power of the patentee and the increase of welfare from knowledge creation.

The second level of analysis presents two applications of the environmental patent problem. An abundant literature on patent policy has demonstrated the high sensitivity of the optimal policy to the competition regime in place during the protection period, a feature explained by Denicolò (1996, (44)). Hence, our two applications do not pretend to give systematic guidelines to policymakers but rather to illustrate the general principles derived from the first level of analysis.

The first application considers that the patentee has a Stackelberg leadership and that there are market opportunities for a competitive fringe. It appears nonetheless that the optimal strategy for the regulator is to exclude the competitors by setting the environmental tax they pay equal to the level of MED and a lower tax for the patent holder. This lower tax makes the market price equals to the MED and it prevents the competitive fringe to enter the market. Since an increasing marginal cost of production is considered, the temporary dead weight loss of the patent, compared to perfect competition, arises from the fact that the patentee carries the totality of the production. In comparison of the post patent period, there is an additional cost due to the concentration of the production in a single firm.

The second application focuses on the articulation between the patent length and the environmental taxation. Because the optimal breadth was found to be minimum in the previous application, it is now assumed that the breadth is maximum and that the patentee is in monopoly situation. The dead weight loss resulting from the monopoly position during the patent period can be suppressed by implementing a *low* environmental tax that makes the monopoly price equals to the marginal social cost of production. Here, the term *low* refers to an environmental tax smaller than the level of MED of production. Hence, the welfare during the patent period is at its first best level. The taxation of a pollutant monopoly is a question that has been investigated by Buchanan (1969, (20)), Lee (1975, (103)) and Barnett (1980, (8)). What interests us here is the opportunity for the regulator to suppress the temporary dead weight loss of the patent by adjusting the tax paid by the patent holder.

Simultaneously, the patent's length is adjusted to the particular taxation conditions enjoyed by the patentee and it is shortened, compared to the optimal length of a patent protecting a regular invention. Despite the attractiveness of this solution it suffers however from a lack of realism. We assume that the regulator has perfect information about the market structure and is able to fully *control* the monopoly with the sole tool of the environmental tax. Second, the tax could be negative for some values of the parameters, especially when the new invention allows a low level of MED. It would be relevant to investigate the funding of this subsidy as well as its social acceptability. Despite the differences between the two applications in terms of competition regimes the optimal policies follow the same principle: the market power of the patentee is counterbalanced by a low environmental tax that reduces, and possibly annihilates, the temporary social burden of the patent system. It has another consequence: the low environmental tax has a positive impact on the patentee's profit and it makes the patent's length shorter.

We can summarize the main idea of this paper as follows. Consider a regular process invention that decreases the marginal cost of production without changing the environmental damage of the production. The profit of the inventor will depend on the cost savings allowed by the new process. These cost savings are exogenous and consequently outside the scope of the regulator's intervention. For an environmental invention the situation is different. In fact, the *conversion* of the environmental gains into private gains is made through the environmental taxation defined by the regulator. Contrary to the regular case, environmental taxation comes in addition to the two dimensions of the patent system, its breadth and its length. This provides for broader possibilities to the regulator who can differentiate the private reward between the patentee and its competitors from the environmental gains. Hence, the role of the breadth is rendered obsolete when coupling the patent system with a discriminatory environmental taxation. Indeed, in a regular patent system the breadth will delimit the access of the competitors to the new technology. When the regulator chooses the breadth of the patent, she knows it will induce the difference of the production cost between the patentee and its competitors and indirectly the difference of profits. In the environmental patent problem the breadth does not raise the same issues: it will have a social impact through the level of environmental damage. The difference of production cost between the patentee and its competitors will be endorsed by the discriminating environmental taxation.

To conclude, the goal of this model is to demonstrate that patent policy and environmental taxation should be jointly designed by the regulator. The interaction between the two policies advocates for a patent system dedicated to environmental technologies and jointly implemented with an *ad hoc* environmental taxation of the patent holder. However, our results remain to be tested against real world. The first barrier to a patent system dedicated to environmental inventions is to identify to what extent an invention is effectively environmental. To this extent, the experiments of the 'fast-track green patent applications' are useful. These systems are implemented in many countries[6] and allow to accelerate the examination process of applications that are considered to be 'green'. It proves that such identification exercise can be conducted by patent offices. Moreover, the idea of a discriminatory taxation can be realized trough a tax credit, refunded to the inventor that pays an environmental tax during the patent period. Nonetheless, several additional issues arise. First, environmental damages are currently underpriced. A cautious optimism suggests that it will evolve in the next years but for the moment it limits our purpose. Second, different institutions are responsible of patent and environmental policies. The representation of a unique regulator is too simplistic. Third, this is hard to think of an invention that would be strictly 'environmental'; the model should extended to an invention that reduce, for instance, both the production cost and the environmental damage from production. Finally, our paper focuses only on patent policy but the same issues deserve to be investigated for different instruments of support to knowledge creation, such as R&D subsidies.

[6]This is the case , for instance, in the United-Kingdom, the United-States of America, Japan, Canada and Australia. The first systems have been implemented in 2009, for an analysis of these see Dechezleprêtre, 2013, (200).

Appendix

4.A Appendix A: Optimal patent length

We give proof that the optimal patent length defined in equation (4.18) is, *ceteris paribus*, shorter than the optimal length for a regular invention in a context where there is no market failure on environment. We consider that the regular invention allows a decrease of the marginal cost of production from c_0 to c and the environmental invention a decrease of the MED from e_0 to e. Since we consider two inventions with the same social value we have $e_0 - e = c_0 - c$. The first inventor (regular inventor) produces a non polluting good and the second inventor (environmental inventor) produces a polluting good at a zero cost, tax excluded. Computing the optimal patent length using the incentive constraint where x^* is the same for both inventions, it appears that if the profit of the environmental innovator (Π_{green}) is higher than the profit of the regular innovator ($\Pi_{regular}$), then the optimal length is shorter for the former. The two inventor's profits are:

$$\begin{cases} \Pi_{green} = \dfrac{1}{d}(a - de)^2 \\ \Pi_{regular} = \dfrac{1}{4d}(a - dc)^2 \end{cases}$$

As $e = c$, the environmental patent is shorter.

Chapter 5

Analyse globale des résultats

Pour situer le rôle de l'innovation dans le changement technique il est utile de décomposer ce dernier en trois stades: l'invention (la génération de nouvelles idées), l'innovation (la conversion des inventions en produits ou techniques commercialisables) et la diffusion (la propagation de l'innovation dans la société). Cette décomposition du changement technique, proposée en 1943 par Schumpeter, implique que chaque étape soit conditionnée par la réalisation de la précédente (1943, (190)). Le changement technique amorcé grâce aux technologies de l'énergie bas-carbone ne répond pourtant pas nécessairement à cette logique, et ce pour deux raisons :

- Premièrement, le signal de marché informant les agents des bénéfices environnementaux de ces technologies est faible, voire inexistant, ce qui fait d'une partie des inventions des innovations latentes, car en attente d'un signal de marché leur assurant des débouchés commerciaux.

- Deuxièmement, les politiques publiques telles qu'elles ont été mises en place ont pu contribuer à promouvoir la diffusion d'une technologie bas-carbone, sans garantie qu'elle soit fondée sur l'innovation.

De fait, la diffusion des nouvelles technologies de l'énergie bas-carbone, et plus spécifiquement les TERs, offre un indicateur biaisé du changement technique vers un système énergétique décarboné. Il convient donc dans un premier temps de disséquer la diffusion de ces technologies telle qu'elle s'est amorcée, en vue d'isoler le rôle des politiques de soutien *demand-pull*.

La diffusion de la technologie éolienne

Puisque la production d'électricité d'origine éolienne est désormais considérée comme proche de la parité réseau[1] (IEA, 2015, (217)) et que la diffusion de cette technologie bas-carbone constitue l'une des premières, avec celle du solaire photovoltaïque (PV), à avoir bénéficié d'un important soutien demand-pull, l'étude proposée dans le Chapitre 2 peut servir de référence à l'analyse du soutien au déploiement des TERs. Cette étude s'inscrit dans un contexte particulier de politique de soutien à l'innovation. Ces dernières peuvent être scindées en deux catégories : le soutien à l'innovation *demand-pull* et le soutien à l'innovation *supply-push*. Or en Europe, la répartition entre les deux approches est pour le moins inégale et ce déséquilibre est soupçonné de réduire l'efficacité du soutien (Albrecht et al., 2015, (3)). Une quantification de ce déséquilibre est proposée par Zachmann et al. (2014, (193)) dont l'étude révèle que dans les cinq plus grands pays Européens, ainsi qu'en République Tchèque, le coût du déploiement de l'éolien et du solaire PV a atteint pour la seule année 2010 la somme de 48 298 millions €, tandis que les dépenses publiques de R&D destinées à ces deux technologies étaient de 315 millions €.

L'impact des instruments demand-pull sur la diffusion de la technologie éolienne est quantifié pour six pays, choisis de manière à isoler deux profils :

- Les pays producteurs & consommateurs d'équipements éoliens que sont l'Allemagne, le Danemark et l'Espagne.
- Les pays consommateurs d'équipements éoliens que sont la France, l'Italie et le Portugal.

Le soutien demand-pull à la diffusion de l'éolien dans les pays producteurs & consommateurs a commencé plus tôt, relativement aux pays consommateurs[2]. Il a été accompagné par la création de filières industrielles nationales dans la technologie éolienne qui ont bénéficié d'un soutien supply-push important de la part des pouvoirs publics. Ce soutien supply-push s'est ensuite prolongé comme l'illustrent les différences de dépenses publiques de RD&D rapportées[3] dans le Tableau 5.1.

[1]La parité réseau correspond à la situation où le coût moyen de génération de l'électricité d'origine renouvelable est égal au prix de marché de l'électricité.

[2]Les premières formes de soutien demand-pull à l'éolien sont mises en place en 1980 en Espagne, en 1981 au Danemark, en 1991 en Allemagne puis en 1992 en Italie et en 1996 en France (Johnstone et al., 2010, (81); IEA, 2004, (210)). Au Portugal c'est en 1988 que le premier soutien à la demande d'énergie renouvelable voit le jour, mais il se limite initialement aux petites installations hydro avant d'être étendu à l'éolien en 1995.

[3]La source des données est la base de données de l'IEA: Energy Technology RD&D, 2015 edition. Le choix des années est conditionné par la disponibilité des données.

	Allemagne	Danemark	Espagne	Italie	France	Portugal
Dépenses de RD&D cumulées (1993-2011)	468,15	247,7	138,5	68,35	33,5	1,6

Table 5.1: Dépenses de RD&D dédiées à la technologie éolienne (en millions € constant de 2014).

Dans un premier temps, le couplage des approches demand-pull et supply-push aura permis aux industries nationales d'avoir accès à un marché domestique en pleine expansion assurant les débouchés de la filière[4]. Dans un second temps, ces industries bénéficieront des opportunités de marché offertes par leurs voisins européens. En 2008, sept firmes d'origines allemandes, danoises et espagnoles se partageaient 94% de la puissance éolienne installée cumulée en Italie et 93% au Portugal[5].

Comment l'existence d'une filière industrielle se traduit-elle dans les dynamiques de diffusion de l'éolien?

Les diffusions de l'éolien à l'échelle nationale dans les pays producteurs & consommateurs se distinguent par un caractère partiellement auto-entretenu. La diffusion est dite partiellement auto-entretenue quand elle résiste de manière significative à la suppression des politiques demand-pull, aussi bien nationales qu'étrangères.

En dépit du surplus de profitabilité induit par les instruments de soutien demand-pull, les simulations menées dans le Chapitre 2 indiquent que la suppression unilatérale[6] par un pays producteur & consommateur aurait certes impacté à la baisse la diffusion de l'éolien, mais qu'une partie significative de la diffusion aurait pu avoir lieu en l'absence d'une subvention s'ajoutant au prix de marché; et ce avec pour seule garantie de la part de l'État celle d'une priorité d'accès au réseau de l'électricité éolienne. Si l'Allemagne avait supprimé unilatéralement son soutien demand-pull en 2001, la capacité cumulée installée en 2012 aurait été réduite de 32,4%. Pour le Danemark et l'Espagne des ordres de grandeurs similaires

[4]Prenant l'année 2000 comme année de référence, on observe que respectivement 58%, 65% et 92% de la puissance éolienne nouvellement installée dans l'année en Allemagne, au Danemark et en Espagne, sont des turbines produites par des firmes nationales. Celles produites à l'étranger provenaient généralement des deux autres pays. Tous les calculs de parts de marché sont réalisés avec les données disponibles dans les rapports annuels de l'IEA Wind, sauf dans le cas du Danemark où les données sont produites par la base Master data on Register wind turbines. A notre connaissance, les données pour la France ne sont pas disponibles.

[5]Ces firmes sont Enercon, REpower, Gamesa, Vestas, Ecotechia, Nordex et Siemens.

[6]La suppression unilatérale par un pays est la suppression de l'instrument demand-pull dans un contexte où les autres pays, au contraire, maintiennent leurs politiques de soutien demand-pull.

sont trouvés puisque la réduction aurait été de respectivement 34,6% et 43,3%. Le soutien demand-pull a donc agi dans ces pays comme un accélérateur de la diffusion.

Les dynamiques de diffusion au sein des pays consommateurs, au contraire, ne présentent pas ce caractère partiellement auto-entrenu puisqu'elles s'avèrent être presque exclusivement expliquées par l'existence des instruments de soutien demand-pull. Dans ces pays, la diffusion est fortement imputable à ces instruments puisque leurs suppressions unilatérales en 2001 auraient réduit la capacité éolienne installée cumulée en 2012 de 95,3% en France, de 71,5% au Portugal et de 84,5% en Italie.

Intuitivement, on pourrait penser que la diffusion observée dans les pays producteurs & consommateurs s'explique par l'apprentissage acquis via les ventes réalisées chez leurs voisins européens. Ces ventes permettent aux secteurs des équipements éoliens d'accumuler de l'expérience qui se traduit par une réduction des coûts et, en augmentant la profitabilité des installations éoliennes, stimulent la diffusion de la technologie. Nos conclusions ne vont pas dans ce sens puisque la diffusion de la technologie éolienne dans les pays producteurs & consommateurs n'est que partiellement expliquée par les politiques mises en place dans les autres pays. En effet, une suppression commune aux six pays des politiques demand-pull en 2001 auraient respectivement réduit d'environ 41%, 41% et 54% la capacité cumulée installée en 2012 en Allemagne, au Danemark et en Espagne. Les impacts sur les diffusions sont donc certes plus forts que ceux résultants des suppressions unilatérales, mais il demeure qu'une partie substantielle de la diffusion résiste aux suppressions jointes des politiques demand-pull[7].

Le caractère auto-entretenu de la diffusion dans les pays producteurs & consommateurs s'explique par : (1) l'avantage de first mover que confère l'antériorité du début de la diffusion, par rapport aux pays consommateurs, et qui se traduit par une plus forte baisse des coûts en début de diffusion permettant d'amorcer un cercle vertueux d'apprentissage; (2) la sensibilité de la diffusion à l'apprentissage technologique dont profite le pays, relativement plus forte au learning-by-doing national que régional (i.e. européen). En effet, le modèle utilisé intègre une distinction entre les deux échelles d'apprentissage et les dynamiques de diffusion de l'éolien dans les pays producteurs & consommateurs sont d'avantage dictées par l'apprentissage national, relativement à l'apprentissage régional, que ne le sont les pays consommateurs[8].

[7]En 2001, les six pays analysés représentaient 89,43% de la puissance installée éolienne en Europe (EU-28). Cette part a diminué progressivement pour atteindre 74% de la capacité installée éolienne en 2012 (parts calculées d'après les données de l'EWEA). Ces six pays cumulaient donc la majeure partie de l'apprentissage européen.

[8]Concernant l'échelle géographique de l'apprentissage dans l'éolien et son évolution avec la maturité de la technologie, voir Langniss et Neij, 2004, (96).

Les avantages de fonder la diffusion d'une technologie sur un secteur de l'offre performant

Sur la base de ces résultats, nous pouvons conclure que l'existence d'une filière industrielle sur laquelle fonder la politique de soutien demand-pull présente deux avantages. Premièrement, elle permet d'accélérer la diffusion de la technologie soutenue. Deuxièmement, elle permet de garantir son déploiement, au moins partiel, aux conditions de marché avec pour seul forme de soutien la priorité d'accès au réseau de l'électricité d'origine renouvelable. Ce deuxième avantage suggère qu'un prix carbone aurait pu se substituer aux soutiens demand-pull sans pour autant réduire drastiquement la diffusion de l'éolien ; *a fortiori* si celle-ci est fondée sur l'existence d'une filière industrielle.

Ce constat soulève la question de la répartition des compétences techniques entre les pays et des performances des technologies de l'énergie bas-carbone en termes d'innovation. D'une part, la localisation géographique des compétences techniques produit une information sur laquelle construire une politique de soutien à l'innovation. D'autre part, les pouvoirs publics peuvent ajuster le soutien accordé à une technologie selon ses performances en termes d'innovation. La méthode développée dans le Chapitre 3 permet de répondre à ces questions.

La distribution de la connaissance selon les pays et les technologies

L'accumulation de connaissance technique dans les technologies de l'énergie bas-carbone n'est pas un phénomène récent. Comme en témoigne la Figure 5.1, le niveau de connaissance produite pendant l'année 1981 par les sept pays et dans les 15 technologies de l'énergie bas-carbone analysés ne sera pas atteint de nouveau avant 2008. La production annuelle de connaissance technique, mesurée par le flux annuel d'inventions pondérées par leur qualité, est représentée par la courbe en trait plein sur la Figure 5.1. La courbe en pointillés représente l'évolution du prix déflaté du pétrole et souligne ainsi la corrélation avec la connaissance produite dans les technologies de l'énergie bas-carbone. Cette corrélation soutient l'hypothèse de changement technique induit selon laquelle ce dernier est dirigé par les prix relatifs des facteurs de production (Hicks, 1932, (183)).

La majeure partie du stock de connaissance accumulée entre 1980 et 2010 dans les technologies de l'énergie bas-carbone est détenue par les USA (50,67%), l'Allemagne (18,42%) et la France (13,67%). La composition des stocks de connaissance de ces pays fait état d'une forte diversification technologique. Il en ressort toutefois que les technologies ayant le plus

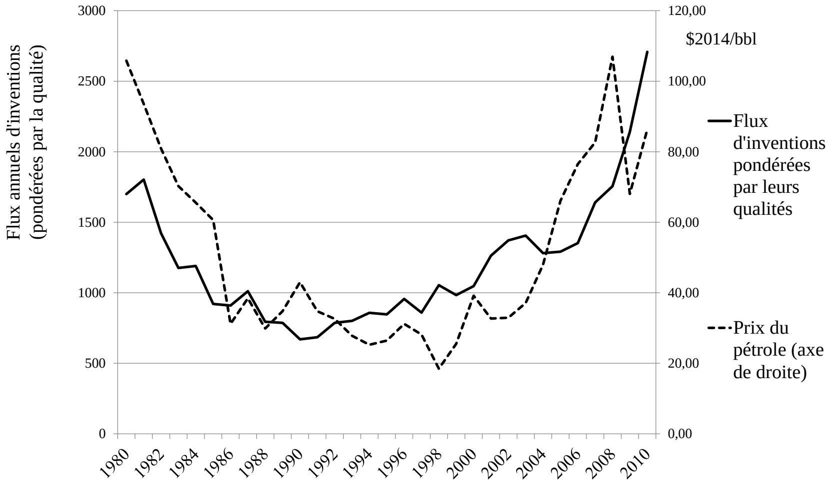

Figure 5.1: Flux annuels d'inventions pondérées par leur qualité, dans les sept pays et les quinze technologies.

de poids dans les stocks de connaissance de ces trois pays sont le stockage de l'énergie, le solaire PV, l'éolien et le nucléaire.

Pour compenser un plus faible niveau de production de connaissance, une stratégie adoptée par certains petits pays a été de se spécialiser dans un nombre plus restreint de technologies. L'exemple le plus évident est celui du Danemark dont le stock de connaissance est constitué à 78% de technologie éolienne. L'Espagne et les Pays-Bas ont également choisi de se spécialiser respectivement dans l'éolien et le solaire thermique (57% du stock de connaissance de l'Espagne en 2010), et dans l'éolien, le solaire photovoltaïque et le stockage d'énergie (61% du stock de connaissance des Pays-Bas en 2010).

Ces chiffres illustrent la production de connaissance mesurée en incluant la totalité des inventions de notre base de données. L'indice de qualité développé permet de resserrer notre analyse sur les inventions de haute qualité, candidates favorites à un succès commercial qui traduit l'accès au statut d'innovation. Pour identifier les technologies sur lesquelles les efforts d'innovation se concentrent dans ces pays, nous ne retenons que les 10% d'inventions de plus haute qualité dans chaque pays. Les résultats sont résumés dans le Tableau 5.1 et reflètent les compétences technologiques des sept pays étudiés. Les poids des technologies dans les 10% de meilleures inventions sont rapportés entre parenthèses.

La spécialisation dans un champ technologique peut s'avérer coûteuse car mener à des situations de verrous technologiques (Arthur, 1989, (5)). Les verrous technologiques se forment quand des évènements historiques, a priori insignifiants, vont accorder un gain d'apprentissage à une technologie qui l'emportera sur d'autres en dépit de sa plus faible efficacité de long-terme, i.e. une fois que la technologie est déployée et sortie de sa phase

Pays	Compétences techniques
Allemagne	Éolien (19%), Solaire PV (15%), Nucléaire (14,86%), Solaire thermique (11,7%), Stockage d'énergie (10,4%)
Danemark	Éolien (44,4%), Bio-carburants (18,5%), Énergie des mers (14,8%)
Espagne	Solaire thermique (29,8%), Éolien (29,8%)
France	Nucléaire (33,4%), Stockage d'énergie (13,9%)
Grande-Bretagne	Solaire PV (16,13%), Éolien (14,5%), Stockage d'énergie (10,5%)
Pays-Bas	Solaire thermique (22%), Solaire PV (20,6%), Éolien (16,17%), Bio-carburants (13,2%)
USA	Stockage d'énergie (21,23%), Solaire PV (18,4%)

Table 5.2: Compétences techniques des pays, en pourcentage des meilleures inventions nationales.

d'apprentissage. Ainsi la performance d'un pays dans un secteur dépend du profil de la technologie. L'identification d'une compétence relativement meilleure dans un champ technologique ne constitue donc pas en soi un élément suffisant sur lequel construire une politique de soutien à l'innovation puisque les activités de R&D dans les technologies, selon leurs stades de maturité entre autre, vont être plus ou moins performantes. Sur ce point, l'indice de qualité des inventions brevetées permet de distinguer les technologies selon la performance des inventions en termes de connaissance.

Évolution de la performance des inventions en termes de connaissance

L'originalité de la démarche proposée dans le Chapitre 3 est d'introduire la notion de qualité dans la mesure de la connaissance. Le cumul d'un grand nombre d'inventions n'indique pas en soi l'existence d'une connaissance féconde à l'innovation. Ce passage du statut d'invention à celui d'innovation peut être capté par la performance des inventions en termes de qualité de la connaissance[9]. Suivant les travaux de Popp et al. (2013, (138)), les performances sont analysées de deux manières : (1) la performance moyenne d'une technologie, mesurée par la qualité moyenne des inventions ; (2) la distribution des performances d'une technologie, mesurée par la distribution des inventions en termes de qualité pour une technologie donnée.

Les évolutions dans le temps de ces deux dimensions de la performance révèlent des différences marquées entre les technologies. On se limitera à quelques technologies majeures

[9]Une vaste littérature empirique met en exergue le lien entre les métriques de brevet et la valeur économique des inventions (e.g. Schankerman et Pakes, 1986, (150); Harhoff et Wagner, 2009, (69); Lerner, 2004, (106); Hall et al., 2005, (65)). L'indice de qualité étant construit à l'aide de l'information que contiennent les métriques, il est lui-même relié à la valeur économique de l'invention. Par ailleurs, Lanjouw et Schankerman (2004, (100)) valide le lien entre l'indice de qualité et la valeur boursière des entreprises innovantes.

en ce qu'elles représentent les plus fortes parts du stock de connaissance accumulé à l'année 2010. La performance moyenne des inventions en termes de connaissance a augmenté dans le temps pour le solaire PV, le stockage d'énergie et l'éolien. Conjointement, la distribution de la qualité des inventions s'est progressivement étalée vers des niveaux plus grands de l'indice de qualité, indiquant que le cumul de connaissance s'accompagne d'un accroissement des découvertes d'inventions plus performantes.

Les technologies de l'énergie nucléaire et de l'énergie solaire thermique présentent des résultats opposés. D'une part, la performance moyenne des inventions brevetées dans le nucléaire a diminué dans le temps. D'autre part, la distribution des inventions a eu tendance à progressivement se concentrer autour de valeurs plus faibles de la qualité. La technologie de l'énergie solaire thermique voit également le nombre de découvertes d'innovations performantes décroitre dans le temps. Toutefois la qualité moyenne de l'ensemble des inventions tend à rester stable. Ces résultats plaident en faveur d'un soutien à ces deux technologies se limitant à la recherche fondamentale, visant à provoquer des innovations de ruptures. Celles incrémentales, c'est-à-dire bâties sur la technologie telle qu'existante, ont de plus faibles chances d'être performantes.

Des technologies encore immatures peuvent révéler sur le long terme un important potentiel d'innovation et ainsi contribuer à fortement réduire le coût de la transition énergétique (Popp et al., 2013, (138)). L'augmentation dans le temps de la qualité moyenne des inventions brevetées dans ces technologies suggère qu'elles devraient faire l'attention d'un soutien renforcé de la part des pouvoirs publics. C'est le cas des bio-carburants, de l'énergie des mers, de l'hydro-énergie et de l'hydrogène. Au contraire, la performance moyenne des inventions dans des champs technologiques pourtant clés comme le CCS et les réseaux intelligents a stagné au fil du temps.

La spécificité de l'innovation environnementale

L'analyse empirique se fonde sur la mesure de la connaissance développée dans le Chapitre 3 pose la question des instruments dont dispose le régulateur pour stimuler la création de connaissance. De plus, l'étude du soutien à la diffusion a démontré l'intérêt de construire le déploiement d'une technologie sur l'existence d'un socle de connaissance technique. Les pouvoirs publics disposent de deux moyens d'actions pour orienter les investissements du secteur privé vers la création de connaissance : (1) accroître l'appropriation d'une invention pour permettre à l'inventeur de convertir une part de la connaissance créée en une rente d'innovation, si tant est que l'innovation rencontre une demande ; (2) à niveau d'appropriation donné, accroitre le profit de l'inventeur en diminuant le coût de la R&D ou en augmentant le revenu de la vente de l'innovation.

Le contrôle par un régulateur du degré d'appropriation d'une invention par son inventeur à l'aide d'un système de brevet permet de réduire les coûts sociaux de la dissimulation de la connaissance et du manque d'incitation à innover (Nordhaus, 1967, (129)). Le Chapitre 4 traite la question du système de brevet quand celui-ci s'adresse aux technologies environnementales. Il fait ainsi écho à la discussion amorcée dans le Chapitre 1 portant sur le rôle de la double externalité.

Les différents modèles théoriques pouvant servir de guides aux politiques de soutien à l'innovation dans les technologies de l'énergie bas-carbone, présentés dans le Chapitre 1, se distinguent par leurs traitements des défaillances de marché sur l'environnement et sur la connaissance. Le modèle du 'price fundamentalism' repose sur deux hypothèses centrales pour déduire que les politiques de soutien à l'innovation ne doivent pas traiter différemment les technologies environnementales des autres types de technologies. Deux modèles alternatifs dérivent de l'abandon de l'une et l'autre de ces hypothèses. Pour autant, le modèle du 'price fundamentalism' n'a pas été testé dans le cadre d'un système de brevet, qui pour les raisons détaillées ci-dessus constitue une pierre angulaire des politiques d'innovation. Ainsi, un quatrième modèle alternatif, celui de 'strong double externality', est étudié et propose un système de brevet dédié à l'innovation environnementale.

L'interaction entre l'appropriation de la connaissance et la tarification des dommages environnementaux

Il fait consensus dans la littérature que garantir l'appropriation partielle d'une invention via un système de brevet constitue un arbitrage pour le régulateur entre l'impact positif de long terme qu'aura l'invention sur le bien-être social et le coût social de restreindre temporairement l'accès à cette nouvelle invention pour garantir une rente technologique à l'inventeur, supposée l'inciter à investir (e.g. Nordhaus, 1967, (129); Klemperer, 1990, (91); Gallini, 1992, (53); Denicolò, 1996, (44)).

L'intuition économique sur laquelle se fonde la double externalité dans sa version forte est la suivante. Considérons deux inventions ayant, à niveau égal d'appropriation, le même impact sur la société, l'une nommée régulière et l'autre environnementale. La première constitue par exemple une technique de production dont l'avantage sera rétribué via des marchés, et donc un système de prix, préexistant. La seconde, au contraire, est une technique de production dont le rendement se fait uniquement via l'existence d'une tarification des externalités environnementales, que l'invention permet de réduire toutes choses égales par ailleurs. Le régulateur implémente : (1) un système de brevet qui garantit une appropriation plus ou moins forte de l'invention en vue de garantir une rémunération incitative à l'inventeur, (2) une tarification environnementale pour internaliser les externalités sur l'environnement.

L'invention régulière présente deux dimensions. La première est sa dimension sociale et la seconde sa dimension privée. Le rendement social de l'invention régulière correspond à la création de bien-être social provenant de l'avantage technique que permet l'invention. Le rendement privé de l'invention est celui qui sera internalisé sous forme de profit par l'inventeur. Chacun dépend de deux éléments communs définis ci-dessous.

La magnitude de l'avantage technique qui jouera positivement sur le rendement social et le rendement privé de l'invention. Le raisonnement proposée portant sur deux inventions ayant, à niveaux d'appropriation égaux, le même rendement social les magnitudes des avantages que confèrent ces inventions sont fixes et équivalentes en termes de bien-être social.

L'appropriation de l'invention. Si elle est nulle, l'invention est en accès totalement libre et son rendement social atteint une borne supérieure théorique[10] tandis que son rendement privé tombe à zéro puisque l'inventeur ne profitera d'aucun avantage technologique sur ses concurrents; ces derniers ayant un accès libre à l'innovation. Inversement, si l'appropriation est parfaite, l'invention n'est accessible à personne d'autre que l'inventeur et son rendement social est minimisé, tandis que son rendement privé est maximisé. Les variations des rendements social et privé de l'invention régulière en fonction de son appropriation sont représentées respectivement par la courbe décroissante en trait plein et la courbe croissante en pointillés sur le cadran de gauche de la Figure 5.2. Pour une appropriation totale (i.e. 100%) les deux rendements se confondent puisque seul l'inventeur bénéficie de l'invention.

L'arbitrage auquel fait face le régulateur en mettant en place un système de brevet est de choisir le niveau d'appropriation de manière à garantir à l'inventeur un rendement privé incitatif considéré connu et noté $\overline{R}$ sur la Figure 5.2. Il en résulte le niveau d'appropriation concédé A_r.

L'invention environnementale a également deux dimensions: privée et sociale. Chacune de ces deux dimensions est également impactée par l'appropriation de l'invention de manière similaire au cas de l'invention régulière. Le rendement social de l'invention environnementale est représenté par la courbe pleine sur le cadran de droite de la Figure 5.2.

[10]La borne supérieure est dite théorique car une partie de l'invention, même en l'absence de système de brevet, demeure toujours internalisable par l'inventeur via par exemple des stratégies de secret industriel.

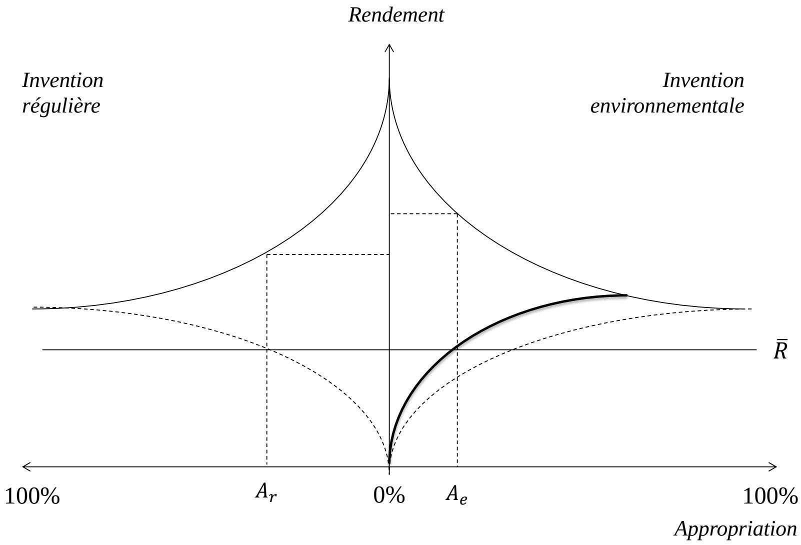

Figure 5.2: Illustration de l'interaction entre la taxation environnementale et l'appropriation d'une invention.

Cependant, la conversion du gain environnemental d'une technique moins polluante en des bénéfices privés se fait par l'intermédiaire de la politique environnementale. Ainsi pour un niveau donné d'appropriation de l'invention le régulateur peut ajuster le rendement privé à l'aide de la taxe environnementale.

Si la taxe environnementale payée par l'inventeur internalise parfaitement les dommages environnementaux, les rendements privés d'une invention environnementale et d'une invention régulière évolueront de la même façon avec l'appropriation de l'invention. Dans ce cas de taxation Pigouvienne (Pigou, 1932, (189)), l'évolution rendement privé d'une invention environnementale avec l'appropriation est décrit par la courbe en pointillés sur le cadran de droite de la figure. Qu'en est-il si le régulateur fixe une tarification des dommages environnementaux plus faible pour l'inventeur ? La courbe de rendement privé de l'invention environnementale se déplace vers le haut, comme l'illustre la courbe en trait gras dans le cadran droit de la Figure 5.2. Pour garantir le rendement privé $\overline{R}$ le régulateur réduit l'appropriation de l'invention via un brevet moins protecteur, comme l'indique le fait que A_e soit plus faible que A_r, et accroît ainsi le rendement social de l'invention.

Cette illustration se fonde sur un raisonnement toutes choses égales par ailleurs et n'a pas valeur de démonstration. Par exemple, faire payer une taxe environnementale plus faible au détenteur du brevet l'incite à produire d'avantage et les répercussions sur l'environnement peuvent, in fine, alourdir le coût du système de brevet. Les analyses développées dans le Chapitre 4 formalisent l'idée de l'interaction entre le système de brevet et la taxation environnementale.

Le design optimal de brevet sur les technologies environnementales

La première étape consiste à poser le problème du système de brevet. Comment minimiser la perte temporaire de bien-être social imputable à l'appropriation partielle d'une invention environnementale sous condition d'induire l'investissement souhaité en R&D[11] de la part des agents privés ? Pour répondre à cette question le régulateur dispose de quatre instruments : la longueur du brevet, sa largeur, la taxe payée par l'inventeur et la taxe payée par ses concurrents. La première étape de notre analyse limite le niveau de détail de la structure du modèle en vue de mettre en avant ses principes généraux. Deux hypothèses réalistes permettent de conclure à l'interaction entre le système de brevet et la taxe environnementale : (1) le profit de l'inventeur est plus fort pendant le brevet qu'après son expiration; (2) le profit de l'inventeur décroît avec le taux de taxe environnementale qu'il doit payer. Deux types d'interactions sont déduits. Dans un premier cas, le coût social temporaire du brevet est supprimé via la taxe environnementale. Dans un second cas, le coût social temporaire du brevet demeure mais la taxe optimale payée par l'inventeur est plus faible que celle maximisant le bien-être social durant la validité du brevet. En ce sens, le couplage avec un système de brevet réduit le niveau optimal de taxe environnementale. Si les questions du système de brevet et de la taxation environnementale étaient traitées indépendamment, les solutions ne seraient pas les mêmes. Ces résultats indiquent que la politique de brevet interagit avec la taxation environnementale quand elle s'adresse à l'innovation environnementale. Deux illustrations des principes généraux sont proposées dans le Chapitre 4.

La première application considère le marché d'un bien de consommation polluant. Le détenteur du brevet dispose d'une technique permettant de réduire le dommage environnemental associé à la production du bien. Sa découverte lui confère de surcroît une position de leader à la Stackelberg. Les firmes qui lui font concurrence peuvent copier la nouvelle méthode de production en payant un coût fixe. En choisissant la largeur du brevet, le régulateur définit dans quelle mesure la copie peut être proche ou non de l'original. La résolution du problème du régulateur conclut qu'il est optimal d'imposer une taxation qui exclut la frange concurrentielle, et confère de fait l'entièreté de la production au détenteur du brevet qui vendra au coût marginal social en raison d'un taux de taxe environnementale plus faible que celui de

[11] Nous suivons Denicolò (1996, (44)) en considérant que le niveau de R&D que le régulateur souhaite induire est connu.

ses concurrents. La longueur du brevet est ajustée en fonction de la taxe environnementale tandis que la largeur, elle, ne joue plus de rôle dans l'arbitrage du régulateur. En effet, cette dernière est nulle puisque réduisant inutilement l'accès à la technologie nouvelle, quand le différentiel de profit entre l'inventeur et ses concurrents peut être généré efficacement par une taxation discriminante.

La seconde application considère ex ante le cas d'une largeur maximale du brevet. Son détenteur est donc en situation de monopole sur le marché. Nous concluons à l'optimalité d'une taxe environnementale plus faible que la taxe Pigouvienne. En retour, la longueur du brevet est réduite en comparaison d'une innovation régulière de même incidence sur le bien-être social. Ces résultats impliquent qu'il est efficace de mettre en œuvre un système de brevet dédié aux technologies environnementales. Si les applications proposées démontrent l'interaction entre la taxation environnementale et le système de brevet, elles illustrent aussi les limites de la mise en œuvre de la politique optimale de soutien à l'innovation environnementale. La plupart de ces limites sont communes au système de brevet en général, certaines sont propres à nos résultats et appellent des recherches supplémentaires.

Conclusion générale

Discussion générale

Les travaux présentés dans cette thèse visent à établir les conditions d'un soutien efficace à l'innovation dans les technologies de l'énergie bas-carbone. Le concept de double externalité se situe au cœur de l'analyse que nous développons. Quatre modèles théoriques sont identifiés pour corriger la double externalité, auxquels correspondent des approches différentes pour soutenir l'innovation dans les technologies de l'énergie bas-carbone. Le premier est celui du 'price fundamentalism' proposé par Nordhaus (Nordhaus, 2011, (130)). Comme son nom l'indique, il repose principalement sur la mise en place d'un prix du carbone optimal dans le sens où ce prix reflèterait le dommage des émissions de GES sur le bien-être social, aussi appelé le coût social du carbone. Cette approche se heurte à deux problèmes : (1) quelle est la valeur de ce coût social du carbone; (2) la mise en place d'un signal de prix lui étant égal est-elle plausible, et ce suffisamment tôt pour éviter les dommages liés à une intervention différée[1]? Nordhaus a proposé des estimations de la valeur du coût marginal social du carbone (Nordhaus, 2014, (131)). Il conclut à une valeur moyenne de 18,6 dollars constants de 2015 par tonne équivalent CO_2 émise (\$2015/tCO_2), qui augmente dans le temps pour atteindre 53,1 \$2015/tCO_2 en 2050. Différentes sources d'incertitude affectent la précision de cette valeur moyenne. Les estimations sont fortement dépendantes du taux d'actualisation, de l'élasticité du bien-être social aux dommages environnementaux et du taux de dépréciation du carbone dans l'atmosphère. De plus, la modélisation se heurte à une limite majeure : la difficulté d'anticiper l'occurrence et l'impact d'évènements catastrophiques. S'ils se réalisent, les prendre en compte viendrait considérablement augmenter le coût social du carbone (Pindyck, 2013, (142)). De nombreux chercheurs ont proposé des estimations du coût marginal social du carbone et l'hétérogénéité des résultats illustre la difficulté d'un tel exercice. Une étude de Tol (2005, (161)) rapporte la distribution des

[1] Sur le coût de différer la réduction des émissions de GES, voir Grubb et al., 1995, (63) et Acemoglu et al., 2012, (1).

résultats pour 103 estimations différentes, issues de 28 études. Le résultat majeur de son travail est de mettre en exergue la très forte incertitude sur la valeur du coût social du carbone. La valeur moyenne du coût social du carbone est de 93 \$2004/tCO_2, mais le mode de 2 \$2004/tCO_2, la médiane de 14 \$2004/tCO_2, tandis que le 95^e percentile est de 350 \$2004/tCO_2.

Les problèmes de mesure ne condamnent pas le principe d'une tarification du carbone à son coût marginal social. Certains auteurs considèrent que sa plus grande limite est celle de son implémentation. Ainsi ils postulent que la tarification du carbone sera contrainte dans le sens où elle n'égalera pas la valeur de son coût social. Elle ne sera donc pas suffisamment incitative pour assurer la compétitivité des technologies bas-carbone, ce qui limite la pertinence du 'price fundamentalism' (Jaffe et al., 2005, (78) ; Fischer et Newell, 2008, (50)). C'est de ce constat que découle le modèle théorique que nous avons appelé dans le Chapitre 1 le problème de double externalité faible d'une tarification de second-rang. L'idée de ce modèle est la suivante : si la tarification du carbone constitue un outil nécessaire à la lutte contre le changement climatique, la compétitivité des technologies bas-carbone demeurera partiellement entravée par une tarification qui ne reflète pas totalement leurs bénéfices environnementaux. Pour pallier à cette distorsion, un soutien additionnel à l'innovation dans les technologies bas-carbone est nécessaire via des politiques de soutien dédiées spécifiquement à ces technologies.

Parallèlement, l'idée du 'price fundamentalism' se construit sur une hypothèse que nous avons nommée l'homogénéité technologique. Elle stipule que les pouvoirs publics ne peuvent pas distinguer les rendements sociaux des innovations selon le secteur dans lequel elles voient le jour ou bien les technologies auxquelles elles se rattachent. Par conséquent, les technologies sont considérées comme parfaitement homogènes par le régulateur. Relâcher cette hypothèse produit le troisième modèle théorique nommé dans le Chapitre 1 le problème de double externalité faible d'une hétérogénéité technologique. Ce modèle constitue un guide à l'intervention publique dans un contexte où les décideurs sont capables de distinguer les bénéfices sociaux espérés d'une invention selon son secteur, voir sa technologie. Le secteur de l'énergie constitue un candidat à un soutien dédié en raison de son rôle dans l'économie, de ses particularités sectorielles et de son poids dans les émissions globales.

Ces deux modèles alternatifs concluent que l'innovation dans les technologies de l'énergie bas-carbone doit être stimulée par les pouvoirs publics via des politiques qui sont spécifiquement dédiées à ces technologies. Ce type de politiques présente des risques qu'illustre l'histoire des politiques de soutien aux énergies renouvelables. Le premier risque de postuler que la tarification du carbone ne reflètera pas son coût social est justement d'abandonner l'idée d'une tarification ambitieuse des émissions de GES. C'est la critique que l'on peut adresser aux politiques de soutien demand-pull mises en place à destination des énergies renouvelables, qui se sont en partie substituées à une tarification du carbone sans pouvoir la remplacer efficacement. L'analyse conduite dans cette thèse jette le doute sur l'efficacité de telles politiques. Elles stimulent la diffusion d'une technologie, mais cette dernière peut être déconnectée d'un apprentissage technique effectif et conditionné par à un soutien supply-push à l'innovation. De plus, elles ne remplacent pas efficacement la tarification du carbone puisqu'elles décalent vers la droite le merit-order du marché de l'électricité sans le réordonner (cf. Figure 1.1). Une meilleure approche consiste à accorder plus de poids à la tarification du carbone dans la diffusion des technologies de l'énergie bas-carbone et de soutenir d'avantage l'innovation par l'offre en vue d'améliorer leurs performances technologiques. Le second risque d'une politique spécifiquement dédiée aux technologies bas-carbone est l'écueil d'attribuer au régulateur le rôle de choisir les technologies 'gagnantes' via un soutien plus fort à l'innovation. Or, le régulateur est en situation d'asymétrie d'information vis-à-vis des secteurs innovateurs qui disposent d'une information privée quant aux bénéfices espérés des différentes technologies (Hall et Lerner, 2009, (182)). Dans le cas des politiques de soutien demand-pull mises en place dans les pays de l'OCDE, ce risque est d'autant plus grand que les pouvoirs publics ont choisi précisément les technologies qui allaient bénéficier d'un soutien additionnel. Une approche plus efficace consiste à soutenir la création de connaissance dans le secteur de l'énergie en l'adaptant aux compétences existantes et en analysant les bénéfices espérés des différentes technologies[2]. Ici encore, le soutien demand-pull pourrait être efficacement remplacé par une tarification du carbone couplée à un soutien supply-push qui, puisque se situant en amont de la chaîne de l'innovation, permet aux pouvoirs publics d'acquérir des informations sur les bénéfices espérés des projets soutenus avant que la diffusion de la technologie n'ait été amorcée.

Conclusion

L'objectif de cette thèse est d'établir les conditions d'un soutien efficace à l'innovation dans les technologies de l'énergie bas-carbone. Les travaux présentés se focalisent sur les instruments de soutien à l'innovation tout en reconnaissant l'importance de la mise en place d'une taxation incitative des émissions de GES. Les modalités du soutien à l'innovation

[2] Le cas du Danemark est illustratif des informations que peuvent obtenir les pouvoirs publics de la part du secteur privé via des partenariats entre des instituts publics et des entreprises (voir Kamp et al., 2004, (85)).

sont donc analysées comme étant complémentaires aux politiques environnementales de tarification des émissions de GES.

Pour répondre à cette question, des analyses théoriques sont menées en conjonction avec des évaluations empiriques. Sur le plan empirique, il est proposé une modélisation ayant pour objectif l'évaluation des effets des instruments de soutien demand-pull mis en place en Europe sur la diffusion d'une technologie bas-carbone représentative. Dans la continuité de ce travail, un modèle à facteur latent commun est utilisé pour améliorer les outils de suivi de l'innovation en estimant la qualité des inventions brevetées. Le but de cette démarche est de quantifier la connaissance accumulée entre 1980 et 2010 dans les technologies des énergies bas-carbone. Sur la base d'analyses théoriques, cette thèse propose une lecture nouvelle du concept de double externalité en étudiant les interactions entre un système de brevet et une tarification environnementale.

L'évaluation empirique proposée dans le Chapitre 2 identifie certaines des limites des instruments de soutien demand-pull. Sur le plan méthodologique, son principal apport est de proposer une modélisation qui évalue l'effet des instruments de soutien sur la diffusion d'une technologie en intégrant au sein de la dynamique de diffusion l'hypothèse de learning-by-doing (Wright, 1936, (169) ; Arrow, 1962, (4)). Les résultats indiquent que, selon les pays, les dynamiques de diffusion de la technologie analysée s'expliquent de manière plus ou moins forte par les mécanismes de soutien demand-pull. De fait, l'existence d'une filière industrielle nationale, en garantissant un socle de connaissance sur lequel fonder la diffusion de la technologie, permet à certains pays de disposer d'un avantage de *first-mover* qui implique qu'une part de la diffusion puisse se faire en l'absence de politique de soutien demand-pull. Ces résultats sont importants car ils s'inscrivent dans le contexte d'un déséquilibre majeur de la répartition du soutien de la part des pouvoirs publics entre un soutien supply-push et un soutien demand-pull. Les résultats suggèrent qu'une réorientation des ressources publiques vers un soutien supply-push pourrait également contribuer à assurer la diffusion d'une technologie bas-carbone.

La principale limite de ce travail se situe dans la modélisation de l'apprentissage. Si le learning-by-doing est largement utilisé dans la littérature[3], un courant de modélisation plus récent introduit un second vecteur d'apprentissage, celui du learning-by-searching (Kouvaritakis et al., 2000, (94); Criqui et al., 2014, (32)). L'implémentation d'une courbe d'apprentissage à deux facteurs dans un modèle de diffusion est un moyen de rendre compte des effets respectifs de la R&D dédiée à une technologie et de son déploiement sur le niveau

[3]Pour une revue de ces modèles, voir Berglund et Söderholm, 2006, (13).

d'innovation. Elle offrirait ainsi une méthode d'évaluation du mix optimal entre le soutien par l'offre et le soutien par la demande.

Le Chapitre 3 présente une méthode d'estimation de la connaissance technique accumulée dans les technologies des énergies bas-carbone. Dans la mesure où nous souhaitons disposer d'une mesure de la connaissance créée, des données de brevets sont utilisées. Or ce type de données présente des risques susceptibles de biaiser la validité des mesures de la connaissance quand elles se fondent sur le simple compte du nombre de brevets, ou l'utilisation d'une métrique unique (Griliches, 1990, (61); Harhoff et al., 2009, (69)). L'avantage de la méthode développée est d'introduire la notion de qualité des inventions pour disposer d'une mesure robuste de la connaissance. C'est un exercice de réduction de l'information qui extraie de chaque invention brevetée la valeur la plus probable de sa qualité; cette dernière étant explicative de ses métriques observées. Plusieurs résultats ressortent de ces estimations. Premièrement, la qualité moyenne des inventions a évolué différemment selon les technologies. Les exemples les plus frappants sont ceux des technologies du nucléaire, de l'éolien et du solaire photovoltaïque ; trois technologies qui se composent d'un grand nombre d'inventions brevetées sur la période étudiée. Si la qualité moyenne des inventions dans la technologie du nucléaire a chuté dans le temps, celles des inventions dans le solaire photovoltaïque et dans l'éolien ont fortement augmenté. Deuxièmement, nous analysons les spécificités de chaque pays. Les principaux innovateurs de notre échantillon de pays sont les USA, l'Allemagne et la France qui présentent les niveaux de production de connaissance les plus élevés. Les pays à niveaux de production plus bas ont tendance à concentrer leurs activités d'innovations sur un nombre plus restreint de technologies.

L'article proposé dans le Chapitre 3 se fixe pour objectif central de mesurer l'innovation. Toutefois, les interprétations déduites de nos résultats gagneraient en qualité et en robustesse à être testées dans une modélisation économétrique de l'influence des facteurs explicatifs du niveau de connaissance accumulée dans une technologie (e.g. taille de marché, dépenses de R&D, existence d'une taxation environnementale, prix de l'énergie).

Le Chapitre 4 revisite la question de la politique optimale de brevet en l'appliquant au cas d'une innovation environnementale de procédé. Dans un cadre simple, inspiré de l'article de Denicolò (1996, (44)), nous explorons l'interaction entre une politique de brevet et une politique de taxation environnementale. Les résultats se rapprochent de ceux de la littérature sur la taxation environnementale des monopoles (Buchanan, 1969, (20); Lee, 1975, (103); Barnett, 1980, (8)) mais l'interaction avec la politique de brevet constitue, à notre connaissance, une nouveauté. Les principes généraux du modèle soulèvent l'intérêt d'ajuster la taxation de l'innovateur en fonction du degré d'appropriation de l'invention. Deux applications illustrent cette interaction et permettent de montrer que la largeur du brevet, qui induit le différentiel de profit de l'innovateur vis-à-vis de ses concurrents, est plus efficacement remplacée par une taxation discriminante et plus avantageuse à l'innovateur. Une première limite de ce travail est commune à la littérature sur les politiques optimales de brevet qui met en évidence sa très forte sensibilité aux structures de marché qui prévalent durant la validité du brevet. Les autres limites sont propres à notre article. Premièrement, nous raisonnons dans un cadre où le régulateur ne dispose que d'un seul instrument pour inciter le secteur privé à innover. Or les subventions à la R&D, par exemple, constituent un autre élément important des politiques d'innovations. Deuxièmement, nos résultats concluent à l'optimalité d'une politique difficile à implémenter pour plusieurs raisons : (1) la politique optimale implique que le régulateur puisse librement adapter la politique de taxation environnementale; (2) le régulateur est unique quand, dans les faits, les offices de brevets agissent indépendamment de la politique environnementale, et réciproquement.

Perspectives de recherches

La première piste de poursuite des recherches consiste à exploiter les résultats des estimations menées dans le Chapitre 3. Dans un premier temps, il conviendra d'évaluer les déterminants de la création de connaissance. Une approche similaire à celle de Johnstone et al. (2010, (81)) peut être mise en place pour tester la valeur-ajoutée de l'indice de qualité. En effet, leur étude se restreint à mesurer l'innovation par un simple compte des brevets, ce qui pour les raisons détaillées dans le Chapitre 3, accroit considérablement le risque d'erreur de mesure. Dans un second temps, l'estimation des courbes d'apprentissage à facteurs multiples pour le solaire photovoltaïque et l'éolien[4] permettra de mieux apprécier les influences respectives sur la baisse des coûts du stock de connaissance d'une part, et de l'expérience accumulée via le déploiement de la technologie d'autre part. Finalement, les résultats permettront de calibrer des modèles de diffusion des technologies bas-carbone dans le secteur électrique. Plus précisément, le calibrage portera sur les taux de learning-by-searching et de learning-by-doing en vue de tester l'efficacité d'une politique de soutien supply-push plus forte.

La seconde piste de recherche s'inscrit dans la continuité du travail effectué dans le Chapitre 4. Trois directions doivent être explorées. Premièrement, le design optimal des politiques de brevets étant fortement sensible à la structure de marché, de nouvelles structures doivent être étudiées. Deuxièmement, la double externalité doit être analysée dans le cadre des

[4] A notre connaissance, des données fiables de coût d'investissement ne sont pas disponibles pour d'autres technologies de l'énergie bas-carbone.

politiques de subventions à la R&D dans le but d'identifier si l'interaction avec la taxation environnementale se limite au seul cas des politiques de brevets. Finalement, une analyse plus poussée nécessite de se départir de la dichotomie entre des innovations purement environnementales et des innovations que nous avons appelé régulières. Pour cela, le cas d'une innovation qui présente à la fois des avantages environnementaux et des avantages rétribués via des marchés préexistants doit être étudié.

Bibliography

Academic literature.

[1] Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D., 2012. The environment and directed technical change. The American Economic Review. Vol. 102, No. 1, pp. 131-166.

[2] Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., Van Reenen, J., 2016. Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry. The Journal of Political Economy. Vol. 124, No. 1, pp. 1-51.

[3] Albrecht, J., Laleman, R., Vulsteke, E., 2015. Balancing demand-pull and supply-push measures to support renewable electricity in Europe. The Renewable and Sustainable Energy Review. Vol. 49, pp. 267-277.

[4] Arrow, K., 1962. The economic implications of learning-by-doing. The Review of Economic Studies. Vol. 29, No. 3 , pp. 155-173.

[5] Arthur, B., 1989. Competing technologies, increasing returns, and lock-in by historical events. The Economic Journal. Vol. 99, No. 394 , pp. 116-131.

[6] Atkinson, R., 2007. Expanding the R&E tax credit to drive innovation, competitiveness and prosperity. The Journal of Technology Transfer. Vol. 32, pp. 617-628.

[7] Ausubel, L., Cramton, P., Pycia, M., Rostek, M., Weretka, M., 2014. Demand reduction and inefficiency in multi-unit auctions. The Review of Economic Studies. Vol. 81, Issue 4, pp. 1366-1400.

[8] Barnett, A., 1980. The Pigouvian tax rule under monopoly. The American Economic Review. Vol. 70, pp. 1037-1041.

[9] Bass, F. M., 1969. A new product growth for model consumer durables. Management Science. Vol. 15, No. 5, pp. 215-227.

[10] Bass, F. M., 1980. The relationship between diffusion rates, experience curves, and demand elasticities for consumer durable technological innovations. The Journal of business. Vol. 53, pp. 551-567.

[11] Benhmad, F., Percebois, J., 2014. Wind power feed-in impacts on electricity system. Cahiers de recherche du CREDEN. 14.11.110.

[12] Bentler, P., Bonett, D., 1980. Significance tests and goodness of fit in the analysis of covariance structures. The Psychological Bulletin. Vol. 88, No. 3, pp. 588-606.

[13] Berglund, C., Söderholm, P., 2006. Modelling technical change in energy system analysis: analysing the introduction of learning-by-doing in bottom-up energy models. Energy Policy. Vol. 34, pp. 1344-1356.

[14] Berry, T., Jaccard, M., 2001. The renewable portfolio standard: design considerations and an implementation survey. Energy policy. Vol. 29, No. 29 , pp. 263-277.

[15] Blanco, M.I., 2009. The economics of wind energy. The Renewable and Sustainable Energy Reviews. Vol. 13, pp. 1372-1382.

[16] Boccard, N., 2009. Capacity factor of wind power realized values vs. estimates. Energy Policy. Vol. 37, pp. 2679-2688.

[17] Bointner, R., 2014. Innovation in the energy sector: Lessons learnt fom R&D expenditures and patents in selected IEA countries. Energy Policy. Vol. 73, pp. 733-747.

[18] Bolinger M., Wiser, R., 2012. Understanding wind turbine price trends in the U.S. over the past decade. Energy Policy. Vol. 42, pp. 628-641.

[19] Brancucci Martinez-Anido, C., Brinkman, G., Hodge, B-M, 2016. The impact of wind power on electricity prices. Renewable Energy. Vol. 94, pp. 474-487.

[20] Buchanan, J., 1969. External diseconomies, corrective taxes and market structure. The American economic review. Vol. 59, No.1 , pp. 174-177.

[21] Brunnermeier, S., B., Cohen, M., A., 2003. Determinants of environmental innovation in US manufacturing industries. The Journal of Environmental Economics and Management. Vol. 45, pp. 278-293.

[22] Buonanno, P., Carraro, C., Galeotti, M., 2003. Endogenous induced technical change and the costs of Kyoto. Resource and Energy Economics. Vol. 25, pp. 11-34.

[23] Calel, R., Dechezleprêtre, 2016. Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. The review of economics and statistics. Vol. 98, No. 1, pp. 173-191.

[24] Cantner, U., Graf, H., Herrmann, J., Kalthaus, M., 2016. Inventor networks in renewable energies: The influence of the policy mix in Germany. Research policy. Vol. 45, pp. 1165-1184.

[25] Caron, F., 1983. Histoire technique et histoire économique. Histoire, Economie et Société. Vol. 2, pp. 7-17.

[26] Carraro, C., Siniscalco, D., 1994. Environmental policy reconsidered: The role of technological innovation. The European economic review. Vol. 38, pp. 545-554.

[27] Chari, V., Weber, R., 1992. How the U.S. treasury should auction is debt. The Federal Reserve of Bank of Minneapolis Quarterly Review. Fall 1992, Vol. 16, No. 4.

[28] Chow, G. C., 1967. Technological change and the demand for computers. The American Economic Review. Vol. 57, pp. 1117-1130.

[29] Cló, S., Cataldi, A., Zoppoli, P., 2015. The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices. Energy Policy. Vol. 77, pp. 79-88.

[30] Cludius, J., Hermann, H., Matthes, F.C., Graichen, V., 2014. The merit order effect of wind and photovoltaic electricity generation in Germany 2008-2016: Estimation and distributional implications. Energy Economics. Vol. 44, pp. 302-313.

[31] Coulomb, L., Neuhoff, K., 2006. Learning curves and changing product attributes: the case of wind turbines. Cambridge Working Papers in Economics. 0618.

[32] Criqui, P., Mima, S., Menanteau, P., Kitous, A., 2014. Mitigation strategies and energy technology learning: An assessment with the POLES model. Technological Forecasting & Social Change. Vol. 90, Part A, pp. 119-136.

[33] Criscuolo, P., Verspagen, B., 2008. Does it matter where patent citations come from? Inventor vs. examiner citations in European patents. Research Policy. Vol. 7, pp. 1892-1908.

[34] Czarnitzki, D., Ebersberger, B., Fier, A., 2007. The relationship between R&D collaboration, subsidies and R&D performance: Empirical evidence for Finland and Germany. The Journal of Applied Econometrics. Vol. 22, issue 7, pp. 1347-1366.

[35] Danchev, S., Tsakanikas, A., 2010. Returns on investment in electricity producing photovoltaic systems under de-escalating feed-in tariffs: the case of Greece. The Renewable and Sustainable Energy Reviews. Vol. 14, pp. 500-505.

[36] DeBrock, L.M., 1985. Market structure, innovation, and optimal patent life. The Journal of Law and Economics. Vol.28, No.1, pp. 223-244.

[37] Dechezleprêtre, A., Glachant, M., Haščič, I., Johnstone, D., Ménière, Y., 2011. Invention and Transfer of Climate Change–Mitigation Technologies: A Global Analysis. The Review of Environmental Economics and Policy. Vol. 5, No. 1, pp. 109-130.

[38] Dechezleprêtre, A., 2014. Fast-tracking green patent applications. ICTSD Programme in Innovation, Technology and Intellectual Property. Issue paper No.37.

[39] Dechezleprêtre, A., Glachant, M., 2014. Does foreign environmental policy influence domestic innovation? Evidence from the wind industry. Environmental and resource economics. Vol. 58, pp. 391-413.

[40] del Rio, P., Bleda, M., 2012. Comparing the innovation effects of support schemes for renewable electricity technologies: A function of innovation approach. Energy Policy. Vol. 50, pp. 272-282.

[41] del Rio, P., Mir-Artigues, P., 2012. Support for solar PV deployment in Spain: Some policy lessons. The Renewable and Sustainable Energy Reviews. Vol. 16, pp. 5557-5566.

[42] del Rio, P., Linares, P., 2014. Back to the future? Rethinking auctions for renewable electricity support. The Renewable and sustainable energy reviews. Vol. 35, pp. 42-56.

[43] Dempster, A., Laird, N., Rubin, D., 1977. Maximum Likelihood from Incomplete Data via the EM algorithm. The Journal of the Royal Statistical Society, Vol. 39, No. 1, pp. 1-38.

[44] Denicolò, V., 1996. Patent race and optimal patent breadth and length. The Journal of Industrial Economics. Vol.44, No.3, pp. 249-265.

[45] de Rassenfosse, G., Dernis, H., Boedt, G., 2014. An introduction to the Patstat Database with Example Queries. Melbourne Institute Working Paper Series, No. 8/14.

[46] Dernis, H., Guellec, D., van Pottelsberghe, B., 2001. Using Patent Counts For Cross-Country Comparisons of Technology Output. STI review No. 27. Organization for Economic Co-operation and Development (OECD).

[47] Dumont, B., 2014. Does patent quality drive damages in patent lawsuits? Lessons from the French judicial system. The Review of Law and Economics. Vol.11, Issue 2, pp. 355-383.

[48] Edenhofer, O., Hirth, L., Knopf, B., Pahle, M., Schlömer, S., Schmid, E., Ueckert, F., 2013. On the economics of renewable energy sources. Energy economics. Vol. 40, S12-S23.

[49] Ferioli, F., Schoots, K., van der Zwaan, B.C.C., 2009. Use and limitations of learning curves for energy technology policy: A component-learning hypothesis. Energy Economics. Vol. 37, pp. 2525-2535.

[50] Fischer, C., Newell, R., 2009. Environmental and technology policies for climate mitigation. The Journal of Environmental Economics and Management. Vol. 55, pp. 142-162.

[51] Fornahl, D., Broekel, T., Boschma, R., 2011. What drives patent performance of German biotech firms? The impact of R&D subsidies, knowledge networks and their location. Regional science. Vol. 90, issue 2, pp. 395-418.

[52] Frondel, M., Ritter, N., Schmidt, C., Vance, C., 2010. Economic impacts from the promotion of renewable energy technologies: the German Experience. Energy Policy. Vol. 38, pp. 4048-4056.

[53] Gallini, N., T., 1992. Patent policy and costly imitation. The RAND Journal of Economics. Vol.23, No.1, pp. 52-63.

[54] Gelabert, L., Labandeira, X., Linares, P., 2011. An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices. Energy Economics. Vol. 33, pp. S59-S65.

[55] Godard, O., 2004. La pensée économique face à la question de l'environnement. Ecole Polytechnique, Laboratoire d'Econométrie. Cahier No. 2004-025.

[56] Gordon, R., 2012. Is U.S. economic growth over? Faltering innovation confronts the six headwinds. NBER working paper series. Working Paper 18315.

[57] Goulder, L.H., 1995. Environmental taxation and the double dividend: A reader's guide. International Tax and Public Finance. Vol. 2, issue 2, pp. 157-183.

[58] Goulder, L., Mathai, K., 2000. Optimal CO_2 Abatement in the Presence of Induced Technological Change. The Journal of Environmental Economics and Management. Vol. 39, pp. 1-38.

[59] Griliches, Z., 1957. Hybrid corn: an exploration in economics of technological change. Econometrica. Vol. 25, pp. 501-522.

[60] Griliches, Z., 1980. Hybrid corn revisited: a reply. Econometrica. Vol. 48, pp. 1463-1465.

[61] Griliches, Z., 1990. Patent Statistics as Economic Indicators: A Survey. The Journal of Economic Literature, Vol. 28, No. 4, pp. 1661-1707.

[62] Gross, R., Blyth, W., Heptonstall, P., 2010. Risks, revenues and investment in electricity generation: Why policy needs to look beyond costs. Energy economics. Vol. 32, pp. 796-804.

[63] Grubb, M., Chapuis, T., Ha Duong, M., 1995. The economics of changing course, implications of adaptability and inertia for optimal climate policy. Energy Policy. Vol. 23, no. 4/5, pp. 417-432.

[64] Grubler, A., 2010. The cost of the French nuclear scale-up: A case of negative learning-by-doing. Energy Policy. Vol. 38, Issue 9, pp. 5174-5188.

[65] Hall, H., Jaffe, A., Trajtenberg, M., 2005. Market Values and Patent Citations. The RAND Journal of Economics. Vol. 36, No. 1, pp. 16-38.

[66] Hamilton, K., Ruta, G., Tajibaeva, L., 2006. Capital accumulation and resource depletion: a Hartwick rule counterfactual. Environmental & Resource Economics. Vol. 34, pp. 517-533.

[67] Harhoff, D., Narin, F., Scherer, F.M., Vopel, K., 1999. Cited Frequency and the Value of Patented Inventions. The Review of Economics and Statistics. Vol. 81(3), pp. 511-515.

[68] Harhoff, D., Scherer, F.M., Vopel, K., 2002. Citations, family size, opposition and the value of patent rights. Research Policy. Vol. 1596, pp. 1-21.

[69] Harhoff, D., Wagner, S., 2009. The Duration of Patent Examination at the European Patent Office. Management Science. Vol. 55, No. 12, pp. 1969-1984.

[70] Haščič, I., Johnstone, N., Kalamova, M., 2009. Environmental policy flexibility, search and innovation. The Journal of Economics and Finance. Vol. 59, pp. 426-441.

[71] Haščič, I., Migotto, M., 2015. Measuring Environmental Innovation using Patent Data: Policy Relevance. Working Party on Environmental Information. The Journal of Economics and Finance. Vol. 59, pp. 426-441.

[72] Hirth, L., 2013. The market value of variable renewables, the effect of solar wind power variability on their relative price. Energy Economics. Vol. 38, pp. 218-236.

[73] Hitaj, C., Schymura, M., Loeschel, A., 2014. The impacts of feed-in tariffs on wind power development in Germany. Discussion paper of the ZEW. 14-035.

[74] Horbach, J., Rammer, C., Rennings, K., 2012. Determinants of eco-innovations by type of environmental impact — The role of regulatory push/pull, technology push and market pull. Ecological Economics. Vol. 78, pp. 112-122.

[75] Jacobsson, S., Lauber, V., 2006. The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. Energy Policy. Vol. 34, pp. 256-276.

[76] Jaffe. A.B., Palmer, K., 1997. Environmental Regulation and Innovation: A Panel Data Study. The Review of Economics and Statistics. Vol. 79, No. 4, pp. 610-619.

[77] Jaffe, A., B., Trajtenberg, M., Henderson, R., 1993. Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations. The Quarterly Journal of Economics. Vol. 108, No. 3, pp. 577-598.

[78] Jaffe, A., Newell, R., Stavins, R., 2005. A tale of two market failures: Technology and environmental policy. Ecological Economics. Vol. 54, pp. 164-174.

[79] Jamasb, T., 2007. Technical Change Theory and Learning Curves: Patterns of Progress in Electricity Generation Technologies. The Energy Journal. Vol. 28, pp. 51-71.

[80] Jenner, S., Groba, F., Indvik, J., 2013. Assessing the strength and effectiveness of renewable electricity feed-in tariffs in European Union countries. Energy Policy. Vol. 52, pp. 385-401.

[81] Johnstone, N., Haščič, I., Popp, D., 2010. Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts. Environmental and Resource Economics. Vol. 45, pp. 133-155.

[82] Johnson, D., Popp, D., 2003. Forced out of the Closet: The Impact of the American Inventors Protection Act on the Timing of Patent Disclosure. The RAND Journal of Economics. Vol. 34, No. 1, pp. 96-112.

[83] Joskow, P., 2011. Comparing the costs of intermittent and dispatchable electricity generating technologies. The American Economic Review. Vol. 101, No. 3, pp. 238-241.

[84] Kaldellis, J., Zafirakis, D., 2011. The wind energy (r)evolution. Renewable energy. Vol. 36, Issue 7, pp. 1887-1901.

[85] Kamp, L., Smits, R., Andriesse, C., 2004. Notions of learning applied to wind turbine development in the Netherlands and Denmark. Energy policy. Vol. 32, pp. 1625-1637.

[86] Kemp, R., 1998. The diffusion of biological wastewater treatment plants in the Dutch food and beverage industry. Environmental and resource economics. Vol. 12, pp. 113-136.

[87] Kemp, R., Pontoglio, S., 2011. The innovation effects of environmental policy instruments — A typical case of the blind men and the elephant? Ecological Economics. Vol. 72, pp. 28-36.

[88] Ketterer, J., 2014. The impact of wind power generation on the electricity price in Germany. Energy economics. Vol. 44, pp. 270-280.

[89] Kitzing, L., 2014. Risk implications of renewable support instruments: Comparative analysis of feed-in tariffs and premiums using a mean-variance approach. Energy. Vol. 64, pp. 495-505.

[90] Klaassen, G., Miketa, A., Katarina, L., Sundqvist, T., 2005. The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom. Ecological Economics. Vol. 54, pp. 227-240.

[91] Klemperer, P., 1990. How broad should the scope of patent protection be? The RAND Journal of Economics. Vol.21, No.1, pp. 113-130.

[92] Kobos, P., H., Erickson, J., D., Drennen, T., E., 2006. Technological learning and renewable energy costs: implications for US renewable energy policy. Energy Policy. Vol. 34, pp. 1645-1658.

[93] Koch, N., Fuss, S., Grosjean, G., Edenhofer, O., 2014. Causes of the EU ETS price drop: Recession, CDM, renewable policies or a bit of everything? - New evidence. Energy policy. Vol. 73, pp. 676-685.

[94] Kouvaritakis, N., Soria, A., Isoard, S., 2000. Modelling energy technology dynamics: methodology for adaptive expectations models with learning by doing and learning by searching. The International Journal of Global Energy Issues. Vol. 14, pp. 104-115.

[95] Laird, F., Stefes, C., 2009. The diverging paths of German and United States policies for renewable energy: sources of difference. Energy policy. Vol. 37, pp. 2619-2629.

[96] Langniss, O., Neij, L., 2004. National and international learning with wind power. Energy and Environment. Vol. 15, No.2, pp. 175-185.

[97] Lanjouw, J.O., Mody, A., 1996. Innovation and the international diffusion of environmentally responsive technology. Research Policy. Vol. 2, pp. 549-571.

[98] Lanjouw, J.O., Schankerman, M., 1997. Stylized Facts of Patent Litigation: Value, Scope and Ownership. NBER Working Paper Series, No. 6297.

[99] Lanjouw, J.O., Schankerman, M., 2001. Enforcing Intellectual Property Rights. NBER Working Paper Series, No. 8656.

[100] Lanjouw, J.O., Schankerman, M., 2004. Patent Quality and Research Productivity: Measuring Innovation with Multiple Indicators. The Economic Journal. Vol. 114, pp. 441-465.

[101] Laleman, R., Albrecht, J., 2014. Comparing push and pull measures for PV and wind in Europe. Renewable Energy, Vol. 61, Issue C, pp. 33-37.

[102] Lanzi, E., Verdolini, E., Haščič, I., 2011. Efficiency-improving fossil fuel technologies for electricity generation: Data selection and trends. Energy Policy. Vol. 39, pp. 7000-7014.

[103] Lee, D., 1975. Efficiency of pollution taxation and market structure. Journal of Environmental Economics and Management. Vol. 2, Issue 1, pp. 69-72.

[104] Lee, T. and Wilde, L., L., 1980. Market structure and innovation: a reformulation. The Quarterly Journal of Economics. Vol.94, No.2, pp. 429-436.

[105] Lemming, J., 2003. Financial risks for green electricity investors and producers in a tradable green certificate market. Energy policy. Vol. 31, Issue 1, pp. 21-32.

[106] Lerner, J., 1994. The Importance of Patent Scope: An Empirical Analysis. The RAND Journal of Economics. Vol. 25, No. 2, pp. 319-333.

[107] Lewis, J., Wiser, R., 2007. Fostering a renewable energy technology industry: An international comparison of wind industry policy support mechanisms. Energy Policy. Vol. 35, Issue 3, pp. 1844-1857.

[108] Lindman, Å., Söderholm, P., 2012. Wind power learning rates: A conceptual review and meta-analysis. Energy Economics. Vol. 34, pp. 754-761.

[109] Lindman, A., Söderholm, P., 2015. Wind energy and green economy in Europe: Measuring policy-induced innovation using patent data. Applied Energy. Vol. 179, pp. 1351-1359.

[110] Löschel, A., 2002. Technological Change in Economics Models of Environmental Policy: a Survey. Ecological Economics. Vol. 43, pp. 105-126.

[111] Loury, G., C., 1979. Market structure and innovation. The Quarterly Journal of Economics. Vol.93, No.3, pp. 395-410.

[112] Lucking-Reiley, D., 2000. Vickrey auctions in practice: From nineteenth-century philately to twenty-first-century E-commerce. The Journal of Economics Perspectives. Vol. 14, No.3, pp. 183-192.

[113] Luthi, S., Prassler, T., 2011. Analyzing policy support instruments and regulatory risk factors for wind energy deployment- a developers' perspective. Energy Policy. Vol. 39, pp. 4876-4892.

[114] Mansfield, E., 1961. Technological change and the rate of imitation. Econometrica. Vol. 29, pp. 741-766.

[115] Marques, A.C., Fuinhas, J.A., 2011. Drivers promoting renewable energy: A dynamic panel approach. The Renewable and Sustainable Energy Reviews. Vol. 15, pp. 1601-1608.

[116] Marques, A.C., Fuinhas, J.A., 2012. Are public policies towards renewable successful? Evidence from European countries. Renewable Energy. Vol. 44, pp. 109-118.

[117] Martin, S., Scott, J., 2000. The nature of innovation market failure and the design of public support for private innovation. Research policy. Vol. 29, pp. 437-447.

[118] Matutes, C., Regibeau, P. and Rockett, K., 1996. Optimal patent design and the diffusion of innovations. The RAND Journal of Economics, Vol.27, No.1, pp. 60-83.

[119] Mazzucato, M., Penna, C., 2015. The rise of mission-oriented state investment banks: the cases of Germany's KfW and Brazil's BNDES. ISI growth Working Paper, 1/2015 October.

[120] Mercure J.-F., Pollitt, H., Chewpreecha, U., Salas, P., Foley, A.M., Holden, P.B., Edwards, N.R., 2014. The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonation of the global electricity sector. Energy Policy. Vol.73, pp. 686-700.

[121] Mir-Artigues, P., Del Rio, P., 2014. Combining tariffs, investment subsidies and soft loans in a renewable electricity deployment policy. Energy Policy. Vol. 69, pp. 430-442.

[122] Mowery, D., Rosemberg, N., 1979. The influence of market demand upon innovation: a critical review of some recent empirical studies. Research Policy. Vol. 8, issue 2, pp. 102-153.

[123] Mowery, D., 1983. Industrial research and firm size, survival, and growth in American manufacturing. The Journal of Economic History. Vol. 43, Issue 4, pp. 953-980.

[124] Mulder, A., 2008. Do economic instruments matter? Wind turbines investments in the EU(15). Energy Economics. Vol. 30, pp. 2980-2991.

[125] Neij, L., 2008. Cost development of future technologies for power generation-A study based on experience curves and complementary bottom-up assessments. Energy policy. Vol. 36, pp. 2200-2211.

[126] Nelson, R., 1994. The co-evolution of technology, industrial structure, and supporting institutions. Industrial and Corporate Change. Vol. 3, Issue 1, pp. 47-63.

[127] Nemet, G., 2009. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. Research Policy. Vol. 38, pp. 700-709.

[128] Noailly, J., Smeets, R., 2015. Directing technical change from fossil-fuel to renewable energy innovation: An application using firm-level patent data. The Journal of Environmental Economics and Management. Vol. 72, pp. 15-37.

[129] Nordhaus, W., D., 1967. The optimal life of a patent. Cowles foundation discussion paper No.241.

[130] Nordhaus, W., 2011. Designing a friendly space for technological change to slow global warming. Energy economics. Vol. 33, pp. 665-673.

[131] Nordhaus, W., 2014. Estimates of the Social Cost of Carbon: concepts and results for the DICE-2013R Model and alternative approaches. Journal of the Association of Environmental and Resource Economists. Vol. 1, No. 1/2, pp. 273-312.

[132] Parry, I., W.H., 1994. Optimal pollution taxes and endogenous technological progress. Resource and Energy Economics. Vol.17, Issue 1, pp. 69-85.

[133] Percebois, J., 2014. Les mécanismes de soutien aux énergies renouvelables, forces et faiblesses. La Revue de l'Energie. Vol. 617.

[134] Peters, M., Schneider, M., Griesshaber, T., Hoffmann, V., 2012. The impact of technology-push and demand-pull policies on technical change – Does the locus of policies matter?. Research Policy. Vol. 41, pp. 1296-1308.

[135] Popp, D., 2003. Induced Innovation and Energy Prices. The American Economic Review. Vol. 92, No. 1, pp. 160-180.

[136] Popp, D., 2005. Lessons from patents: Using patents to measure technological change in environmental models. Ecological Economics. Vol. 54, pp. 209-226.

[137] Popp, D., Haščič, I., Medhi, N., 2011. Technology and the diffusion of renewable energy. Energy Economics. Vol. 33, pp. 648-662.

[138] Popp, D., Santen, N., Fisher-Vanden, K., Webster, M., 2013. Technology variation vs. R&D uncertainty: What matters most for energy patent success? Resource and Energy Economics. Vol. 35, pp. 505-533.

[139] Porter, M., 1990. The competitive advantage of nations. The Harvard Business Review. March-April 1990 Issue.

[140] Porter, M., 1998. Clusters and the new economics of competition. The Harvard Business Review. November-December 1998 Issue.

[141] Putnam, J., 1997. The Value of International Patent Rights. UMI Dissertation Services.

[142] Pindyck, R., 2013. Climate change policy: what do the models tell us? The Journal of Economic Literature. Vol. 51, No.3, pp. 860-872.

[143] Régibeau, P., Rockett, K., 2010. Innovation Cycles and Learning at the Patent Office: Does the Early Patent get the Delay? The Journal of Industrial Economics. Vol. 58, No. 2, pp. 222-246.

[144] Reinganum, J., F., 1983. Uncertain innovation and the persistence of monopoly. The American Economic Review. Vol.73, No.4, pp. 741-748.

[145] Rennings, K., 2000. Redefining innovation—eco-innovation research and the contributions from ecological economics. Ecological Economics. Vol.32, pp. 319-332.

[146] Rosemberg, N., 1990. Why do firms do basic research (with their own money)? Research Policy. Vol. 19, Issue 2, pp. 165-174.

[147] Rubin, D., Thayer, D., 1982. EM algorithms for ML factor analysis. Psychometrika. Vol. 47, No. 1, pp. 69-76.

[148] Sagar, A., van der Zwaan, B., 2006. Technological innovation in the energy sector: R&D, deployment, and learning-by-doing. Energy Policy. Vol. 34, pp. 2601-2608.

[149] Schallenberg-Rodriguez, J., Haas, R., 2012. Fixed feed-in tariff versus premium: A review of the current Spanish system. Renewable and Sustainable Energy Reviews. Vol. 16, Issue 1, pp. 293-305.

[150] Schankerman, M., Pakes, A., 1986. Estimates of the value of patent rights in European countries during the post-1950 period. The Economic Journal. Vol. 96, pp. 1052-1076.

[151] Scherer, F.M., 1965. Firm Size, Market Structure, Opportunity, and the Output of Patented Inventions. The American Economic Review. Vol. 55, No. 5, Part 1, pp. 1097-1125.

[152] Scherer, F.M., Harhoff, D., 2000. Technology policy for a world of skew-distributed outcomes. Research Policy, Vol. 29, pp. 559-566.

[153] Schmidt, J., Lehecka, G., Gass, V., Schimd, E., 2013. Where the wind blows: Assessing the effect of fixed and premium based feed-in tariffs on the spatial diversification of wind turbines. Energy economics. Vol. 40, pp. 269-276.

[154] Sensfuß, F., Ragwitz, M., Genoese, M., 2008. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy. Vol. 36, pp. 3086-3094.

[155] Sovacool, B., 2013. Energy policymaking in Denmark: Implications for global energy security and sustainability. Energy Policy. Vol. 61, pp. 829-839.

[156] Söderholm, P., Klaassen, G., 2007. Wind Power in Europe: A Simultaneous Innovation–Diffusion Model. Environmental and Resource Economics. Vol. 36, pp. 163-190.

[157] Squicciarini, M., Dernis, H., Criscuolo, C., 2013. Measuring Patent Quality: Indicators of Technological and Economic Value. STI Working Paper Series.

[158] Stiglitz, J., Weiss, A., 1981. Credit rationing in markets with imperfect information. The American Economic Review. Vol. 71, Issue 3, pp. 393-410.

[159] Trajtenberg, M., 1990. A Penny for Your Quotes: Patent Citations and the Value of Innovations. The RAND Journal of Economics. Vol. 21, No. 1, pp. 172-187.

[160] Taylor, M., 2008. Beyond technology-push and demand-pull: Lessons from California's solar policy. Energy Economics. Vol. 30, pp. 2829-2854.

[161] Tol, R., 2005. The marginal damage costs of dioxide emissions: an assessment of the uncertainties. Energy policy. Vol. 33, pp. 2064-2074.

[162] Unruh, G., 2008. Understanding carbon lock-in. Energy policy. Vol. 28, pp. 817-830.

[163] Usha Rao, K., Kishore, V.V.N., 2010. A review of technology diffusion models with special reference to renewable energy technologies. Renewable and Sustainable Energy Reviews. Vol. 14, pp. 1070-1078.

[164] Veefkind, V., Hurtado-Albir, J., Angelucci, S., Karachalios, K., Thumm, N., 2012. A new EPO classification scheme for climate change mitigation technologies. World Patent Information. Vol. 34, pp. 106-111.

[165] Vickrey, W., 1961. Counterspeculation, auctions, and competitive sealed tenders. The Journal of Finance. Vol. 16, Issue 1, pp. 8-37.

[166] Watanabe, C., Wakabayashi, K., Miyazawa, T., 2000. Industrial dynamism and the creation of a "virtuous cycle" between R&D, market growth and price reduction The case of photovoltaic power generation (PV) development in Japan. Technovation. Vol. 20, pp. 299-312.

[167] Weyant, J., P., 2011. Accelerating the development and diffusion of new energy technologies: beyond the "valley of death". Energy Economics. Vol.33, Issue 4, pp. 674-682.

[168] Wilson, R., 1979. Auctions of shares. The Quarterly Journal of Economics. Vol. 93, No.4, pp. 675-689.

[169] Wright, T.P., 1936. Factors affecting the Cost of Airplanes. The Journal of Aeronautical Science. Vol. 3, No.4, pp. 122-128.

[170] Wright, B., D., 1983. The economics of invention incentives: patents, prizes and research contracts. The American Economic Review. Vol.73, No.4, pp. 691-707.

[171] Wright, D., J., 1999. Optimal patent breadth and length with costly imitation. The International Journal of Industrial Organization. Vol.17, Issue 3, pp. 419-436.

Books and Chapters.

[172] Arrow, K., 1962. Economic welfare and the allocation of resources for invention. In The Rate and Direction of Inventive Activity: Economic and Social Factors. (Eds.) Universities-National Bureau Committee for Economic Research, Committee on Economic Growth of the Social Science Research Council. Princeton University Press, pp. 609-626.

[173] Anderson, T.W., 2003. An introduction to Multivariate Statistical Analysis. Third Edition. John Wiley & Sons.

[174] Bartholomew, D., Knott, M., Moustaki, I., 2011. Latent Variable Models and Factor Analysis: a unified approach. Third Edition. John Wiley & Sons.

[175] Burton, T., Sharpe, D., Jenkins, N., Bossanyi, E., 2001. Conceptual design of horizontal-axis turbines. In Wind Energy Handbook. John Wiley & Sons, Second Edition, pp. 320-376.

[176] Cerf, C., Navasky, V., 1984. The experts speak: The definitive compendium of authorative misinformation. Pantheon, pp.203, 1984.

[177] Dinica, V., 2002. Renewable energy policy in Spain. In The Handbook of Renewable Energies in the European Union - Case studies of all Member States. (Eds) Reiche, D., Frankfurt am Main: Peter Lang Publishing Group.

[178] Greene, W.H.,2011. Econometric Analysis. Seventh edition. Pearson Education.

[179] Gillingham, K., Sweeney, J., 2010. Market failure and the structure of externalities, in: Harnessing renewable energy. (Eds.) Padilla, J., Schmalensee, R..

[180] Gintis, H., 2009. Chapter 10: Repeated games. In Game theory evolving: A problem-centered introduction to evolutionary game theory. Second Edition, Princeton University Press: Princeton, NJ.

[181] Grubb, M., Vigotti, R., 1997. Renewable energy strategies for Europe, Volume 2, Electricity systems and primary electricity sources. Earthscan/RIIA, London.

[182] Hall, H., Lerner, J., 2009. The financing of R&D and innovation. In the Handbook of the Economics of Innovation. Volume 1, (Eds) Hall, B. and Rosenberg, N., Elsevier-North Holland.

[183] Hicks, J., 1932. The Theory of Wages, London, Macmillan, pp.124-125.

[184] Jevons, W., 1866. The Coal Question. Second edition, London: Macmillan and Co. pp. 54-70.

[185] Mardia, K.V., Kent, J.T., Bibby, J.M., 1979. Multivariate Analysis. Academic Press, Harcourt Brace & Company.

[186] Metcalfe, S., 2008. Technical change. In the New Palgrave Dictionary of Economics, Second Edition, (Eds) Durlauf, S. and Blume, L., Palgrave Macmillan.

[187] Mokyr, J., 2010. The contribution of economic history to the study of innovation and technical change: 1750-1914. In the Handbook of the Economic of Innovation, Volume 1, (Eds) Hall, B. and Rosenberg, N., Elsevier-North Holland.

[188] Nordhaus, W., 2002. Modeling Induced Innovation in Climate Change Policy. In Technological Change and the Environment. Grübler, A., Nakicenovic, N., Nordhaus, W., (Eds) Resources for the Future Press, Washington.

[189] Pigou, A., C., 1932. The economics of welfare. London: Macmillan and Co., fourth edition, p.381.

[190] Schumpeter, J., 1943. Capitalism, socialism and democracy. Taylor & Francis e-Library, fifth edition, 2003.

[191] Stiglitz, J.E., 1990. Whither Socialism? MIT press.

[192] Storey, D., 2005. Entrepreneurship, small and medium sized enterprises and public policies. In Handbook of entrepreneurship research, an interdisciplinary survey and introduction. (Eds) Acs, Z., Audretsch, D., pp. 473-511.

[193] Zachmann, G., Serwaah-Panin, A., Peruzzi, M., 2014. When and how to support renewables? — Letting the data speak, in: Green energy and efficiency. pp. 291-332.

Scientific Reports and non-academic studies.

[194] Agence De l'Environnement et de la Maîtrise de l'Enérgie. Premieres conclusions tirées de l'analyse économiques des projets éoliens en terre et en mer. November 2011.

[195] Berghmans, N., Alberola, E. The power sector in phase 2 of the EU ETS: fewer CO2 emissions but just as much coal. Climate Report, No. 42, November 2013.

[196] Bonnet, C. Revue internationale des politiques de soutien aux énergies renouvelables: les enseignements du Danemark, de l'Allemagne et de la Chine. Les cahiers de la Chaire Economie du Climat, Série Information et Débats, No.33, 2014.

[197] The carbon trust and LEK consulting. Policy frameworks for renewables: analysis on policy frameworks to drive future investment in near and long-term renewable power in the UK. July 2006.

[198] Commission de Régulation de l'Enérgie. Coûts et rentabilité des énergies renouvelables en France métropolitaine. April 2014.

[199] Cramton, P., Stoft, S. The convergence of market designs for adequate generating capacity. A white paper for the Electricity Oversight Board, 25 April 2014.

[200] Dechezleprêtre, A. Fast-tracking green patent applications: An empirical analysis. International Center for Trade and Sustainable Development, Issues Paper No. 37, 2013.

[201] De Jager, D., Rathmann, M., 2008. Policy instruments design to reduce financing costs in renewable energy technology projects. ECOFYS, 2008.

[202] Deloitte. 2014 global survey of R&D tax incentives. March 2014.

[203] European Commission. Guidelines on state aid for environmental protection and energy 2014-2020. Official Journal of the European Commission, 28.6.2014, 2014.

[204] European Renewable Energy Council. Renewable energy policy review: Germany. 2004.

[205] European Renewable Energy Council. Renewable energy policy review: Italy. 2009.

[206] European Wind Energy Association. The economics of wind energy, a report by the European Wind Energy Association. p. 45, 2009.

[207] European Wind Energy Association. Green growth-the impact of wind energy on jobs and the economy. 2012

[208] Fulton, M., Capalino, R. The German feed-in tariff: Recent policy changes. DB climate change advisors, September 2012.

[209] GHK, 2006. Strategic evaluation on environment and risk prevention under structural and cohesion funds for the period 2007-2013. National Evaluation Report for Portugal: Main Report.

[210] International Energy Agency and Organization for Economic Co-operation and Development. Renewable energy market and policy trends in IEA countries. IEA/OECD, 2004.

[211] International Energy Agency, Nuclear Energy Agency and Organization for Economic Co-operation and Development. Projected Costs of Generating Electricity. 2010 Edition, NEA/IEA.

[212] International Energy Agency Wind. 2013 Annual Report. August 2014, p.85.

[213] International Energy Agency and Organization for Economic Co-operation and Development. Technology Roadmap on Carbon Capture and Storage. IEA/OECD, 2013 edition.

[214] International Energy Agency and Organization for Economic Co-operation and Development. Technological Roadmap on Solar Thermal Electricty. IEA/OECD, 2014.

[215] International Energy Agency Wind, 1978-2013. Annual Reports. IEA/EWEA/CWEA.

[216] International Energy Agency and Organization for Economic Co-operation and Development. CO2 emissions form fuel combustion, Highlights. OECD/IEA, 2015.

[217] International Energy Agency, Nuclear Energy Agency and Organization for Economic Co-operation and Development. Projected cost of generating electricty. 2015 edition, NEA/IEA.

[218] Intergovernmental Panel on Climate Change. Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2012.

[219] Intergovernmental Panel on Climate Change. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

[220] Intergovernmental Panel on Climate Change. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 2014.

[221] International Renewable Energy Agency. 30 years of policies for wind energy: Lessons from 12 wind energy markets. 2012.

[222] Organization for Economic Co-operation and Development. OECD Patent Statistics Manual. 2009.

[223] Organization for Economic Co-operation and Development. Clusters, innovation and entrepreneurship. In Local Economic and Employment Development, 2009.

[224] European Patent Office. PATSTAT Data Catalog, 2015 Autumn Edition-Amended, 2016.

[225] Ragwitz, M., Winkler, J., Klessmann, C., Gephart, M., Resch, G. Recent developments of feed-in systems in the EU-A. Research paper for the international Feed-in Cooperation, 2012.

[226] U.S. department of energy. 2010 Wind technologies market report, 2010.

[227] Wiesenthal, T., Dowling, P., Morbee, J., Thiel, C., Schade, B., Russ, P., Simoes, S., Peteves, S., Schoots, K., Londo, M. Technology Learning Curves for Energy Policy Support. JRC scientific and policy reports, 2012