Éléments sur la transition vers du capital bas carbone

Six essays on the transition to clean capital

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Abstract

This thesis shows that while greenhouse gases are a stock pollution that translate into an increasing shadow carbon price, it may be socially desirable to invest now in the deployment of expensive emission-reduction measures, in particular in the secotrs that are more difficult to decarbonize. This results solely from taking into account inertia in the accumulation of low-carbon capital, absent any other market imperfection. In this framework, the key is to make sure that short-term abatement investment in consistent with long-term emission-reduction objectives. For instance, when computing the marginal abatement cost of replacing coal plants with gas or renewable power, one should take into account that only renewable power can lead to the full decarbonization of the power sector. Similarly, the appraisal of electric vehicles should acknowledge that climate stabilization requires zero carbon electricity anyway.

This thesis also covers the choice of policy instruments that imperfect governments can use to make sure that the market implements these investments. It suggests that if governments cannot commit credibly to a carbon price path, or cannot fully compensate those who lose because of the carbon price, then sector-scale policy instruments that incentivize investment in clean capital may be more effective (but not necessarily more efficient) and more acceptable than the carbon price. For instance a feebate in favor of cleaner personal vehicles does not require the government to commit to a carbon price over the lifetime of that vehicles to be effective, and avoids creating stranded assets among exiting inefficient vehicles.

Éléments sur la transition vers du capital bas carbone

Résumé

Cette thèse montre que bien que les gaz à effet de serre représentent une pollution de stock qui impose un cout virtuel du carbone croissant dans le temps, il peut être socialement désirable d'investir des maintenant dans le déploiement de mesures couteuses de réductions de ces émissions. Ce résultat découle uniquement de la prise en compte de l'inertie inhérente à l'accumulation de capital bas carbone, en l'absence de toute autre imperfection de marché. De plus, cette thèse montre que des gouvernements imparfaits (c'est-à-dire qui ne peuvent pas s'engager sur une trajectoire parfaitement crédible de prix du carbone, ou ne peuvent pas compenser parfaitement les perdants de la mise en place de ce prix) peuvent avoir intérêt à utiliser des instruments de politiques sectoriels qui influencent directement les décisions d'investissements. Ces instruments peuvent être plus effectifs et plus acceptables que le prix du carbone.

Sommaire

Liste des auteurs

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Introduction

CETTE thèse contribue à la compréhension de l'écart existant aujourd'hui entre pratique et théorie des politiques d'atténuation du changement climatique. Elle pose la question de savoir si une meilleure prise en compte dans les modèles utilisés en théorie économique de l'*inertie* et des *irréversibilités,* induites notamment par les dynamiques d'accumulation du capital et du déploiement des infrastructures permettant une transition vers une économie décarbonée, pourrait réduire l'écart entre compréhension théorique et pratique réelle des politiques climatiques. Elle s'intéresse plus particulièrement à deux aspects du problème, qui s'avèrent en fait liés par l'inertie et l'irréversibilité : le timing optimal des réductions d'émissions de gaz à effet serre (GES), et les instruments de politiques permettant de mettre en œuvre ces réductions.

En pratique, face au danger que fait peser le changement climatique, les pouvoirs publics se sont fixés un éventail d'objectifs intermédiaires, et ont déployé une variété d'instruments économiques et de réglementations. En Europe, par exemple, les objectifs dits des *trois vingt* visent à réduire les émissions de GES de 20%, augmenter la part d'énergie renouvelable à 20%, et réduire l'intensité énergétique du PIB de 20%. Ces objectifs sont à atteindre en 2020, c'est-à-dire à moyen terme, du point de vue de ceux qui les ont établis en 2007.[1] Par ailleurs, l'Union européenne a mis en place plusieurs instruments pour atteindre ces objectifs : un marché du carbone, des normes d'émissions kilométriques pour les véhicules routiers, des normes d'efficacité énergétique pour les moteurs industriels, l'électroménager, et les ampoules électriques, auxquels s'ajoutent, au niveau national, des règlementations thermiques

[1]En Octobre 2014, la commission européenne a proposé de nouveaux objectifs pour 2030 : réduire les émissions de 40%, augmenter la part du renouvelable à 27%, et améliorer l'efficacité énergétique de 27%. Pour les objectifs de 2020 et de 2030, l'amélioration de l'efficacité énergétique et les réductions d'émissions de gaz à effet de serre se comprennent par rapport au niveau de 1990.

pour les bâtiments neufs, des tarifs d'achat bonifiés ou des obligations de production en faveur de l'électricité d'origine renouvelable, et des incitations fiscales en faveur des véhicules hybrides ou rechargeables (IEA, 2015). Au sein de cette panoplie d'instruments, le prix du carbone semble finalement relégué à un second rôle.

Pourtant, la théorie économique la plus élémentaire établit que la meilleure stratégie, pour un gouvernement qui souhaite lutter contre une *externalité* comme la pollution atmosphérique, consiste à utiliser un unique instrument économique (Tinbergen, 1956) : une taxe pigouvienne, ou, de façon similaire, un marché de permis d'émissions (Pigou, 1932; Coase, 1960). Il doit s'agir en l'occurrence d'un prix du carbone, s'appliquant à tous les secteurs de l'économie, et croissant dans le temps (Pearce, 1991; Nordhaus, 1991). La discussion de l'instrument à privilégier, entre taxe ou quotas, a occupé une place importante dans la littérature,[2] mais est ici laissée de côté. A la place, on s'intéresse aux interprétations politiques souvent faites du profil temporel optimal du prix du carbone.

En effet, il est bien établi que le prix du carbone optimal croît dans le temps. Par exemple, William Nordhaus a développé dans les années 1990 le modèle DICE (Nordhaus, 1991), qui fait depuis référence dans l'étude du timing optimal des réductions d'émissions de GES (Dietz et Stern, 2014; Espagne et al., 2012). DICE recommande qu'une taxe carbone soit introduite à un niveau bas puis augmente progressivement au cours du temps, afin de prendre en compte la préférence pour le présent des agents économiques, et le moindre regret des générations futures, plus riches que les générations présentes, à renoncer à de la consommation au profit de la lutte contre le changement climatique. Plus généralement, la littérature théorique s'accorde sur le fait que la concentration atmosphérique de dioxyde de carbone étant une pollution de stock, le prix du carbone doit croitre progressivement au cours du

[2]Notamment depuis que Pizer (1999) a relevé l'importance des pentes relatives de courbes de coûts et de bénéfice associés à la réductions d'émissions de GES, et de l'incertitude qui pèse sur celles-ci. Goulder et Schein (2013) proposent un revue récente des différences entre ces deux outils, qui se limitent en théorie à deux aspects, tous deux en faveur de la taxe carbone : l'interaction avec d'autres politiques climatiques, et l'interaction stratégique avec les producteurs de pétrole capables d'influencer son prix sur les marchés internationaux. Il est à noter également que des contraintes purement institutionnelles peuvent empêcher la mise en place ce certains instruments, comme le montre l'exemple européen, où toute taxe carbone devrait être approuvée à l'unanimité des États membres pour pouvoir être mise en place (Branger, Lecuyer, et Quirion 2015).

temps (Goulder et Mathai 2000). Dans le cas simplifié d'un budget carbone, l'air pur est analogue à un dépôt d'une ressource fossile. Son prix doit donc suivre la règle d'Hotelling (1931), c'est-à-dire croitre au taux d'intérêt, afin d'égaliser la valeur actuelle d'une tonne abattue aujourd'hui et d'une tonne abattue dans vingt ans.[3]

En principe, face à ce prix croissant, le marché lui-même doit arbitrer entre des réductions d'émissions dans des différents secteurs (par exemple bâtiment ou transport). Cet arbitrage se prolonge au choix des techniques au sein de chaque secteur (par exemple gaz ou énergie renouvelable pour remplacer du charbon dans la production d'électricité). Enfin et surtout, cet arbitrage doit se faire de façon inter-temporelle ; le marché doit notamment déterminer la quantité et la répartition des réductions d'émissions de GES à moyen terme, par exemple la quantité d'énergie renouvelable à mobiliser en 2020. Un détail, que l'on montrera crucial, est souvent omis dans l'exposition de cette théorie : le marché doit partir de la donnée de la trajectoire entière du prix futur du carbone, ou, dans le cas d'un marché, du budget carbone total.

Le point peut-être le plus important pour le débat public est que le profil exponentiel du prix du carbone optimal a été interprété comme une raison de différer les efforts de réduction des émissions de gaz à effet de serre le plus possible. Il s'agirait de se concentrer à court terme uniquement sur les options de réduction les moins couteuses, laissant à plus tard la mobilisation d'options couteuses comme l'énergie renouvelable ou des réductions d'émissions dans le secteur des transports.

Cette façon de voir les choses est rendue particulièrement saillante, dans le débat public, par l'utilisation et l'interprétation de *courbes de cout marginal d'abattement*, ou MACC par leurs initiales anglaises. Ces courbes illustrent une série de mesures permettant de réduire les émissions de GES, caractérisées par la quantité de GES qu'elles permettent de réduire et le cout auquel elles peuvent le faire, et, surtout, ordonnées par ordre de cout croissant. Elles ont étés introduites dans le débat académique dès les années 1990 (Jackson 1991 ; Rubin et al. 1992), mais ont atteint un public large plus récemment (Enkvist et al., 2007; McKinsey, 2009). Parce qu'elles ressemblent à des courbes d'offre, elles

[3] Des analyses plus sophistiquées de la dynamique d'accumulation d'une pollution de stock et de ses conséquences sur l'activité économique montrent que le prix du carbone ne doit pas croitre indéfiniment (il se stabilise une fois que la concentration de pollution atteint sa valeur d'équilibre) mais confirment que, dans le cas pertinent pour analyser le changement climatique, il doit d'abord croitre presqu'exponentiellement (Fischer et al., 2004).

sont souvent interprétées comme telles, y compris par des académiques (Wächter, 2013; Haab, 2007) et des agences gouvernementales (DECC, 2011), c'est à dire comme montrant qu'il faut mettre en œuvre les mesures par ordre de cout croissant.[4]

De façon plus générale, l'argument de la comparaison des couts d'abattement est souvent utilisé pour critiquer les politiques climatiques, par exemples en faveur d'un soutien à l'énergie renouvelable ou aux véhicules électriques : ces politiques favoriseraient un déploiement trop précoce de ces mesures de réductions des émissions de GES. Et pour revenir à DICE, le modèle de référence évoqué plus haut, il représente de fait les réductions d'émissions à l'aide d'une simple courbe de coût d'abattement, qui lie dans ce cas pourcentage de réduction des émissions de gaz à effet de serre et pourcentage du PIB dépensé à cette fin *à chaque instant du temps.* DICE conclue donc également que les efforts optimaux de réduction des émissions de gaz commencent par mobiliser les options dont le cout d'abattement est le plus faible, et mobilisent ensuite des mesures de plus en plus couteuses, au fur et à mesure que le prix du carbone augmente.

La première contribution de cette thèse est de montrer que lorsque l'on prend en compte explicitement les dynamiques d'accumulation du capital, les relations entre profil du prix du carbone, cout d'abattement des mesures à mobiliser, et rythme optimal des réductions des émissions de GES sont plus complexes. A cause de l'inertie, l'action à court ou moyen terme ne peut pas être déconnectée de l'objectif de long terme. Plutôt que de se concentrer uniquement sur les options les moins chères, une stratégie efficace de décarbonisation de l'économie doit également privilégier certaines options chères mais *inertes*, c'est-à-dire dont

[4]Même Sweeney et Weyant (2008), qui ont par ailleurs passé leur carrière à analyser la dynamique optimale des réductions d'émissions de GES, font un pas vers cette interprétation de la MACC qu'ils ont produite pour le gouvernement Californien. "*Once a MAC curve is constructed, one can find the total number of measures needed to reach the target level of emissions reduction by drawing a line designating this target. That total reduction will then imply the cost of the most expensive feasible measure necessary to achieve that reduction in the ordered list of measures. [...W]e can use this description along with the MAC curve to guide policy : we choose an emission reduction target (e.g., sufficient to bring emissions to 1990 levels by 2020), estimate the marginal abatement cost for that level of emissions reductions, and implement all feasible measures to reduce emissions that cost less than the marginal cost associated with the target emission reduction.*"(pages 5 à 6). Cet exemple montre la facilité avec laquelle le dessin d'une MACC mène naturellement à cette conclusion.

on aura besoin à long terme pour décarboniser l'économie, et dont la mise en œuvre complète à un cout raisonnable requiert plusieurs décennies, comme par exemple le déploiement d'infrastructure de transport propre.

Ainsi, les mesures mises en place en Europe pour atteindre l'objectif de réduction des émissions de GES de 20% en 2020 doivent être jugées non seulement sur leur capacité à atteindre ce point de passage au moindre cout, mais également sur leur capacité à garder l'objectif de 80% de réduction en 2050 à portée de main. Par exemple, le remplacement de centrales à charbon par des centrales à gaz permettrait de réduire les émissions de carbone à un cout modéré, mais porte le risque d'un enfermement dans des modes de productions trop intensifs en carbone (*carbon-intensive lock-in*). L'énergie renouvelable peut sembler plus couteuse à court terme, mais permet en revanche de progresser vers la décarbonisation totale. Plus généralement, tout investissement destiné à réduire les émissions de gaz à effet de serre doit être évalué à la lumière d'une stratégie entière de décarbonisation de l'économie (c'est-à-dire à l'aide d'une vision prospective), en s'intéressant aux temps nécessaires à la mise en œuvre de chacune des options techniques permettant de réduire les émissions.

En particulier, la contribution de technologies particulières aux efforts de réductions d'émissions de gaz à effet de serre ne peut pas s'apprécier en dehors du système technique dans lequel elle doit s'inscrire. Par exemple, le calcul du cout d'abattement derrière le remplacement d'un véhicule classique par une voiture électrique peut paraitre élevé là où le contenu carbone de l'électricité est élevé et le bénéfice environnemental semble donc faible (Hawkins, Gausen, et Strømman 2012). Mais la pertinence d'un soutien public à l'électrification des transports ne dépend pas seulement du contenu carbone de l'électricité contemporaine, mais aussi et surtout de ce qu'il sera dans quelques années, lorsque les véhicules électriques représenteront une part significative du parc, et que la production d'électricité aura évolué.[5]

Cette thèse montre donc que, malgré le prix du carbone croissant dans le temps, la transition optimale vers une économie bas carbone démarre par des efforts significatifs, et il peut être optimal de mobiliser

[5]L'autre élément crucial à prendre en compte est l'évolution future des couts, non seulement des technologies d'électrification, mais ici aussi du système technique dans lequel elles s'inscrivent (Gritsevskyi et Nakicenovi, 2000), c'est-à-dire ici centrales électriques, réseaux de transport et distribution, et peut être *smart grids* – capacités de stockage, de gestion de la demande et de recharge intelligente.

des options techniques relativement plus couteuses dès le début de cette transition. Ces résultats peuvent rappeler ceux issus de la littérature sur le changement technique dirigé, qui concluent eux aussi que des efforts soutenus à court terme sont nécessaires pour mettre l'économie sur la voie du développement décarboné.[6] Toutefois, leur argument est basé sur la prise en compte d'une deuxième imperfection de marché (en plus de la pollution causée par les émissions de gaz à effet de serre) : les externalités liées aux effets d'apprentissage. C'est également l'argument des effets d'apprentissage qu'utilisent par exemple Rosendhal (2004) ou Bramoullé et Olson (2005) pour justifier des efforts plus importants dans les secteurs qui y sont le plus soumis.

Ici, la simple dynamique d'accumulation du capital, en l'absence de toute autre imperfection de marché ou objectif politique, se traduit par des efforts transitoires substantiellement différents dans différents secteurs. En cela, les travaux présentés ici s'inscrivent dans la littérature qui étudie l'impact de l'inertie technique sur la transition vers une économie bas carbone, dans la tradition de Grubb et al. (1995), Ha-Duong et al. (1997), Lecocq et al. (1998), Jacoby et Wing (1999), van der Zwaan et al. (2002) et Gilotte et Fortin (2004). Les travaux exposés dans cette thèse sont les premiers à étudier analytiquement le tempo optimal d'investissement propre dans plusieurs secteurs, à proposer une distinction claire entre inertie causée par l'accumulation du capital et effet d'apprentissage,[7] et à séparer analytiquement le prix du carbone, les réductions d'émissions, le déploiement de capital propre, et le cout et la quantité optimale des investissements dans ce capital

[6] (André et Smulders, 2014; Acemoglu et al., 2012; Gerlagh et al., 2009; Grimaud et Lafforgue, 2008)

[7] Bien que l'inertie due à l'accumulation du capital et les effets d'apprentissage aient un effet similaire sur la distribution optimale des efforts entre secteurs, ce sont deux phénomènes différents. Certains secteurs, comme peut-être la construction d'infrastructure de transports, peuvent être soumis à l'inertie induite par l'accumulation lente de capital, sans être soumis aux effets d'apprentissage. L'implication opérationnelle des deux phénomènes est également différente : les externalités de connaissance appellent à subventionner la recherche, une activité de bureau ou laboratoire, alors que l'inertie due à l'accumulation de capital invite à commencer la construction de capital propre au plus vite, sur le terrain. Enfin, l'ampleur quantitative des deux phénomènes n'a pas de raison d'être comparable. Par exemple, Fischer et al. (2012) trouvent que les effets d'apprentissage justifient une subvention optimale de l'ordre de 1 à 6 c\$/kWh pour l'électricité renouvelable, très inférieure aux tarifs de rachat pratiqués, alors que dans une application au secteur de l'électricité (Lecuyer et Vogt-Schilb, 2014), nous trouvons que l'inertie justifie un coût de déploiement des centrales renouvelables à un cout initial de l'ordre de 20c\$/kWh plus élevées que le prix de l'électricité.

propre. Parce qu'on y modélise explicitement l'investissement, ces travaux sont les premiers à mettre en avant le fait qu'un prix du carbone qui croît dans le temps est compatible avec un investissement soutenu à court terme, concentré sur les secteurs où les réductions d'émissions sont les plus difficiles à mettre en œuvre.

Cette clarification théorique de l'importance de la prise en compte de l'inertie sur l'ordonnancement optimal des efforts de réduction des émissions de gaz à effet de serre n'a un intérêt pratique que s'il conduit à réviser la conception des instruments économiques utilisés par les pouvoirs publics pour les mettre en œuvre. C'est l'objet de la deuxième contribution cette thèse, qui porte sur les conséquences de l'inertie et de l'irréversibilité sur le choix d'instruments en présence de défaillances de l'État. Elle mobilise deux arguments.

Le premier argument est la crédibilité limitée des prix du carbone à long ou même moyen terme. Pour déclencher les bonnes décisions d'investissement dans des secteurs inertes, comme celui de la production d'électricité, où la durée de vie du capital varie entre 30 et 60 ans, un prix du carbone doit être crédible sur 30 à 60 ans. Les décisions touchant à la forme des villes et aux infrastructures de transport, elles, doivent considérer que le prix du carbone est donné pour les cinq à vingt prochaines décennies. Même dans le secteur automobile, les voitures personnelles sont utilisées près de dix ans. Ce besoin de crédibilité des signaux prix sur le long terme contraste avec les exemples Australien et Canadien, qui montrent que les gouvernements peuvent à tout moment défaire ce qu'ont fait leurs prédécesseurs. Les prix du carbone, qu'ils proviennent d'un marché ou d'une taxe, peuvent alors être considérés par le marché comme des contraintes temporaires, qu'il conviendrait de satisfaire en investissant uniquement dans les mesures les moins chères. Or, cette stratégie (menant par exemple à remplacer les centrales à charbon par des centrales à gaz, sans s'intéresser aux renouvelables) peut conduire à s'enfermer dans un système de production trop carboné.

Au contraire, des politiques comme les normes d'efficacité énergétique dans le bâtiment, les bonus/malus pour influencer l'achat d'équipements plus propres, ou la planification urbaine ont l'avantage d'influencer directement l'investissement contemporain. Couplé à des objectifs sectoriels, comme les 20% d'énergie renouvelable en 2020, ils permettent de s'assurer que les réductions à court terme sont réalisées grâce à des mesures qui permettent de progresser vers une économie décarbonée. Ce type d'instruments peut donc être utilisé par un gouvernement imparfait (incapable de s'engager sur plusieurs décennies) pour réduire les émissions et influencer durablement la structure de l'économie – au prix d'une transparence réduite quant au cout marginal d'abattement, et donc probablement d'une efficacité économique réduite.[8]

Le second facteur est l'acceptabilité sociale d'un changement soudain des prix induit par la mise en place d'un prix du carbone. Ici, l'inertie et l'irréversibilité jouent un rôle clé. À chaque instant, le système de production économique est donné, et dépend de décisions d'investissements passées. Un prix du carbone redirige l'investissement, et permet donc de progressivement modifier la structure de l'économie. Mais à court terme, certains agents sont quasiment contraints, pour s'y adapter, de réduire leur production. Le propriétaire d'une centrale à charbon ne peut pas transformer sa centrale en parc éolien, et doit donc ajuster sa production à la baisse, voire fermer entièrement la centrale, si un prix du carbone est mis en place. Pareillement, un ménage ayant élu domicile loin de son lieu de travail et ayant acquis une voiture gourmande en énergie ne peut pas déménager près d'une ligne de transport en commun ou changer de véhicule dès qu'un prix du carbone est mis en place. Face à une montée des prix de l'énergie, ce ménage va peut-être choisir de réduire ses déplacements de loisirs. Plus généralement, les propriétaires du capital intensif en carbone (et les travailleurs qui en dépendent) paient une part disproportionnée du cout total d'un prix du carbone.

Le prix du carbone, dont les bénéfices sont étalés dans le temps et sur l'ensemble de la société (mondiale), impose donc un cout immédiat et disproportionné sur des intérêts acquis (dans le pays où il est mis en œuvre), qui peuvent être en mesure de bloquer sa mise en place (Olson, 1977; Trebilcock, 2014). Idéalement, le gouvernement devrait être en mesure de séparer *équité* et *efficacité* des politiques climatiques, et de compenser les perdants de la mise en place d'un prix du carbone en utilisant des transferts monétaires purs, des transferts en nature par exemple sous formes de prestations sociales (Combet 2013), voire des baisses de taxes ciblées (Metcalf, 2014).[9] En pratique, un gouvernement

[8]D'autres études ont mis en avant le problème causé par l'incapacité du gouvernement à s'engager sur des politiques climatiques, mais en se concentrant là encore sur l'interaction avec les externalités d'apprentissage (Golombek et al., 2010; Ulph et Ulph, 2013)

[9]Goulder et al. (2010) montrent qu'une autre politique, la distribution gratuite d'une fraction des permis d'émissions, permet de compenser les propriétaires du capital polluant. Cette stratégie ne permet toutefois pas de compenser les travailleurs

non omniscient aura du mal à identifier chaque perdant de la mise en place d'un prix du carbone, incluant par exemple chacun des acheteurs récents d'un véhicule polluant, les travailleurs qui dépendent du capital polluant (par exemple les employés d'une mine) ou des agents dont l'activité n'a pas de rapport direct avec les émissions de gaz à effet de serre, comme un prestataire de service travaillant pour le fournisseur d'une centrale à charbon devant fermer.

En revanche, des instruments de politiques alternatifs, qui se contentent de rediriger l'investissement vers du capital propre dans chaque secteur (comme, ici encore, le bonus/malus automobile, les normes d'efficacité énergétique sur les bâtiments neufs, ou des projets pilotes pour développer l'énergie renouvelable), n'ont pas d'effet direct sur le capital polluant préexistant. Ces instruments repartissent le cout de la transition vers une économie décarbonée sur une population plus large et une période de temps plus longue. Ils sont donc peut-être plus socialement acceptables qu'un prix du carbone, bien qu'en termes de pure efficacité économique ils lui soient inférieurs.

Cette deuxième contribution enrichit donc la littérature qui étudie les raisons que les gouvernements peuvent avoir à utiliser plusieurs instruments de politiques climatiques. Le principe de Tinbergen (1956) établit qu'une unique externalité, ici l'accumulation dans l'atmosphère de GES, doit être réglée par un unique instrument, ici un prix du carbone. La littérature existante reconnait toutefois l'intérêt d'autres instruments de politique venant s'ajouter au prix du carbone, afin de remplir des objectifs politiques complètement différents, comme la sécurité énergétique (Fischer et Preonas, 2010) ; ou afin de corriger d'autres défaillances de marché que l'externalité carbone, comme les effets d'apprentissage sur les nouvelles technologies propres (Fischer et al., 2012; Jaffe et al., 2005), le manque d'information, notamment sur la consommation énergétique de l'équipement (Davis et Metcalf, 2014; Gillingham et Palmer, 2014; Allcott et Greenstone, 2012), ou les problèmes de principal-agent, notamment en ce qui concerne l'isolation des bâtiments (Gillingham et al., 2012; Giraudet et Houde, 2014). Ici, ce sont l'incapacité des gouvernements à s'engager sur des prix du carbone, et leur capacité limitée à compenser les perdants d'un prix du carbone, qui tendent à justifier l'utilisation d'instruments alternatifs.

En résumé, cette thèse montre que bien que les gaz à effet de serre représentent une pollution de stock qui impose un cout virtuel du carbone

qui dépendent directement ou indirectement de ce capital.

croissant dans le temps, il peut être socialement désirable d'investir des maintenant dans le déploiement de mesures couteuses de réductions d'émissions de GES. Ce résultat découle uniquement de la prise en compte de l'inertie inhérente à l'accumulation de capital bas carbone, en l'absence de toute autre imperfection de marché. De plus, pour mettre en œuvre ce déploiement, des gouvernements imparfaits (c'est-à-dire qui ne peuvent pas s'engager sur une trajectoire parfaitement crédible de prix du carbone, ou compenser parfaitement les perdants de la mise en place de ce prix) peuvent avoir intérêt à utiliser des instruments de politiques sectoriels, plus effectifs et plus acceptables que le prix du carbone, afin de s'assurer que le marché mette en œuvre ces investissements.

Resumé des chapitres

Le **premier chapitre** de cette thèse esquisse une théorie de la transition vers du capital propre. L'un des enjeux majeurs des politiques de stabilisation du climat est de remplacer un stock existant de capital polluant par un stock comparable de capital propre. Or, une composante centrale du cout de cette transformation dépend de la vitesse à laquelle elle est menée : une transformation plus rapide demande de détourner plus de travailleurs et plus de capitaux d'un autre usage productif. Le cout marginal des investissements bas carbone est donc une fonction croissante de la vitesse à laquelle l'appareil productif est transformé, un phénomène connu sous le terme de *cout d'ajustement* dans la théorie générale de l'investissement (Gould 1968 ; Lucas 1967).

Pour minimiser le cout d'ajustement, la stratégie optimale doit anticiper l'objectif de long terme, et étaler l'investissement total dans le temps. Le résultat, détaillé dans le texte, est qu'un prix du carbone qui croit exponentiellement dans le temps se traduit par des investissements en forme de cloche, qui peuvent démarrer au-dessus du prix du carbone. A long terme, la transition vers du capital bas carbone est terminée, et l'investissement retombe donc, malgré un prix du carbone élevé (Figure 1).

Par ailleurs, puisque le capital propre a une longue durée de vie, la valeur optimale d'un investissement bas carbone ne dépend pas uniquement du prix du carbone, mais également de la valeur du capital bas carbone dans le futur. En particulier, le cout technique des abattements, c'est-à-dire le rapport de leur surcout (par rapport au capital polluant) sur la somme actualisée des émissions évitées, ne doit pas directement être comparé au prix du carbone. Pourtant, c'est souvent cette valeur, appelée *cout annualisé des réductions d'émission* par le GIEC (Kolstad et Urama 2014) ou simplement *cout marginal d'abattement* dans de nombreuses études (McKinsey and Company 2009), qui est utilisée en pratique pour jauger la valeur d'une mesure de réduction des émissions.

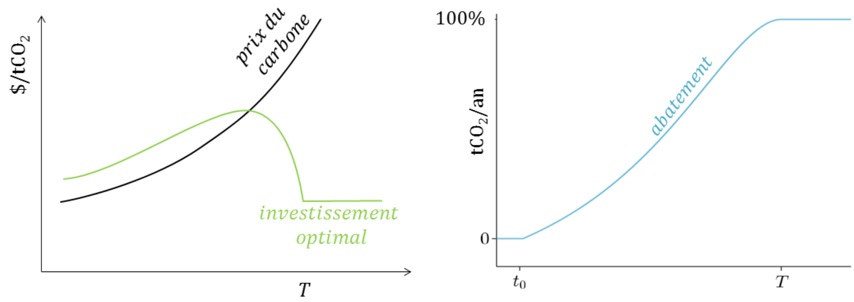


Figure 1 – Profil temporel d'une taxe carbone, de l'investissement bas carbone, et de l'abattement qui en résulte. Le cadran de gauche montre qu'un prix du carbone qui croit exponentiellement se traduit par un profil d'investissement en cloche. A droite, l'abattement croit selon une courbe en S. Une fois que tout le capital sale a été remplacé par du capital propre (en T), 100% des émissions sont abattues, et l'investissement ne sert qu'à maintenir le stock de capital propre en place.

De plus, différents secteurs de l'économie (production d'électricité, bâtiments, transport), sont caractérisés par différent potentiels maximum d'abattement, et différent couts du capital bas carbone. De ce fait, la valeur du capital bas carbone diffère dans chaque secteur, et un unique prix du carbone se traduit par des investissements différents dans chaque secteur, notamment lorsque ceux-ci sont exprimés en euros dépensés par tonne de carbone évitée, c'est-à-dire grâce au cout annualisé d'investissement. On montre qu'ils doivent être supérieurs, toute chose égale par ailleurs, dans les secteurs où le capital bas carbone est plus cher (comme le secteur des transports), et ceux où le potentiel de réduction des émissions de gaz à effet de serre est plus important (comme la production d'électricité). Ces secteurs font en effet face à un plus grand besoin d'investissement total, qu'il convient d'étaler le plus possible pour réduire les couts d'ajustements, et donc de commencer le plus tôt possible.

Le **deuxième chapitre** vise à prolonger les résultats du premier dans deux directions. D'abord, le premier chapitre étudie la répartition de l'effort de réduction dans des secteurs distincts de l'économie, en faisant l'hypothèse qu'ils n'interagissent pas entre eux. Le second chapitre s'intéresse à la comparaison d'investissements en compétition à l'intérieur d'un secteur. Ensuite, le premier chapitre ignore la question de l'usage optimal des ressources fossiles (pétrole, charbon, gaz), qui peut pourtant jouer un rôle dans le timing optimal des réductions d'émissions de gaz à effet de serre. Ce chapitre combine donc ces deux aspects dans un seul modèle.

Il prend l'exemple archétypal d'une économie dont la production d'électricité est assurée par des centrales à charbon, qui peuvent être remplacées soit par de l'énergie renouvelable (éolienne, solaire), chère mais presqu'entièrement décarbonée, soit par des centrales à gaz, moins chères mais au potentiel de réduction plus réduit. Il étudie la transition optimale des centrales à charbon vers l'énergie renouvelable, et le rôle que le gaz peut jouer dans cette transition, sous contrainte d'un objectif climatique.

Ici aussi, prendre en compte l'inertie inhérente aux dynamiques d'accumulation du capital s'avère crucial (alors que l'impact de la modélisation explicite des ressources fossiles s'avère limité). Comme dans le chapitre précédent, il serait bien trop cher de remplacer du jour au lendemain le parc de production existant par un parc entièrement décarboné ; au contraire, les ressources de l'économie (travailleurs qualifiés, lignes de production) établissent un rythme optimal auquel construire et déployer le nouveau capital, par exemple des éoliennes. De ce fait, la stratégie optimale démarre l'installation d'éoliennes tôt, plutôt que de remplacer séquentiellement le charbon par du gaz, puis le gaz par du renouvelable – comme une application hâtive de la règle d'Herfindahl (1967),[10] qui ignore les dynamiques d'accumulation du capital, pourrait suggérer.

Par ailleurs, le rôle que jouent les centrales à gaz dans une transition vers une électricité entièrement décarboné est purement temporaire : il permet de réduire le besoin d'investissement dans le renouvelable à court terme, et donc les coûts d'ajustement ; mais à moyen terme, il doit être déclassé afin de laisser la voie libre à plus de renouvelable (Figure 2). Ce dernier résultat est spécifique à ce chapitre, car il demande de modéliser deux options concurrentes de réductions d'émissions de gaz à effet de serre, l'une pouvant remplacer l'autre. En l'occurrence, le gaz permet de réduire les émissions à court terme, mais ne peut pas être utilisé pour atteindre l'objectif final de décarbonisation presqu'entière de l'économie. Ce résultat illustre de nouveau l'importance de l'anticipation du long terme lors de la comparaison des options disponibles à court terme – en l'espèce, il y a un risque de sur-

[10] La règle d'Herfindahl établit que des dépôts de ressources fossiles qui diffèrent par leur cout d'extraction doivent être exploités par ordre de cout croissant. Le chapitre 2 discute les ajouts qui ont été fait à la théorie d'Herfindahl depuis 1967.

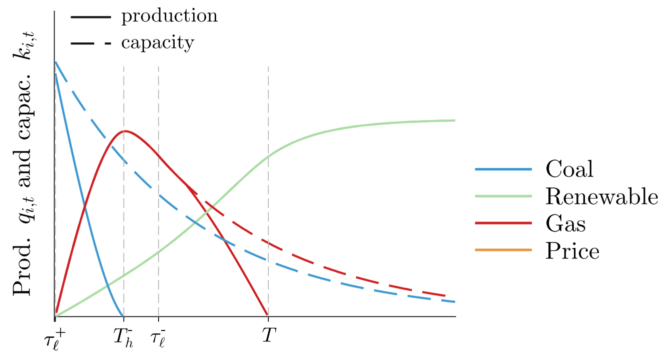


Figure 2 – Transition optimale du charbon vers le gaz et l'énergie renouvelable. Sur le sentier optimal, l'investissement et la production à base d'énergie renouvelable peuvent commencer tôt, c'est-à-dire avant d'arrêter la production d'énergie fossile. Sous contrainte de budget carbone, le gaz permet de réduire le besoin d'énergie renouvelable à court terme, mais doit finalement être sous-utilisé et être remplacé par du renouvelable.

évaluer la valeur des centrales à gaz si on ignore qu'elles sont appelées à être remplacées elles-mêmes par du renouvelable à moyen terme.

Le **troisième chapitre** illustre d'une autre façon comment la prise en compte de l'inertie et des objectifs de long terme est essentiel à l'évaluation d'options destinées à réduire les émissions de GES. Il prend l'exemple de l'*électrification* comme moyen de réduire les émissions de gaz à effet de serre (c'est-à-dire à l'utilisation de technologies telles que fourneaux électriques, véhicules électriques, ou pompes à chaleur en remplacement de fourneaux au charbon, véhicules à essence, ou chauffage au gaz). Il suggère que, du fait de l'inertie des systèmes techniques, la contribution des technologies aux réductions d'émissions de gaz à effet serre, à l'instar de leur cout, ne peut pas s'apprécier indépendamment d'une vision concernant le tempo de leur déploiement et le système technique dans lesquelles elles s'inscrivent.[11]

De nombreux rapport d'experts et études académiques ont établi que l'effet de l'électrification sur les émissions de gaz à effet de serre dépend de la source d'énergie utilisée pour produire l'électricité. Par exemple, les voitures électriques rechargées sur des centrales à charbon émettent plus de carbone que les voitures à essence traditionnelles (Ademe 2009 ; Hawkins, Gausen, et Strømman 2012). Dans le débat pu-

[11] Une analyse similaire à celle de ce chapitre, limitée au cas du véhicules électrique en Europe, est également développée dans un article qui ne fait pas partie de ce manuscrit (Vogt-Schilb et al., 2013).

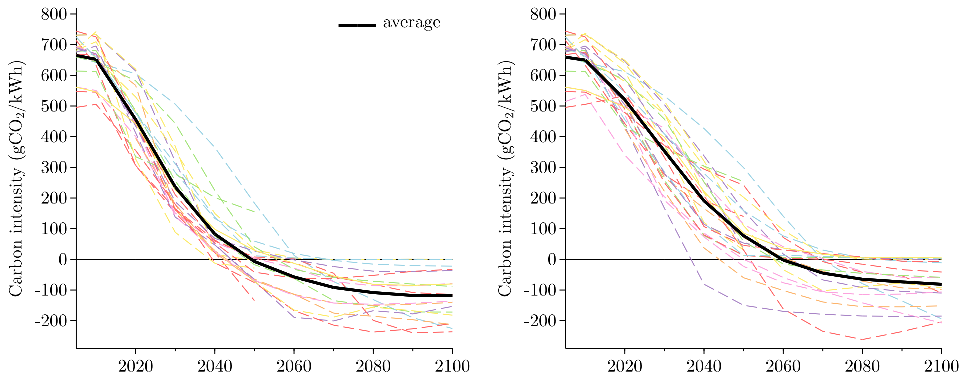


Figure 3 – Contenu carbone de l'électricité mondiale dans les scenarios de l'IPCC. Gauche : pour atteindre une concentration de gaz à effet de serre (grossièrement) compatible avec la cible des 2°C (Droite : 3°C). Chaque ligne de couleur représente un modèle différent. Tous les modèle s'accordent pour dire que la stabilisation du changement climatique passe par de l'électricité bas carbone. L'utilisation de biomasse couplée à la séquestration et capture du carbone permet de produire de l'électricité à contenu carbone négatif (le chapitre 3 montre que cette technologie n'est pas nécessaire à la décarbonisation du secteur de l'électricité).

blic, ces résultats sont trop souvent interprétés comme mettant sérieusement en doute la pertinence de l'électrification comme moyen d'atténuer le changement climatique (BBC 2012).

Le chapitre 3 explicite les mécanismes clés qui justifient qu'au sein de la communauté de modélisation prospective, l'électrification est vue comme l'un des piliers de la stabilisation du changement climatique (Williams et al. 2012 ; Krey et al. 2014). Cette communauté utilise des modèles (les « *integrated assessment models* ») qui sont parfois qualifiés de boîte noires par des économistes plus à l'aise avec des petits modèles analytiques, en raison de la richesse en détail technologique et de leur complexité qui empêchent d'en décrire exhaustivement le fonctionnement en quelques équations (et qui mènent ces modélisateurs à utiliser des méthodes de résolution numériques assistées par ordinateur). Ce chapitre met en avant un consensus au sein de la communauté de la modélisation prospective : la stabilisation du réchauffement climatique passe nécessairement par la production d'électricité décarbonée (à horizon 2050 à 2100, en fonction des pays, des hypothèses faites sur le coût des moyens de production d'électricité bas carbone, et du seuil d'augmentation de la température atmosphérique visé).

A la lumière de ce résultat, la question pertinente n'est plus de savoir *si* il est désirable d'électrifier, mais plutôt *quand* le faire. Pour répondre à cette question, les décideurs ont besoin de deux éléments. Le premier est une estimation de la vitesse à laquelle l'électricité peut être décarbonée, et le chapitre 3 fournit de telles estimations pour 4 économies majeures de la planète (Chine, Europe, Etats-Unis, Inde). Le deuxième est une estimation du temps nécessaire pour opérer une transition vers un système électrifié, par exemple pour remplacer le parc de voiture à essence ou diesel par un parc de voitures hybrides rechargeables ou électriques – on pourrait dire une estimation de l'*inertie* de chaque secteur de l'économie. L'enjeu d'une politique d'électrification n'est pas de réduire les émissions de gaz à effet de serre dès sa mise en œuvre, mais d'opérer une transition progressive vers une économie bas carbone, dans laquelle l'électricité est propre et permet de satisfaire un nombre étendu de besoins énergétiques.

Le **quatrième chapitre** de cette thèse, et les deux suivants, mettent moins l'accent sur l'explication des principes théoriques justifiant une nouvelle approche des liens entre prix du carbone, coût des options technologies, et ordonnancement temporel de leur mise en place, pour revenir à une discussion plus centrée sur le débat public, et à la façon dont on pourrait le faire évoluer. Une première étape, essentielle, serait de communiquer aux décideurs et au public une caractérisation de l'inertie des mesures de réduction des émissions de gaz à effet de serre.

Le quatrième chapitre s'intéresse en particulier au cas des courbes de coût marginal (MACC), un outil populaire dans le débat politique, et qui représente une liste de mesures de réductions d'émissions de gaz à effet de serre (isolation des bâtiments, installation d'éoliennes, gestion des déchets...), caractérisées par leur coût (donné en ordonnée) et leur potentiel d'abattement (donné en abscisse), et triée par ordre de coût croissant. Les MACC ressemblent à des *courbes d'offre* d'abattement, et sont souvent interprétées comme telles. Selon cette interprétation, les options de réductions d'émission de gaz à effet de serre doivent être mise en œuvre par ordre de coût croissant, c'est-à-dire en commençant par la moins chère (Taylor, 2012; Wächter, 2013).

Or, en plus du coût et du potentiel, une dimension importante de chaque mesure est le temps nécessaire à sa mise en œuvre, limitée par des facteurs comme la durée de vie du capital, la disponibilité de travailleurs qualifiés et la quantité d'épargne mobilisable pour financer les investissements bas carbone. Par exemple, la main d'œuvre qualifiée disponible dans un pays peut limiter le nombre de bâtiments pouvant être isolés chaque année.

Dans ce cadre,[12] les stratégies optimales d'atténuation du changement climatique doivent se faire en deux temps. D'abord, partir des objectifs de long terme (par exemple réduire les émissions de 80% en 2050), et établir, en fonction de leur cout et potentiel, le panier optimal de mesures qui doivent avoir été déployées en 2050 pour atteindre cet objectif (énergie renouvelable, isolation des bâtiments, infrastructures de transport, etc.).

Ensuite, en prenant en compte une estimation de la vitesse à laquelle chacune de ses mesures peut être mise en œuvre, déterminer la date à laquelle le déploiement de chacune d'entre elles doit commencer. En particulier, les objectifs de court terme (comme réduire les émissions de 20% à horizon 2020) doivent être atteints avec certaines des options qui sont nécessaires pour accomplir les objectifs de plus long terme et qui ont besoin de temps pour être déployées, et ce même si ces options ne sont pas les moins coûteuse à court terme (par exemple, peut-être grâce à 20% d'énergie renouvelable).

Réciproquement, on montre que, du fait de l'irréversibilité, décider de stratégies de court terme sans prendre en compte les objectifs de long terme mènerait à des stratégies sous-optimales. En caricaturant, un décideur « découvrant » en 2021 que les réductions de 2020 ne sont qu'une première étape vers plus de réductions en 2050 pourrait s'apercevoir qu'il n'a pas le temps, entre 2021 et 2050, de mettre en œuvre l'ensemble des mesures nécessaires pour atteindre l'objectif de 2050.

Ce chapitre permet donc d'expliquer simplement le résultat, bien connu dans la communauté de la modélisation prospective, qu'une quantité suffisante de réductions d'émissions de GES est nécessaires à court terme pour atteindre des objectifs ambitieux à long terme (Luderer

[12]Ce chapitre et le suivant abandonnent momentanément les couts d'ajustements convexes pesant sur la vitesse à laquelle les investissements bas carbone sont mis en œuvre, au profit d'un cout d'abattement donné et d'une vitesse de mise en œuvre maximale. Ce cas de figure peut être vu comme un cas particulier des couts d'ajustement – négligeables en dessous de la vitesse maximale, et prohibitifs audessus. Surtout, il est peut-être plus conforme à l'information dont disposent les décideurs publics. Il est peut-être plus aisé, et en tout cas plus courant, d'estimer le cout d'une éolienne et le temps nécessaire à remplacer un parc de centrales électriques que d'estimer une fonction de cout convexe, liant le cout de l'éolienne marginale à la vitesse de déploiement instantanée des éoliennes.

et al. 2013 ; Riahi et al. 2015). Il le prolonge également, en montrant que ces réductions de court terme doivent avoir lieu dans « les bons secteurs », c'est-à-dire ceux soumis à l'inertie.

Ces résultats tendent donc à encourager l'utilisation d'objectifs et de politiques sectorielles (comme la cible de 20% d'énergie renouvelable en Europe en 2020) et de politiques affectant directement l'investissement (comme les normes d'efficacité énergétique sur les bâtiments ou les véhicules). Leur rôle ici est de s'assurer, en l'absence de crédibilité d'une trajectoire de prix du carbone s'étendant jusqu'à 2050 et au-delà, que les objectifs agrégés de court terme (comme réduire l'ensemble des émissions de 20% en 2020) soient atteints avec des réductions de *qualité* suffisante, c'est-à-dire avec certaines des mesures requises à long terme, par exemple pour atteindre un objectif de 80% de réductions en 2050.

Le **cinquième chapitre** quantifie et donne un aspect plus concret aux résultats du chapitre 4. Il s'intéresse à une *MAC curve* développée à la Banque Mondiale pour étudier le développement bas carbone du Brésil sur la période 2010-2030 (de Gouvello 2010). Il montre que pour une même quantité d'abattement en 2020, ignorer l'objectif de 2030 conduit à sous-investir dans des infrastructures de transport propre – métro et train – c'est-à-dire dans des options chères mais inertes, et à sur-investir dans des améliorations marginales d'efficacité énergétique dans les raffineries, une option peu chère mais au potentiel limité (Figure 4).[13] Là où la première ligne de métro ouvre la possibilité à une deuxième ligne de métro, et à un système de transport cohérent avec l'objectif de décarbonisation de l'économie à long terme, l'amélioration des raffineries ne peut déboucher que sur un parc de raffineries marginalement plus efficaces, mais tout de même émettrices de carbone. De ce fait, 9 $MtCO_2$ évitées grâce à une première ligne de métro peuvent avoir plus de valeur que 11 $MtCO_2$ évitées dans les raffineries.

Pour éviter que les *MAC curves* ne soient interprétées comme des courbes d'offre d'abattement, le chapitre 5 propose qu'elles soient systématiquement flanquées d'une représentation graphique des scénarios de pénétrations des différentes mesures, pour insister sur le caractère dynamique des stratégies de sabilisation du climat, informant ainsi le lecteur du temps nécessaire à la mise en œuvre des différentes mesures (Figure 5).

Finalement, le **sixième chapitre** de cette thèse explore un autre as-

[13] L'absence de données ne nous permet pas d'étudier comment un objectif d plus long terme, par exemple 2050, peut influencer l'action de court terme.

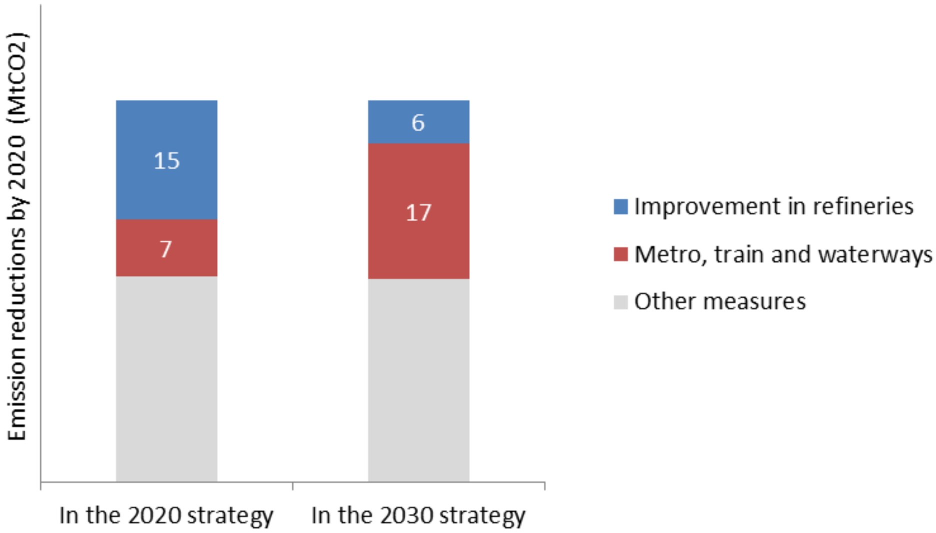


Figure 4 – L'investissement à court terme dépend de l'objectif de long terme. Les deux barres verticales atteignent la même quantité de réductions d'émission de GES en 2020, mais en utilisant des mesures différentes. Lorsque l'objectif de 2030 est pris en compte (à droite), l'abattement à 2020 repose plus sur des options inertes, telles que les infrastructures de transport propre.

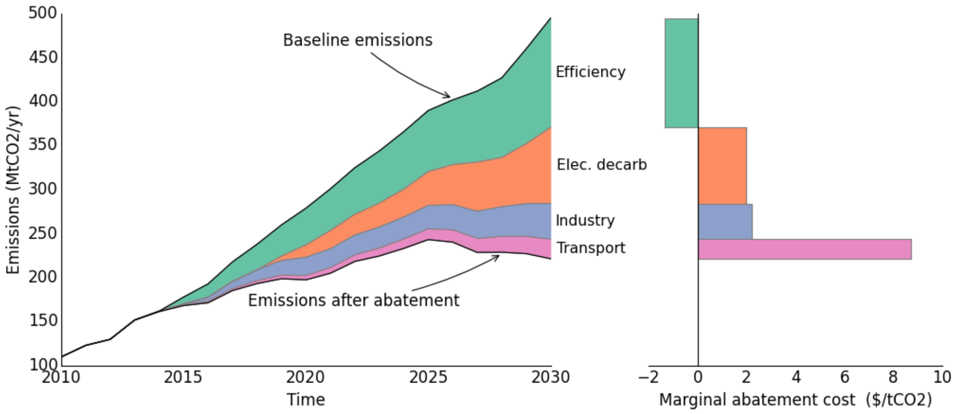


Figure 5 – Les trois dimensions essentielles des mesures d'abattement : le profil de pénétration, le cout, et l'abattement finalement atteint. En retournant la MAC curve (à droite) et en l'affichant face aux profils temporels de pénétration (à gauche), on évite son interprétation comme une courbe d'offre d'abattement. Par exemple, le secteur des transports est ici le plus cher à décarbonner, mais la figure montre que l'action dans le secteur des transports doit commencer tôt.

pect des instruments, qui, à l'instar des normes d'efficacité énergétique, des systèmes de bonus-malus, ou des prêts financiers bonifiés, agissent directement sur les décisions d'investissement. Il compare le prix du carbone et des instruments agissant directement sur l'investissement, dans un modèle de Ramsey avec deux types de capital : l'un polluant et préexistant (centrales à charbon, voitures à essence), et l'autre, propre (éoliennes, voitures électriques), dans lequel il faut investir pour stabiliser le climat. Il compare l'efficacité économique et l'impact distributif du prix du carbone et des instruments alternatifs.

Il confirme qu'en l'absence d'autres imperfections de marché ou objectifs politiques, le prix du carbone permet de minimiser le coût actualisé de la transition vers du capital propre. En effet, un prix du carbone parfaitement crédible et anticipé par le marché agit sur tous les leviers disponibles pour réduire les émissions : redirection de l'investissement, mais aussi ajustement du taux d'utilisation du capital polluant, par exemple en réduisant les distances parcourues en automobile, ou en déclassant les centrales à charbon les plus polluantes. En économie, le *principe d'équi-marginalité* établit que tous les leviers permettant d'arriver à un même résultat doivent être utilisés avec la même intensité pour atteindre ce résultat à un cout minimal.

Mais ce second levier fait justement peser un coût disproportionné sur les propriétaires du capital polluant, et sur les travailleurs qui en dépendent dans les filières les plus intensives en carbone. Les acteurs de ces filières, qui se sont développées avant la mise en place d'un prix du carbone, peuvent donc se constituer en opposants à la mise en place de ce dernier, et peut-être empêcher toute réforme (Olson 1977 ; Trebilcock 2014). De plus, la sous-utilisation soudaine du capital polluant fait peser une part significative de l'effort sur les générations (et l'électorat) présents, pour le bénéfice des générations futures.

En revanche, des instruments comme les normes d'efficacité énergétique sur les voitures neuves ou les bâtiments redirigent l'investissement vers du capital propre (Figure 6), sans toucher directement au capital polluant existant. Ces instruments sont donc moins efficaces, et réduisent les émissions plus lentement ; mais ils lissent la distribution de l'effort dans le temps, et ne réduisent pas la valeur du capital polluant existant.[14] Au contraire, en rendant la construction de nouveau capital polluant plus difficile, mais ne changeant pas son cout d'utilisation, les instruments tels que les normes d'efficacité énergétique et autre bonus/malus augmentent la valeur du capital polluant préexistant sur le marché secondaire. De tels instruments peuvent donc éveiller moins d'opposition politique.

On ne peut pas conclure de ce chapitre que les instruments agissant directement sur les investissements sont *en théorie* plus justes ou plus acceptables que le prix du carbone. Au contraire, la théorie économique la plus élémentaire conclue qu'idéalement, les revenus de la taxe carbone peuvent être redistribués à la faveur de ceux qui perdent le plus à sa mise en œuvre, afin de préserver une distribution des richesses souhaitée tout en incitant chacun à réduire les émissions grâce à tous les leviers disponibles. Mais en pratique, il peut être malaisé d'identifier chaque

[14] On peut ici faire le parallèle avec les travaux de Chichilnisky et Heal (1994), qui montrent qu'en l'absence de transferts entre différents acteurs d'une économie, il n'est plus optimal d'égaliser le cout marginal d'abattement dans l'économie. Ici, il n'y a pas de transfert aisément possible entre les agents qui décident dans quel type de capital investir, et les propriétaires du capital polluant qui décident de son taux d'utilisation, et cela peut conduire le gouvernement à ne pas leur imposer le même cout marginal d'abattement. Signalons par ailleurs que d'autres études ont déjà montré que les instruments alternatifs étalent leur cout sur une population plus large que le prix du carbone (Giraudet et Quirion 2008 ; Fullerton et Heutel 2010), mais en se limitant à un cadre statique. (Grimaud et Lafforgue, 2008) montrent également que subventionner la recherche et le développement de technologies propres, sans mettre en place de prix du carbone, permet d'épargner les générations présentes.

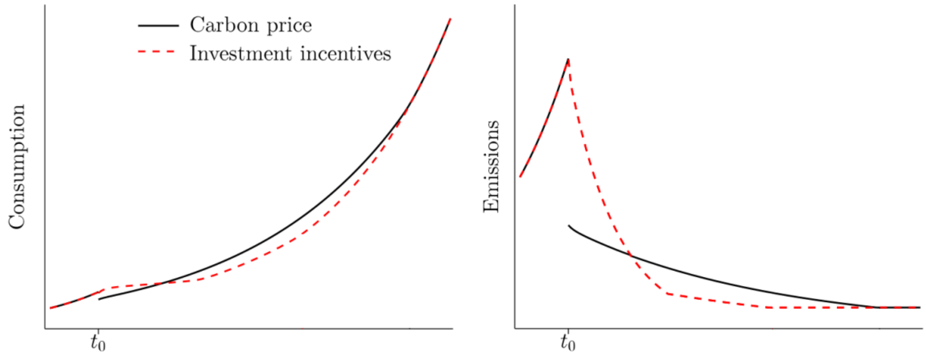


Figure 6 – Comparaison d'un prix du carbone et de mesures régulant uniquement l'investissement. Le prix du carbone permet de réduire les émissions plus rapidement (droite), mais il mène à une chute de consommation pour les générations (et l'électorat) présent (gauche). La régulation des investissements évite ce travers, au prix d'un cout plus élevé pour les générations futures.

perdant à la mise en place d'une taxe carbone, et de le dédommager à hauteur de ses pertes. Les résultats de ce chapitre contribuent peut-être à expliquer pourquoi les instruments qui, comme les normes d'efficacité énergétique, redirigent l'investissement sans imposer de prix du carbone explicite, semblent avoir la préférence des décideurs publics.

1

Optimal timing, cost and sectoral distribution of abatement investment

Many governments aim to stabilize climate change to mitigate subsequent damages (e.g., G7, 2015; UNFCCC, 2011). This will require transitioning from an economy based on polluting capital, such as inefficient buildings and polluting cars, to clean capital, such as retrofitted buildings or electric vehicles. A critical question for public policy is to determine the optimal cost and timing of such *abatement investment*. Is action as urgent as frequently advocated? In addition, there are many options to reduce greenhouse gas (GHG) emissions, from renewable power plants to improved building insulation and more efficient cars; a second important issue is the optimal allocation of abatement. Should mitigation start with the least expensive options and progressively clean the economy by ascending cost order?

To shed light on these questions, we study the optimal timing, cost, and sectoral allocation of abatement investment. We capture the transition to clean capital using a simple abatement investment model with three basic features. First, emissions reduction requires investments that have long-lasting effects on emissions. For instance, once a coal power plant is retrofitted with carbon capture and storage, emissions from that power plant are lowered for years to decades. Second, we assume convex investment costs. This convexity, sometimes referred to as *adjustment costs* in the theory of investment (Lucas, 1967; Gould, 1968), captures increasing opportunity costs to use scarce resources (skilled workers and appropriate capital) to perform abatement investment. For instance, retrofitting all buildings in a country in three months would be much more expensive than doing it over three decades. Third, we take into account limited abatement potential in each sector of the economy. Once all the buildings are retrofitted, no more GHG can be saved in the building sector; and once every coal power plant is replaced with renewable power or retrofitted with carbon capture and storage, the abatement potential of the power sector is depleted.

Our analysis brings three main findings. First, while the optimal carbon price increases over time (a familiar result), the optimal abatement investment profile is bell-shaped or even strictly decreasing; in particular, a growing carbon price is compatible with ambitious short term investment. Second, optimal marginal abatement investment costs, expressed in dollars invested per discounted abated ton of carbon (a metric called the *levelized cost of conserved carbon*, or sometimes simply the marginal abatement cost), can be higher than the carbon price. Third, optimal marginal abatement investment costs, still in dollars invested per discounted abated ton, should be higher in sectors where abatement capital is more expensive and sectors with higher abatement potential. By and large, optimal climate change mitigation can start with ambition action focused on the options with higher abatement potential or higher abatement cost, even if the optimal carbon price starts low and grows progressively over time.

The reason is that abatement investment has two effects. First, it reduces emissions, and the optimal valuation of abatement investment involves comparing future abatement (discounted at the usual discount rate) and the price of carbon (which increases at the same discount rate). And second, abatement investment increases the future stock of abatement capital. Therefore, the value of abatement investment today also depends on the value of abatement capital tomorrow. When the value of abatement capital grows over time, both optimal marginal abatement investment costs and optimal abatement investment are higher than suggested when looking only at the current carbon price. This second effect is stronger in sectors with higher abatement needs, that is in sectors where abatement capital is more expensive and sectors with higher abatement potential. On the other hand, when the value of abatement capital decreases over time, abatement investment is worth less than the value of avoided emissions. This happens at the end the transition, when the abatement potential will soon be depleted.

These results suggest that under a well-functioning forward-looking market, a perfectly credible carbon price would trigger more investment in the sectors of the economy with higher abatement potential, and, maybe more surprisingly, where abatement is the most expensive. In practice, while carbon prices are gaining momentum, no existing carbon price is scheduled to grow automatically over time (World Bank, 2014).[1] In addition, many existing climate policies, such as feed-in-tariffs, renewable portfolio mandates, feebates, and performance standards, are implemented at the sector scale (IEA, 2015). In this setting, our results suggest that second-best sector-specific policies depend on both the abatement potential and the cost of abatement investment in each sector, in addition to the social cost of carbon. If the future value of abatement capital is disregarded, second-best sector-scale policies may thus appear to impose too much costs in the short term, and would appear to set a higher shadow cost of carbon in sectors where abatement is more expensive.

This paper relates to several branches of the literature. First, and motivating to this paper, our findings contrast with those from the literature on the optimal timing of GHG emission reductions. Since the seminal contributions by Nordhaus (1991, 1992), which have established the DICE model as a reference framework for studying this question (Dietz et Stern, 2014), studies have found that abatement effort should start low and grow over time. The reason is that in DICE, abatement can be chosen at each point in time on an *abatement cost curve*, independently of previous abatement (see Nordhaus et Sztorc, 2013 and G). In a model based on abatement cost curves, the optimal carbon price, the quantity of abatement and the abatement cost increase together over time. In particular, contemporaneous mitigation action, relevant for today's decision makers, is desirable only if today's carbon price

[1]For instance, the British Columbia carbon tax was phased-in, increasing from 10 to 30 C $/t$CO_2$ between 2008 and 2012, but is currently not scheduled to increase any more (Ministry of Finance, 2015). Also, the European carbon market sets a cap over a few *years* (the current phase runs until 2020), but optimal abatement investment in long-lived capital such as power plants would require allowances to be credibly announced several *decades* in advance.

is high enough. Advocates of early voluntarism in climate mitigation, such as Stern (2006), have thus proposed modifications in DICE that would result in higher carbon prices, hence higher abatement in the short term (Dietz et Stern, 2014; Espagne et al., 2012).

Many papers expand the DICE framework to investigate the impact of particular aspects of the climate-economy system on the optimal timing of climate mitigation. Examples include Kolstad (1996) and Keller et al. (2004) on learning that reduces climate uncertainty over time; Bruin et al. (2009) and Bosello et al. (2010) on how considering adaptation to climate change impacts may affect optimal mitigation; Hwang et al. (2013) and Lemoine et Traeger (2014) on the impact of fat-tailed risks and the role of tipping points; and Heal et Millner (2014) on the choice of the appropriate discount rate for climate policy. Dietz et Stern (2014) propose many modifications to DICE, including to use a lower discount rate, and higher estimates for climate-change-related damages. In all these papers, the question of the optimal timing of emission reduction and the optimal timing of mitigation expenses boil down to the question of the optimal carbon price.[2]

Compared to a model based on abatement cost curves, abatement investment allows disentangling the optimal carbon price, the optimal cost of emission reductions, and the optimal timing of emission reductions. We illustrate this difference with a numerical comparison of an abatement-cost-curve model and an abatement-investment model. We calibrate both models with the same sectoral costs and potentials from IPCC data, and an economy-wide carbon budget compatible with the 2°C target. While the two models virtually agree on the optimal carbon price, they lead to radically different emission reductions and abatement effort in the short term. The abatement-cost-curve model recommends spending 100 billion dollars on mitigation the first year and, somewhat unrealistically, to reduce as much as 12 $GtCO_2$ that same year (about forty percent of global emissions). In contrast, the abatement-investment model recommends spending three times more, that is 300 billion dollars, while reducing less than 1 $GtCO_2$ the first year. Only the abatement-investment framework captures the fact that emission reductions cannot happen overnight, but still require substantial short-term investment. The abatement investment framework can thus reconcile the idea that climate change, caused by a stock pollution,

[2]Similarly, a literature on the optimal distribution of effort across sectors focuses on pinning down sector-specific market or government failures that would justify different carbon prices in different sectors (e.g., Hoel, 1996; Rosendahl, 2004a).

imposes a growing shadow price of carbon; and the need for immediate and significant abatement investment stressed by the international community (NCE, 2014; IPCC, 2014b).

Moreover, in the abatement-cost-curve framework, optimal mitigation expenses grow over time until all emissions are abated (and remain constant after that). In contrast, in the abatement-investment framework, climate stabilization requires to fund a temporal transition to clean capital. Optimal abatement investment is bell-shaped or decreasing over time, and, in the long term, investment is only required to maintain abatement capital at its maximum potential.

Finally, the sectoral allocation of abatement effort is also different in the abatement-cost-curve framework and in the abatement-investment framework. With abatement cost curves, the carbon price provides direct guidance on where and when to spend on emission reductions; in each sector, the best option is always to start with the cheapest option. This is because abatement-cost-curve models implicitly assume that emissions can be adjusted instantaneously to the carbon price. With abatement investment, optimal decisions depend on what happens in the future, and the same carbon price translates to different levelized cost of conserved carbon in different sectors. For instance, we find that an abatement option at 25 $/tCO_2$ in the industrial sector may be preferable to a 15 $/tCO_2$ option in the building sector, because the industrial sector is both more expensive to decarbonize and has a greater abatement potential.[3]

Second, our paper also relates to the literature that studies optimal emission reductions when knowledge accumulation can reduce abatement costs. It is well established that the double market failure of GHG emissions and learning spillovers in the development of new technologies means that the optimal climate mitigation strategy starts with some investment in research and development (e.g., Wigley et al., 1996; Kverndokk et Rosendahl, 2007; Acemoglu et al., 2012). In particular, the effect of learning by doing has been studied in models based on abatement cost curves, including by extending DICE (Goulder et Mathai, 2000; Popp, 2004). On the distribution of effort across options, Rosendahl (2004a), Bramoullé et Olson (2005), and del Rio Gonzalez (2008) find that more short-term effort should go to options that will

[3] As explained below, these numbers should not be directly interpreted as policy recommendations, because simulations adopt a short time horizon and are based on limited data.

experience more learning-by-doing. But they investigate options competing within a single sector (such as photovoltaic versus wind power). Here, we investigate abatement investment across different sectors of the economy (such as buildings versus transportation), and we focus on capital instead of knowledge accumulation. Our analysis provides a somewhat different rationale for early mitigation action, and of a different nature: early investment in physical capital that will take time to deploy, especially in sectors with large baseline emissions or large abatement costs.[4]

Last but not least, our contribution is also not the first to consider abatement capital. In their seminal papers, Jacoby et Wing (1999) and van der Zwaan et al. (2002) propose numerical models that emphasize capital turnover and adjustment costs. Both focus on implications for the optimal carbon price profile, showing that the higher adjustment costs are, the highest the carbon price needs to be to reach the same environmental target. Fischer et al. (2004) investigate the trade-offs between energy production from clean capacity and dirty energy, and damages from pollution in a single-sector analytical model; and they also focus on optimal pathways for the carbon price. Williams (2010), Slechten (2013) and Rozenberg et al. (2014) model abatement capital accumulation, also in a single-sector economy, but they focus on policy design or political economy concerns. Finally, Lecocq et al. (1998), Jaccard et Rivers (2007) and Vogt-Schilb et al. (2014a) have also found that large short-term effort is needed in sectors with high abatement potential and large inertia, but they entirely rely on numerical resolution.

[4]Capital and knowledge accumulation, if similar, differ slightly in theory and greatly in practice. For instance, knowledge accumulation can continue to reduce costs once emissions are entirely abated, but it does not make sense to accumulate more abatement capital than what suffice to reduce emissions down to zero. Spillovers is a prominent feature of most knowledge accumulation related to climate mitigation, while private ownership is a feature of most power plants, vehicles and buildings, clean or dirty. In addition, a key component of capital is its turnover rate, which is not necessarily linked to the obsolescence of the knowledge used to built it (as illustrated by old bridges and buildings in use in Europe). In practice, a given sector, such as maybe public transportation, can be subject to negligible learning dynamics, while still requiring early action for the reasons exposed in this paper. Finally, the operational policy operations also differ: putting researchers to work on better turbines, as recommended by Acemoglu et al. (2012), and building and deploying wind turbines, as suggested by this paper, are not the same thing. As discussed in the conclusion, it remains an avenue for further research to account for the two phenomena in a single model.

To the best of our knowledge, this paper is the first to disentangle the optimal carbon price, the optimal timing of emission reduction, and the optimal abatement investment pathways in a multi-sector analytical model. Other contributions have focused on the optimal carbon price, generally found to grow over time, and optimal abatement capital stocks, also found to grow smoothly over time. Our focus is on the explicit modeling and discussion of the optimal allocation and measurement of abatement *investment* across sectors and over time. A novel finding is that a growing carbon price translates into optimal abatement investment concentrated in the short term, and focused on the sectors where abatement capital is most expensive or the abatement potential is larger. Another is that the levelized cost of conserved carbon should not be equal to the carbon price. Both are relevant for public policy.

The paper proceeds as follows. Section 1 presents the basic abatement investment model. Section 2 derives analytical results concerning the optimal timing of abatement investment. Section 3 examines the optimal cost of emission reductions. Section 4 investigates the optimal allocation of abatement investment. Section 5 compares abatement investment and abatement cost curves with numerical illustrations calibrated with IPCC data. Section 6 concludes.

1 Model

A social planner needs to constrain cumulative GHG emissions below a given ceiling, or carbon budget B. The carbon budget B can be interpreted as the allowable emissions to stabilize global warming to a given temperature target (Matthews et Caldeira, 2008; Meinshausen et al., 2009a), or as a tipping point beyond which the environment is catastrophically damaged. This keeps the model as simple as possible, and allows us to focus on the dynamics of emission reductions *costs*, keeping the dynamics of climate change and climate damages out — that is abstracting from the *benefits* of emission reductions.[5]

[5]The ideal approach to determine the price of carbon is to perform a cost-benefit analysis. Due to the various scientific uncertainties surrounding climate change and resulting damages, assessing the benefits from climate mitigation is not straightforward (Manne et Richels, 1992; Ambrosi et al., 2003; Stern, 2013; Pindyck, 2013), and it is common to use targets expressed in global warming (such as the 2°C target from the United Nations Framework Convention on Climate Change), or, similarly, cumulative emissions (Allen et al., 2009; Matthews et al., 2009b; Zickfeld et al., 2009). B shows that the results exposed in this paper hold under cost-benefit analysis.

We denote m_t the cumulative atmospheric emissions at date t. The emission dynamics and carbon budget read (dotted variables represent temporal derivatives):

$$\begin{aligned} & m_0 \text{ given} \\ & \dot{m}_t = e_{ref} - a_t \\ & m_t \leq B \end{aligned} \tag{1.1}$$

Where e_{ref} represents baseline emissions (assumed constant for simplicity), and a_t represents abatement at time t.

To reduce emissions, the social planner must invest in abatement capital, which has a long-lived effect on emissions. Borrowing the wording by Davis et Socolow (2014), investment in electric vehicles or building retrofitting is a hard *commitment* to emit less GHG during a few years to decades. For simplicity, abatement capital is directly measured in terms of avoided emissions, and baseline emissions are assumed constant. We also assume the stock of abatement capital starts at zero (without loss of generality). None of these three simplifying assumptions are essential to derive our results, but they considerably ease exposition, allowing us to focus on relevant insights instead of technical details.

At each time step t, the social planner chooses a positive amount of physical investment x_t in abatement capital a_t, which otherwise depreciates at rate δ:

$$a_{t_0} = 0 \tag{1.2}$$

$$\dot{a}_t = x_t - \delta a_t \tag{1.3}$$

Abatement investment costs $c(x_t)$, where the function c is positive, increasing, differentiable and convex:

$$\begin{aligned} \forall x_t, \quad c''(x_t) &\geq 0 \\ c'(x_t) &\geq 0 \\ c(x_t) &\geq 0 \end{aligned} \tag{1.4}$$

$c'(x_t)$ is referred to as the *marginal abatement investment cost*. The convexity of the abatement investment cost c, sometimes referred to as *adjustment costs*(Lucas, 1967; Gould, 1968), captures increasing opportunity costs to use scarce resources (skilled workers and appropriate capital) to build and deploy abatement capital. As noted by Mussa

(1977), $c'(x_t)$ can simply be seen as the marginal cost curve for the industry that supplies abatement investment — e.g., clean vehicle manufacturers or insulation contractors.

For instance, x_t is the pace — measured in buildings per year — at which old buildings are being retrofitted at date t (the abatement a_t would then be proportional to the share of retrofitted buildings in the stock). Retrofitting buildings at a given pace requires to pay a given number of scarce skilled workers. If workers are hired in the merit order and paid at the marginal productivity, the marginal price of retrofitting buildings $c'(x_t)$ is an increasing function of the pace x_t. The cost $c(x_t)$ may also be interpreted as the net present cost of building and operating low-carbon capital (e.g., an electric vehicle) instead of, or in replacement for, polluting capital.

The social planner chooses when to perform abatement investment in order to meet a carbon budget at the lowest inter-temporal cost, under the constraint set by the maximum abatement potential e_{ref}:

$$\min_{x_t} \int_0^\infty e^{-rt} c(x_t)\, dt \tag{1.5}$$

$$\begin{aligned}
\text{subject to} \quad & m_t \leq B && (\phi_t) \\
& \dot{m}_t = e_{ref} - a_t && (\mu_t) \\
& \dot{a}_t = x_t - \delta a_t && (\nu_t) \\
& a_t \leq e_{ref} && (\lambda_t)
\end{aligned}$$

Importantly, the social planner does not control directly abatement a_t, but abatement investment x_t, linked to the temporal derivative of a_t. For instance, he controls and pays for a number of buildings to retrofit each year, which indirectly translates to a total share of retrofitted buildings in the stock, which in turn translates to reduced GHG emissions. The Greek letters in parentheses are the co-state variables and Lagrangian multipliers (chosen in current value and such that they are positive): ν_t is the shadow value of abatement capital, μ_t is the shadow cost of carbon emissions, and λ_t is the shadow cost of the maximum abatement potential e_{ref}, that quantifies the scarcity of investment opportunities.

2 Optimal timing of abatement investment

We start the resolution of problem 1.5 from the steady state. The cumulative emission ceiling B is reached at an endogenous date T. After T, emissions net of abatement are null, meaning that the abatement potential e_{ref} is reached, and abatement investment only compensates for depreciation (A):

$$\begin{aligned} \forall t \geq T, \quad & m_t = B \\ \implies & a_t = e_{ref} \\ \implies & x_t = \delta e_{ref} \end{aligned} \tag{1.6}$$

Before T, the optimal shadow price of carbon μ_t increases at the discount rate r (A demonstrates this familiar result):

$$\forall t < T, \quad \mu_t = \mu e^{rt} \tag{1.7}$$

The exponentially-increasing carbon price ensures that the present value of the carbon price is constant along the optimal path until full decarbonization, such that the social planner is indifferent between one unit of abatement at any two dates. (In the following, we frequently omit the term "shadow" when referring to co-state variables and Lagrangian multipliers. We also freely switch between the social planner's perspective and the equivalent point of view of private agents facing the optimal carbon price.) The initial carbon price, μ, is chosen at the lowest value such that the carbon budget is met.

Before T, emissions are strictly positive, abatement capital is lower than its potential $a_t < e_{ref}$, and optimal investment dynamics are described by the first order condition (A) :

$$\forall t < T, \quad (r + \delta)\, c'(x_t) - \frac{dc'(x_t)}{dt} = \mu e^{rt} \tag{1.8}$$

We call the left hand side of (1.8) the *marginal implicit rental cost of capital*, adapting to the case of endogenous capacity prices the concept of implicit rental cost of capital first proposed by Jorgenson (1967). It is the rental price that ensures agents would be indifferent between buying abatement capital at $c'(x_t)$ or renting it at the rental price.[6] Equation

[6]The expression of the rental price translates that there is no profitable tradeoff between the two following strategies: (i) buy capital at t at a cost ${c_i}'(x_{i,t})$, rent it out during one period dt at the rental price, then sell the depreciated (δ) capacities

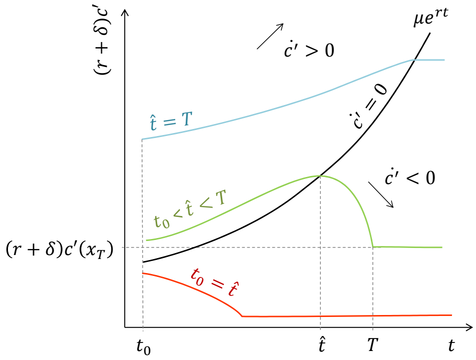


Figure 1.1: The carbon price and the two possible optimal abatement investment pathways. While the carbon price grows exponentially over time, the optimal abatement investment cost $(r+\delta)c'(x_t)$, and thus optimal investment x_t, may either draw a bell shape or decrease over time.

(1.8) thus simply means that if there was a well-functioning market for abatement capital, the rental cost of abatement capital would be equal to the carbon price.

For instance, consider a taxi company that meets a fixed demand for travel, rents the vehicles it uses, and pays a carbon tax on the carbon it emits. Consider the taxi company faces two similar vehicles available for rent, differing only in their carbon emissions and rental price. Equation 1.8 suggests the company will chose the cleaner vehicle for a given year if and only if the difference in rental costs (in dollars per vehicle per year) is lower or equal to avoided emissions (in tons of carbon per year per vehicle) valued at the carbon price that year (in dollars per ton).

The exponentially-increasing carbon price then influences indirectly abatement investment. In particular it does not translate into increasing abatement investment:

Proposition 1. *Along the optimal trajectory, investment is either bell-shaped or decreasing over time, and so is the optimal marginal investment cost.*

Proof. See A for a formal proof. As a sketch, equation 1.8 may be

at $t + dt$ at a price $c_i'(x_{i,t}) + \frac{d}{dt}c_i'(x_{i,t})dt$ or (ii) simply lend money at the interest rate r (Jorgenson, 1967). D proposes an alternative explanation of the marginal implicit rental cost of abatement capital.

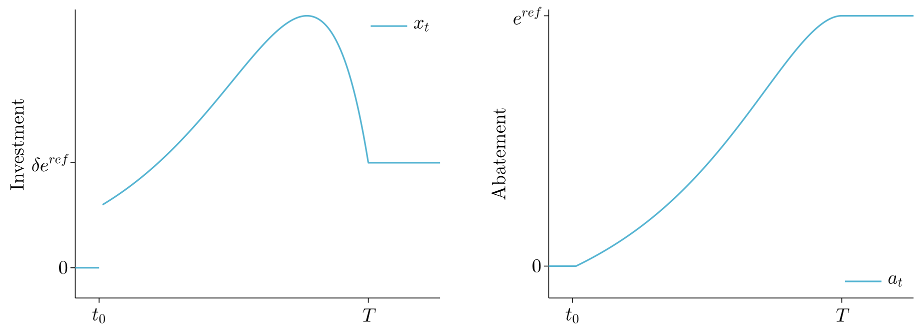


Figure 1.2: Optimal timing of abatement investment and resulting abatement pathway. Left: Abatement investment is bell-shaped. Right: Abatement continuously grows over time.

re-arranged as:

$$\forall t < T, \quad \frac{dc'(x_t)}{dt} = (r + \delta)\, c'(x_t) - \mu e^{rt} \tag{1.9}$$

Fig. 1.1 plots the carbon price μe^{rt} and two possible cases of $(r + \delta)\, c'$ against time t. In the upper region, $(r + \delta)\, c' > \mu e^{rt}$, implying that $dc'(x_t)/dt > 0$. In the lower region, $(r + \delta)\, c' < \mu e^{rt}$, implying that $dc'(x_t)/dt < 0$.

The strictly decreasing profile happens for stringent climate targets, that is for high carbon prices compared to abatement investment costs $\mu \gg (r+\delta)\, c'\,(\delta e_{ref})$ (see Fig. 1.1). The bell shaped profile happens for low carbon prices or high investment costs $\mu \ll (r + \delta)\, c'\,(\delta e_{ref})$.[7] $\square$

$\square$

Prop. 1 means that the combination of two simple assumptions — adjustment costs and finite abatement potential — in a model with a single externality — climate change in the absence of learning spillovers — is sufficient to reconcile the views that the optimal policy is a growing carbon price and that early investment is needed to stabilize climate change.[8] Fig. 1.2 illustrates how such bell-shaped abatement invest-

[7]The threshold value corresponds to the case where $\mu = (r + \delta)c'(x_0)$. Such condition is not easily linked analytically to the parameters of the model because x_0 is endogenous.

[8]Simple calculations show that each feature separately does not provide similar results; only the combination of both adjustment costs and a maximum abatement potential leads to a transition with bell-shaped investment. If one assumes

ment translates into an increasing abatement pathway — A formally demonstrates that a_t increases steadily to e_{ref}.

There is some empirical evidence that optimal investment in long-lived capital can actually be bell-shaped. For instance, Lecocq et Shalizi (2014) report bell-shaped investment pathways in the case of the transition to nuclear power in France and the building of the national interstate highways in the United States.

3 Optimal cost of abatement investment

3.1 Optimal marginal abatement investment costs

When emission reduction requires abatement investment and is limited with a maximum abatement potential, the carbon price is only one of two parts of the information required to value abatement investment:

Proposition 2. *Before full decarbonization, the optimal marginal cost of abatement investment $c'(x_t)$ equals the sum of two terms: (1) the value of avoided emissions before the maximum abatement potential is reached; and (2) the cost of maintaining the investment over the long-term, after emissions have reached zero.*

Proof. The solution of the differential equation (1.8) is (A):

$$\forall t < T, \quad c'(x_t) = \int_t^T \mu e^{r\theta} e^{-(\delta+r)(\theta-t)}\, d\theta + e^{-(\delta+r)(T-t)}\, c'\left(\delta e_{ref}\right) \tag{1.10}$$

In equation 1.10, output from the marginal unit of abatement capital $e^{-(\delta+r)(\theta-t)}$ is valued at the carbon price $\mu e^{r\theta}$ before T, and the $c'\left(\delta e_{ref}\right)$ is the value of the abatement capital built at t that remains at T. □

□

that investment costs are not strictly convex, that is $\forall x,\ c'(x) = C$, then the optimal schedule is to cap all emissions in a *bang bang* fashion at the date t when $\mu e^{rt} = (r+\delta)C$. A model without abatement potential makes no sense. Without a maximum abatement potential, an exponential carbon price would result in exponentially growing investment, the total stock of abatement capital would also grow exponentially towards infinity, and emissions will thus decrease towards negative infinity.

: the exponential carbon price would yield exponentially-increasing investment, exponentially-increasing abatement, and

Proposition 2 means that optimal investment in abatement capacity cannot be decided based only on the current carbon price, investors have to anticipate a full decarbonization strategy. Take the example of a firm that builds cleaner personal vehicles with the intend of renting them to a taxi company facing a carbon price. When deciding how many vehicles to build at a given date, and at what cost, the manufacturer cannot rely only on the current carbon price — in particular, the optimal cost of a clean vehicle is not equal to the value of future avoided emissions. The car manufacturer has to anticipate its full investment pathway, including the date T when all taxi vehicles will have been replaced by cleaner vehicles, and the cost of replacing these cleaner vehicles after T.

The marginal abatement investment cost $c'(x_t)$ represents the optimal cost of physical capital used to reduce emissions. For instance, it could be expressed in dollars per building retrofitted, or dollars per vehicle replaced with an electric vehicle. When seeing this equipment as abatement capital, one unit of capital, e.g. an electric vehicle, translates into a flux of emission reductions, e.g. $1\,\mathrm{tCO_2/yr}$. As a result, $c'(x_t)$ is to be expressed in dollars per ton of avoided carbon per year ($\$/(\mathrm{tCO_2/yr})$). Because the marginal investment cost $c'(x_t)$ leaves the lifetime of abatement capital implicit, it does not inform directly on the amount of GHG saved thanks to a marginal investment $x_t dt$. An alternative metric to measure abatement investment is the levelized cost of avoided carbon emissions, which compares investment costs to discounted committed emission reductions, as discussed in the following subsection.

3.2 An operational metric? The levelized cost of conserved carbon

A natural metric to measure and compare the cost of abatement investments in different options (e.g electric vehicles versus retrofitting buildings) is the ratio of the cost of using a given option (e.g in dollars) to the discounted sum of GHG emissions avoided thanks to that option (e.g in $\mathrm{tCO_2}$). This ratio is widely used to compare abatement options, for instance to build marginal abatement cost curves, and is then simply called "marginal abatement cost" (McKinsey, 2009; Vogt-Schilb et Hallegatte, 2014). The IPCC (2014a) calls this ratio the *Levelized Cost of Conserved Carbon* (LCCC).

Definition 1. *We call* Levelized Cost of Conserved Carbon (LCCC) *the* *ratio of marginal investment to the corresponding discounted abatement.*

The LCCC ℓ_t expresses in dollars per ton. It reads $\ell_t = (r+\delta)\, c'(x_t)$ (C).

Practitioners often use the LCCC when comparing and assessing abatement investments (IPCC, 2014a), for instance replacing conventional cars with electric vehicles (EV). Assume the additional cost of an EV built at time t, compared to the cost of a conventional car, is $7\,000\,\$/\mathrm{EV}$. If cars are driven $13\,000\,\mathrm{km}$ per year and electric cars emit $110\ \mathrm{gCO_2/km}$ less than a comparable internal combustion engine vehicle, each EV allows to save $1.43\,\mathrm{tCO_2/yr}$. The abatement investment cost in this case would be $4\,900\,\$/(\mathrm{tCO_2/yr})$. If electric cars depreciate at a constant rate such that their average lifetime is 10 years ($1/\delta = 10$ yr) and the discount rate is 5%/yr , then $r+\delta = 15\%/\mathrm{yr}$ and the LCCC is $730\,\$/\mathrm{tCO_2}$.[9]

LCCCs are homogeneous to a carbon price, and, unlike the marginal rental cost of abatement capital, they fully characterize an investment pathway.[10] They are a straightforward measure of abatement investment, as they relate how much the social planner invests in the marginal unit of abatement capital to the emission reduction resulting from this marginal investment. It may thus be counter-intuitive that LCCCs should not be equal to the carbon price. As stated before, the reason is that the value of abatement investment comes from both reduced emissions and the value of abatement capital in the future — D shows how an investment strategy aiming at reducing emissions without changing the future stock of abatement capital would simply equalize the marginal implicit rental cost of capital to the carbon price, as in (1.8).

Indeed, another way of reading (1.8) is:

$$\ell_t = (r+\delta)\, c'(x_t) = \mu e^{rt} + \frac{dc'(x_t)}{dt} \tag{1.11}$$

Equation (1.11) shows that the optimal value of abatement capital, ex-

[9]The investment cost was computed as $7\,000\,\$/(1.43\,\mathrm{tCO_2/yr}) = 4\,895\,\$/(\mathrm{tCO_2/yr})$; and the levelized cost as $0.15\,\mathrm{yr}^{-1} \cdot 4\,895\,\$/(\mathrm{tCO_2/yr}) = 734\,\$/\mathrm{tCO_2}$.

[10]Investment x_t can be calculated from the LCCC ℓ_t as $x_t = c'^{-1}\left(\frac{\ell_t}{r+\delta}\right)$. This contrasts with the rental cost of abatement capital, which defines a differential equation that has to be completed with a boundary condition to define a single investment pathway (1.29).

pressed using the levelized cost of capital ℓ_t, equals the carbon price μe^{rt} plus the current variation of the value of abatement capital $\frac{dc'(x_t)}{dt}$. When the value of abatement capital is increasing over time $\left(\frac{dc'(x_t)}{dt} > 0\right)$, the optimal LCCC is higher than the carbon price. This happens, if ever, at the beginning of the transition (Fig. 1.1). When the value of abatement capital decreases over time, the optimal LCCC is lower than the carbon price. This happen in the second phase of transition, when the abatement potential is close to be depleted (Fig. 1.1). In the following we analyze how in a multi-sector economy, the temporal evlution of the value of abatement capital differs across sectors, and thus the optimal LCCC differs across sectors.

4 Optimal sectoral allocation of abatement investment

In this section, we extend the model of abatement capital accumulation to investigate optimal allocation of abatement investment across sectors. The economy is partitioned in a set of sectors indexed by i. For simplicity, we assume that abatement in each sector does not interact with the others.[11] Each sector is described by an abatement potential $\bar{a}_i$ (such that $\sum_i \bar{a}_i = e_{ref}$), a depreciation rate δ_i, and a cost function c_i. The social planner's program becomes:

$$\min_{x_{i,t}} \int_0^\infty e^{-rt} \sum_i \left(c_i(x_{i,t})\right) dt \tag{1.12}$$

$$\begin{aligned}
\text{subject to}\quad & \dot{a}_{i,t} = x_{i,t} - \delta_i\, a_{i,t} && (\nu_{i,t}) \\
& a_{i,t} \leq \bar{a}_i && (\lambda_{i,t}) \\
& \dot{m}_t = \sum_i \left(\bar{a}_i - a_{i,t}\right) && (\mu_t) \\
& m_t \leq B && (\phi_t)
\end{aligned}$$

The value of abatement capital $\nu_{i,t}$ and the cost of the sectoral potentials $\lambda_{i,t}$ now depend on the sector i, while there is still a single carbon price μ_t for the whole economy.

[11]This is not entirely realistic, for instance abatement realized in the power sector may actually increase the potential and reduce the cost to implement abatement in other sectors thanks to electrification (Williams et al., 2012; Audoly et al., 2014).

Similarly to the case with a single sector, the implicit rental cost in each sector is equal to the single current carbon price (see E).

$$\forall i,\ \forall t < T_i, \quad (r + \delta_i)\, c_i{}'(x_{i,t}) - \frac{dc_i{}'(x_{i,t})}{dt} = \mu e^{rt} \tag{1.13}$$

But the single implicit rental cost translates into different investment costs across sectors:

Proposition 3. *Each sector i reaches its abatement potential at a different date T_i, and the optimal marginal investment cost is different in each sector:*

$$\forall i,\ \forall t < T_i,$$
$$c_i{}'(x_{i,t}) = \int_t^{T_i} \mu e^{r\theta} e^{-(\delta_i + r)(\theta - t)}\, d\theta + +e^{-(\delta + r)(T_i - t)}\, c_i'\left(\delta_i \bar{a}_i\right) \tag{1.14}$$

Proof. Equation 1.14 is the generalization of equation 1.10 to the case of several sectors (E). □ □

In Fig. 1.1, the two pathways may now be seen as corresponding to two different sectors facing the same carbon price. In the following, we derive some conditions under which a sector should receive more investment than others.

Corollary 1. *Along the optimal path, investment costs are higher (i) in sectors with larger abatement potential:*

$$\left(\delta_i = \delta_j, \bar{a}_i > \bar{a}_j \ \textit{and}\ \forall y,\ c_i'(y) = c_j'(y)\right) \implies \forall t,\ c_i{}'(x_{i,t}) > c_j{}'(x_{j,t})$$

and (ii) in sectors where abatement capital is more expensive:

$$\left(\delta_i = \delta_j,\ \bar{a}_i = \bar{a}_j \ \textit{and}\ \forall y,\ c_i'(y) > c_j'(y)\right) \implies \forall t,\ c_i{}'(x_{i,t}) > c_j{}'(x_{j,t})$$

Proof. E.a □

The intuition behind Coroll. 1 is the following. The value of abatement investment comes from avoided emissions and from the future value of abatment capital. The future value of abatement capital is greater in sectors where future investment needs are greater. These are the sectors with larger abatement potential (as more abatement investment is then required to exploit this potential); and — maybe more surprisingly — sectors where abatement capital is more expensive, as these sectors also need to invest more money to fully exploit their abatement potential.

Interestingly, the ranking established by Coroll. 1 holds when measuring marginal investment costs with the levelized cost of conserved carbon:

Corollary 2. *Everything else being equal, optimal levelized costs of conserved carbon (LCCC) is higher in sectors with larger abatement potential $\bar{a}_i$ or greater marginal abatement investment costs c_i'.*

Proof. This corollary is a direct consequence of Coroll. 1. □ □

This corollary provides counter-intuitive policy guidance, as it suggests that more investments should be done in the sectors with higher abatement investment costs. The rationale should however be clear: in a sector with higher abatement potential or more expensive abatement capital, the value of abatement capital is higher in the long run, and thus, it is more profitable to build abatement capital in the short term.

This result is relevant when designing an abatement strategy. For instance, when abatement options are presented in a marginal abatement cost curves *à la* McKinsey (2009), it may be desirable to implement some of the "expensive" measures on the right-hand side of the curve, even if their LCCC is higher than the carbon price, and higher than the LCCC of alternative abatement options. Coroll. 2 does not mean that different sectors should face different carbon prices; F shows that, in the absence of any other market failure, a single carbon price can decentralize the social optimum. If a government is able to impose the optimal carbon price pathway in a perfectly credible fashion to a well-functioning forward-looking economy, the market will thus perform the socially-optimal amount of abatement investment. If governments are using non-optimal policy instruments (such as sector-scale performance standards), however, or cannot commit to perfectly credible carbon price signals, Coroll. 2 suggests that second-best policy instrument need to be designed accounting for different total abatement potentials and different costs of abatement investment in different sectors (not just the social cost of carbon).

5 Abatement investment vs. abatement cost curves

In this section, we compare the model of abatement investment to a model based on abatement cost curves. As stated in the introduction, models of abatement cost curves are popular in the literature on the optimal timing of mitigation. G provides a very simple model based on abatement cost curves and its analytical resolution. It shows that under abatement cost curves, the optimal strategy of equalizing marginal abatement costs across sectors to the unique, exponentially-increasing carbon price simply leads to increasing abatement similarly in all sectors.

We investigate with both models the optimal cost and timing of emission reduction, at sector scale, over the 2007-2030 period. We set a policy objective over this period only,[12] and use abatement cost information derived from IPCC (2007, Fig. SPM 6). Because of data limitations and of the short time horizon,[13] this exercise is not supposed to suggest an optimal climate policy. It aims at illustrating the impact of two contrasting approaches to model emission reductions on the optimal abatement strategy: abatement cost curves or abatement investment.

5.1 Specification and calibration

We calibrate the model of abatement cost curve presented in G with seven sectors of the economy: energy, industry, buildings, transport, forestry, agriculture and waste. We assume quadratic abatement costs, which grants that the abatement cost curves γ_i are convex, and simplifies the resolution as marginal abatement costs are linear:

$$\begin{aligned} \forall i,\ \forall a_{i,t} \in [0, \bar{a}_i] \quad \gamma_i(a_{i,t}) &= \frac{1}{2}\,\gamma_i^m\, a_{i,t}^2 \\ {\gamma_i}'(a_{i,t}) &= \gamma_i^m\, a \end{aligned} \tag{1.15}$$

where γ_i^m are parameters specific to each sector. We calibrate these using emission reductions corresponding to a 20 \$/tCO$_2$ marginal cost in figure SPM.6 in IPCC (2007). We calibrate the sectoral potentials $\bar{a}_i$ as the potential at 100 \$/tCO$_2$ provided by the IPCC (this is the highest

[12]The infinite-horizon model exposed in sections 2 has to be slightly modified; all the results exposed in the previous sections hold.

[13]The newer IPCC report does not feature an estimation of marginal abatement costs and potentials across sectors.

	Abatement potential $\bar{a}_i$ [$GtCO_2$/yr]	Abatement cost γ_i^m $\left[\frac{\$/tCO_2}{GtCO_2/yr}\right]$	Depreciation rate δ_i [%/yr]	Investment cost c_i^m $\left[\frac{\$/tCO_2}{GtCO_2/yr^3}\right]$
Waste	0.76	34	3.3	2309
Industry	4.08	17.6	4	1195
Forestry	2.75	15.9	0.8	1080
Agriculture	4.39	11.9	5	808
Transport	2.1	11.6	6.7	788
Energy	3.68	10.3	2.5	699
Buildings	5.99	3.6	1.7	244

Table 1.1: Values used in the numerical simulations.

potential provided for each sector). Numerical values are gathered in Tab. 1.1.

To calibrate the abatement investment model, we assume quadratic investment costs:

$$\begin{aligned} \forall i,\ \forall x_{i,t} \geq 0, \quad c_i(x_{i,t}) &= \frac{1}{2}\, c_i^m\, x_{i,t}^2 \\ c_i{}'(x_{i,t}) &= c_i^m\, x_{i,t} \end{aligned} \tag{1.16}$$

To calibrate the c_i^m, we ensure that relative costs, when comparing two sectors, are equal in the two models, in the sense that:

$$\forall (i,j), \quad \frac{c_i^m}{c_j^m} = \frac{\gamma_i^m}{\gamma_j^m} \tag{1.17}$$

This defines all the c_i^m off by a common multiplicative constant. We calibrate this multiplicative constant such that the discounted costs of reaching the same target are equal in the two models (following Grubb et al. 1995). This way, we aim at reducing differences in optimal strategies to the different models of emission reductions (cost curves vs. investment).

We call $\bar{T} = 23$ yr the time span from the publication date of IPCC (2007) and the time horizon of IPCC data (2030). We set the discount rate to $r = 4\%$/yr. We constrain the cumulative emissions over the period as:

$$\int_0^{\bar{T}} \sum_i (\bar{a}_i - a_{i,t}) \leq B$$

To compute the carbon budget B, we chose the Representative Concentration Pathway RCP 8.5 (from WRI, 2015) as the emission baseline. An emission scenario consistent with the 2°C target is the RCP3-PD. Remarkably, the difference in carbon emissions in 2030 between these two RCPs amounts to 24 $GtCO_2$/yr, which matches $\sum_i \bar{a}_i$ as calibrated from IPCC (Tab. 1.1). We use the difference in cumulative emissions from 2007 to 2030 in the two RCPs to calibrate $B = 153\,GtCO_2$.

Finally, we estimate the depreciation rates of capital as the inverse of typical capital lifetimes in the different sectors of the economy (Philibert, 2007; World Bank, 2012, Tab. 6.1). The resulting rates of depreciation δ_i are displayed in Tab. 1.1.

We solve the two models numerically in continuous time.[14]

5.2 Results

Fig. 1.3 compares the optimal mitigation strategy by the two models and Fig. 1.4 compares the aggregated pathways in terms of abatement and financial effort.

The two models give the same result in the long run: abatement in each sector eventually reaches its maximum potential (Fig. 1.3). By construction, they also achieve the aggregated abatement target at the same discounted cost. And the carbon budget implies that the carbon price grows exponentially, regardless of how emission reductions are modeled (Fig. 1.3, upper panels). Moreover, the models find similar carbon prices, at 17 \$/tCO_2 with cost curves and 18.6 \$/tCO_2 with abatement investment, reflecting that they are calibrated on the same data.

However, the similar carbon prices lead to radically different strategies in terms of the temporal and sectoral distribution of aggregated abatement and costs. First, the two frameworks differ in their optimal abatement pathway: in the abatement-cost-curve framework, abatement jumps when the climate policy is implemented (to emphasize this,

[14] All data and source code, including for figures in the analytical sections and appendixes, will be available online.

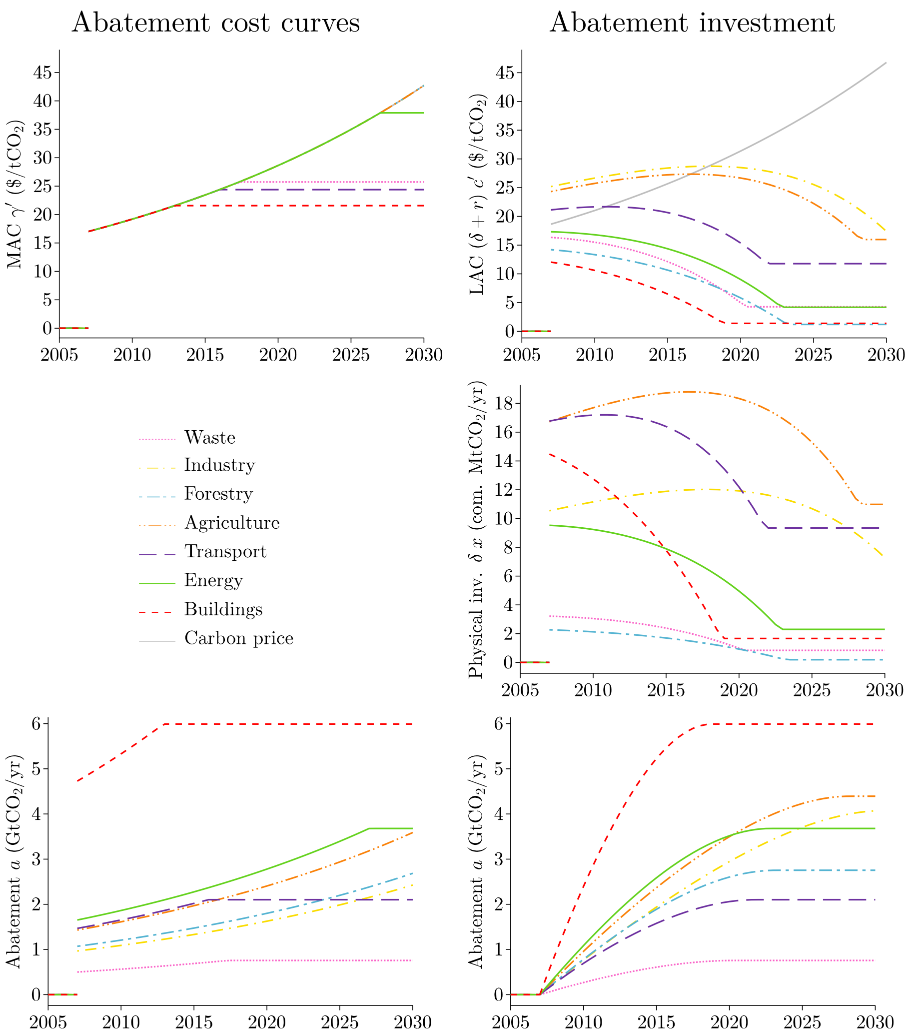


Figure 1.3: Comparison of optimal abatement strategies to achieve the same amount of abatement, when the costs from IPCC (2007, SPM6) are understood in an abatement-cost-curve framework (left) vs. an abatement investment framework (right).

Note: We follow Davis et Socolow (2014) in measuring investment in *committed* abatement, ($\delta_i x_{i,t}$ in $\mathrm{MtCO_2/yr}$) instead of crude investment ($x_{i,t}$ in $\mathrm{MtCO_2/yr^2}$). With committed abatement, 1 000 electric vehicles built in 2010 that will each save 11 tCO$_2$ during their lifetime count as committed abatement of 1,1 ktCO$_2$/yr in 2010. In the abatement-cost-curve framework, there is no equivalent to the physical abatement investments $x_{i,t}$, as the planner controls directly the abatement level $a_{i,t}$.

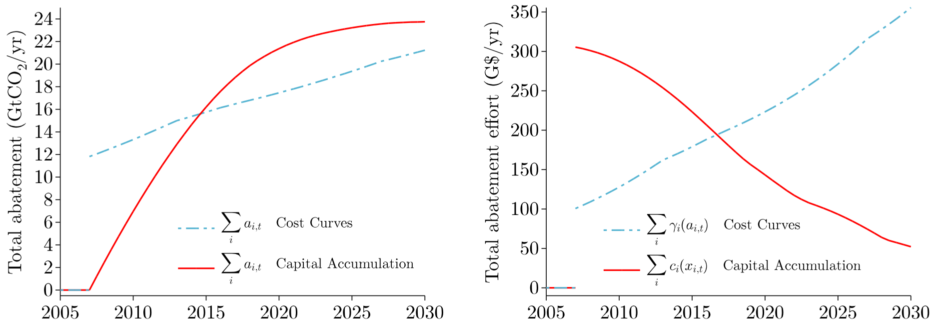


Figure 1.4: Optimal timing and cost of GHG emissions in the two models (abatement cost curves vs abatement capital accumulation). When abatement is assumed to be freely chosen on a cost curve at each time step, the abatement can jump to any amount instantaneously at the beginning of the period. When abatement requires accumulating capital, abatement has to grow continuously. The same carbon price (not shown) translates in radically different short-term expenses in the two models (right panel).

we plotted a null abatement between 2005 and the start of the climate policy in 2007). In contrast, the abatement pathway according to the abatement-investment model starts at zero and increases continuously (Fig. 1.3, lower panels).

Second, the two frameworks give different results in terms of temporal distribution of abatement costs: with abatement cost curves, abatement expenses starts low and increases over time; in the abatement investment framework, abatement investment starts high and then decreases over time (Fig. 1.4, right). In the latter case, abatement investment is concentrated on the short term, because once all the emissions in a sector has been avoided using abatement capital, the only cost is that of maintaining the stock of abatement capital. Importantly, the appropriate level of effort that current decision makers have to implement is substantially different in the two models: 100 billion dollars of abatement expenditures versus 300 billion dollars of abatement investment.[15]

[15]Results from our abatement investment model are compatible with estimates reported by Fay et al. (2015), that is between 300 and 400 billion dollars per year of investment required to meet the 2°C target. Again, we do not claim that ours are optimal pathways to mitigate climate change: in particular, they only consider a target in the 2007-2030 window. Considering the long-term objective would impose a higher abatement investment.

Third, in the abatement-cost-curve framework, the carbon price gives a straightforward indication on where and when effort should be concentrated. In contrast, the increasing carbon price is a poor indicator of the optimal distribution of abatement investment (Fig. 1.3, higher panels). For instance, in the abatement cost curve framework, complete decarbonization in the building sector is realized in 5 years — a somewhat unrealistic result. In the abatement investment framework, doing so would imply a very high level of investment in building retrofit, and therefore very high marginal costs. As a result, the model with abatement investment distributes these investments over 12 years, to smooth investments and reduce the overall cost of decarbonizing the building sector. Since costs differ across sectors, this smoothing mechanism is different across sectors, leading to different marginal abatement investment costs and different levelized costs of conserved carbon (LCCC).

For instance, in this numerical example, the optimal short-term LCCC is twice as high in the industrial sector than in the building sector even if the climate policy is implemented with a single carbon price. Forward-looking investors facing a perfectly credible carbon price would therefore be ready to pay twice as much per ton of abated carbon emissions in the industrial sector than in the building sector. Facing an abatement option that cost 25 $\$/tCO_2$ in the industrial sector and an abatement option at 15 $\$/tCO_2$ in the building sector, the optimal choice is to invest in the former, not in the latter.

This numerical application illustrates that using LCCCs to compare abatement investment across sectors can be misleading. It also suggests using abatement cost curves with caution, in particular when assessing options that involve investment in long-lived capital. Symmetrically, the abatement-investment model proposed here should not be used to assess measures, such as driving less miles per year or reducing air conditioning, that are best modeled using abatement cost curves.

6 Conclusion

Two types of emission-reduction actions should be distinguished to investigate when and where reducing greenhouse gases emissions. In every sector of the economy, some actions bring immediate and short-lived environmental benefits, such as driving less miles per year, using existing gas power plants more hours per year and existing coal power plants fewer hours per year, or reducing air conditioning. These are appropriately modeled with *abatement cost curves.* For these actions, the increasing carbon price provides direct guidance on where and when effort to reduce emissions should be allocated.

But in every sector, other actions imply punctual investment and persistent emission reductions over a long period of time — such as replacing gasoline vehicles with plug-in hybrid or electric vehicles, replacing fossil-fueled power plants with renewable power, or retrofitting buildings. These are best modeled as *abatement investment.* In these cases, decision-makers have control on the rate of change of emission reductions, rather than on the emission level directly. For these actions, the carbon price does not provide a direct indication of the optimal distribution of emission reductions over time and across sectors; one must also take into account the future value of abatement capital when assessing abatement investment. An increasing carbon price translates into optimal abatement investment that can be bell-shaped or concentrated over the short run. Moreover, more investment per abated ton is needed in sectors with larger abatement potentials and in sectors where abatement capital is more expensive, even though the same carbon price applies to all sectors. For instance, we find in an illustrative example that an abatement option at 25 $\$/tCO_2$ in the industrial sector can be preferable to a 15 $\$/tCO_2$ option in the building sector.

These results suggest that when assessing abatement investment, the ratio of annualized investment to discounted abatement is a poor indicator of where abatement investment should be concentrated — such ratio, sometimes labeled "levelized cost of conserved carbon" or simply "marginal abatement cost", is however broadly used in the policy debate to compare abatement options, for instance in marginal abatement cost curves *a la* McKinsey (2009). Our results also suggest that the dynamics of abatement capital accumulation cannot be represented with abatement cost curves. It can thus be misleading to use models based solely on abatement cost curves to design or assess abatement strategies, or to investigate the optimal timing or distribution across sectors of abatement effort.

These results should be interpreted cautiously, as we disregarded several mechanisms that would affect the cost and timing of climate policies, such as knowledge accumulation, knowledge spill-overs and economic growth. We also leave for further research the effect of uncertainty on climate impacts and future technologies, limited foresight by investors, policy-makers and regulators, and the limited ability of the government to commit. Notwithstanding these limitations, this analysis may help clarify public economic questions related to the optimal response to climate change.

Appendices

A Optimal accumulation of abatement capital

A.a Hamiltonian

The Hamiltonian associated with (1.5) reads:

$$\begin{aligned} H(x_t, a_t, m_t) = e^{-rt} \Big(& c(x_t) + \lambda_t \left(a_t - e_{ref}\right) + \nu_t \left(\delta a_t - x_t\right) \\ & + \mu_t \left(e_{ref} - a_t\right) + \phi_t \left(m_t - B\right) \Big) \end{aligned} \tag{1.18}$$

A.b First order conditions

The first order conditions read:

$$\frac{\partial H}{\partial x_t} = 0 \iff \quad c'(x_t) = \nu_t \tag{1.19}$$

$$\frac{\partial H}{\partial a_t} - \frac{d\left(e^{-rt}\nu_t\right)}{dt} = 0 \iff \quad \dot{\nu}_t - (\delta + r)\nu_t = \lambda_t - \mu_t \tag{1.20}$$

$$\frac{\partial H}{\partial m} + \frac{d\left(e^{-rt}\mu_t\right)}{dt} = 0 \iff \quad \dot{\mu}_t - r\mu_t = -\phi_t \tag{1.21}$$

Where ν_t is the current value of abatement capital, μ is the current cost of carbon, and λ_t is the current social cost of the maximum abatement potential.[16]

Equations (1.20) and (1.19) can be rearranged as:

$$(r + \delta)\, c'(x_t) - \frac{dc'(x_t)}{dt} = (\mu_t - \lambda_t) \tag{1.22}$$

[16] Note that the FOCs do not depend on e_{ref}, showing that the assumption that e_{ref} is constant over time does not impact the basic dynamics of the model.

A.c Complementary slackness conditions

The following complementary slackness condition implies that the carbon price grows at the discount rate before the steady state:

$$\begin{aligned} \forall t, \quad (m_t - B)\phi_t = 0 \\ m_t \leq B \implies \mu_t = \mu e^{rt} \end{aligned} \tag{1.23}$$

Equation (1.23) is similar to a Hotelling rule: here, the carbon budget is analogous to a nonrenewable resource. The other complementary slackness conditions is

$$\forall t, \quad (a_t - e_{ref})\lambda_t = 0 \tag{1.24}$$

A.d Steady state

We call T the date when the carbon budget is reached. After T, emission are null and investment is used to counterbalance depreciation:

$$\forall t \geq T, \quad \dot{m}_t = 0 \implies a_t = e_{ref} \implies x_t = \delta e_{ref} \tag{1.25}$$

A.e The optimal temporal profile of abatement and investment

In this subsection, we show that along the optimal trajectory, abatement capital increases over time before T; and that optimal investment is either bell-shaped or decreasing with respect to time and so is the marginal investment cost, even though the carbon price is exponentially increasing. We first show that

Lemma 1. *if $a_t < e_{ref}$ then x_t is either decreasing or increasing then decreasing,*

then we show that

Lemma 2. *a_t is increasing and is strictly lower than e_{ref} before the finite date T.*

Lemma 1 formalizes one of the main messages from this paper: a growing carbon price does not translate into growing abatement investment. Lemma 2 reflects that since the only reason to invest in abatement is to reach the carbon budget, it cannot be optimal to abate all emissions before the date when the carbon budget is reached.

Proof.

- Lemma 1 If $a_t < e_{ref}$, equation 1.22 may be re-arranged as:

$$\forall t \text{ s.t. } a_t < e_{ref}, \quad \frac{dc'(x_t)}{dt} = (r+\delta)\, c'(x_t) - \mu e^{rt} \tag{1.26}$$

  Equation (1.26) implies that if optimal investment is decreasing at a date θ, it continues to decrease $\forall t > \theta$ s.t. $a_t < e_{ref}$, since $(r+\delta)\, c'(x_\theta) < \mu e^{r\theta}$, with the LHS of the inequality decreasing over time, and the RHS increasing. In addition, $(r+\delta)\, c'(x_t)$ could not increase indefinitely, since this would lead to infinite abatement capital, higher than e_{ref}.

  In addition, if there is a θ such that $(r+\delta)\, c'(x_\theta) = \mu e^{r\theta}$, then $\frac{dc'(x_\theta)}{d\theta} = 0$ and c' has reached its maximum at θ. Immediately after θ, c' starts decreasing. By and large, investment can either decrease over time, or increase until it crosses the carbon price, and then decrease to its steady-state value afterward (Fig. 1.1). □

- Lemma 2 Let us now show that a_t is increasing $\forall t < T$. First, note that a_t starts from 0 and is necessarily increasing at first. Second, if a_t is not continuously increasing, then there is a date t such that $\dot{a}_t = 0$ and $\ddot{a}_t \leq 0$. Then, at this date $\dot{a}_t = x_t - \delta a_t$ and $\ddot{a}_t = \dot{x}_t - \delta \dot{a}_t = \dot{x}_t$, so $\dot{x}_t \leq 0$ and x_t decreases for all future dates (Lemma 1). This implies that a_t also decreases at all future dates (otherwise, reproducing the reasoning would give a date $\tau > t$ with $\dot{x}_\tau \geq 0$), and m_t ends up above B, a contradiction. a_t is thus steadily increasing over time. A direct consequence is that $\forall t < T, a_t < e_{ref}$.[17] Finally, let us show that abatement reaches its potential in finite time, $T < +\infty$: otherwise (1.26) is satisfied at all dates, and

$$c'(x_t) = c'(x_0) e^{(r+\delta)t} - \frac{\mu e^{rt}}{\delta} \left(e^{\delta t} - 1 \right)$$

  which converges either toward $+\infty$ or $-\infty$, a contradiction □.

[17] If we assume that e_{ref} depends on t, then T has to be defined as the last moment such as $\forall t \geq T, \quad a_t = e_{ref}$. In that case, a_t can be decreasing before T, if $e_{ref,t}$ decreases before T. This makes exposition less easy without providing additional insight on the optimal cost, timing, and sectoral allocation of abatement investment.

$\square$

Since emissions are null after T and strictly positive before, it means that social cost of the maximum potential is null before the steady state:

$$\begin{aligned} \forall t < T, \quad & a_t < e_{ref} \;\text{ and }\; \lambda_t = 0 \\ \forall t \geq T, \quad & a_t = e_{ref} \;\text{ and }\; \lambda_t \geq 0 \end{aligned} \tag{1.27}$$

A.f Solving for c'

Before T, (1.27) allows simplifying (1.22) to:

$$\forall t < T, \quad (r+\delta)\, c'(x_t) - \frac{dc'(x_t)}{dt} = \mu e^{rt} \tag{1.28}$$

The solutions of this first order linear differential equation read:

$$\forall t < T, \quad c'(x_t) = e^{(r+\delta)t} \int_t^T e^{-(r+\delta)\theta} \mu e^{r\theta}\, d\theta + e^{(r+\delta)t}\, C \tag{1.29}$$

Where C is a constant. Any C defines an investment pathway that is consistent with the exponentially growing carbon price (1.28). The optimal investment pathways also satisfies a boundary condition: the full potential must be reached at the date T.

A.g Boundary conditions

After T, a_t is constant and the investment x_t is used to counterbalance the depreciation of abatement capital.

$$c'(x_T) = c'\left(\delta e_{ref}\right) \qquad \text{(from eq. 1.25)} \tag{1.30}$$

A.h Optimal marginal investment costs (MICs)

Injecting 1.30 in 1.29 and re-arranging, one gets:

$$\forall t < T,$$

$$c'(x_t) = \mu e^{rt} \int_t^T e^{-\delta(\theta - t)}\, d\theta + e^{-(\delta+r)(T-t)}\, c'\left(\delta e_{ref}\right) \tag{1.31}$$

which can also be written as:

$$c'(x_t) = \int_t^T \mu e^{r\theta} e^{-(\delta+r)(\theta-t)}\, d\theta + \int_T^\infty (r+\delta)\, c'\left(\delta e_{ref}\right)\, e^{-(\delta+r)(\theta-t)}\, d\theta \tag{1.32}$$

In equation 1.32, output from the marginal, deprecating, abatement capital is valued at the current carbon price before T, and valued at the replacement cost of abatement capital $c'\left(\delta e_{ref}\right)$ after T.[18]

A.i The forgone-opportunity effect

Here we explain how the previous result compares to Slechten (2013). Equation (1.32) can be rewritten to show that the marginal abatement investment cost $c'(x_t)$ can be expressed as the sum of three terms: (1) the value $\mathcal{E}$ of avoided emissions along the full lifetime of the investment; (2) the value $\mathcal{O}$ of the forgone opportunity, since each investment in abatement capital reduces future investment opportunities; and (3) the value $\mathcal{K}$ of abatement capital in the long run:

$$\forall t < T, \quad c'(x_t) = \underbrace{\mu e^{rt} \int_t^\infty e^{-\delta(\theta-t)}\, d\theta}_{\mathcal{E}} - \underbrace{\mu e^{rt} \int_T^\infty e^{-\delta(\theta-t)}\, d\theta}_{\mathcal{O}} \tag{1.33}$$

$$+ \underbrace{e^{-(r+\delta)(T-t)}\, c'\left(\delta e_{ref}\right)}_{\mathcal{K}} \tag{1.34}$$

The second term $\mathcal{O}$ echoes previous findings by Slechten (2013) and can be interpreted as a forgone-opportunity effect. The limited potential e_{ref} behaves here like a non-renewable resource, an abatement deposit. After T, accumulating more abatement capital does not allow to reduce emissions. The value $\mathcal{O}$ of this forgone opportunity is the value of the GHG that the maximum potential prevents to save after T. Slechten (2013) does not have an analog to $\mathcal{K}$ as she neglects depreciation.

[18] $c'\left(\delta e_{ref}\right)$ is the replacement cost of the capital after T. It is the cost one has to pay to buy one unit of abatement capital and keep it for its lifetime. $(r+\delta)c'\left(\delta e_{ref}\right)$ is the corresponding rental cost, since $dc'(x_t)/dt = 0$ after T. It is the price one has to pay for renting abatement capital for one unit of time.

B Optimal investment dynamics are similar under cost-effectiveness and cost-benefit

Here, we clarify that the results exposed in the previous section do not depend on the fact that we used a cost-effectiveness analysis instead of a cost-benefit analysis.

Consider the following problem, where a social problem minimizes the sum of abatement investment costs and the cost of climate change impacts:

$$\min_{x_t} \int_0^\infty e^{-rt} \Big(c(x_t) + d(m_t) \Big) \, dt \tag{1.35}$$

$$\begin{aligned} \text{subject to} \quad & \dot{m}_t = e_{ref} - a_t & (\mu_t) \\ & \dot{a}_t = x_t - \delta a_t & (\nu_t) \\ & a_t \le e_{ref} & (\lambda_t) \end{aligned}$$

Where $d(m_t)$ is an increasing and convex function that captures damages from climate change impacts.

The Hamiltonian associated with (1.35) reads:

$$\begin{aligned} H(x_t, a_t, m_t) = e^{-rt} \Big(& c(x_t) + d(m_t) + \lambda_t \left(a_t - e_{ref}\right) + \nu_t \left(\delta a_t - x_t\right) \\ & + \mu_t \left(e_{ref} - a_t\right) \Big) \end{aligned} \tag{1.36}$$

The first order conditions read:

$$\frac{\partial H}{\partial x_t} = 0 \iff \qquad c'(x_t) = \nu_t \tag{1.37}$$

$$\frac{\partial H}{\partial a_t} - \frac{d\left(e^{-rt}\nu_t\right)}{dt} = 0 \iff \qquad \dot{\nu}_t - (\delta + r)\nu_t = \lambda_t - \mu_t \tag{1.38}$$

$$\frac{\partial H}{\partial m} + \frac{d\left(e^{-rt}\mu_t\right)}{dt} = 0 \iff \qquad \dot{\mu}_t = r\mu_t - d'(m_t) \tag{1.39}$$

Compared to the case of a carbon budget, the optimal carbon price is now more complex, and cannot be expressed analytically in general. Fischer et al. (2004) study the possible temporal profiles of the carbon price resulting from (1.39). In the case relevant to this paper, the optimal carbon price first increases over time and then tends to a constant value at the steady state, once GHG concentration in the atmosphere have stabilized at an endogenous level $B^\star$ (see figures 2 and 3 in Fischer et al., 2004).

In this paper, we focus on how the carbon price translates to optimal abatement investment (and how optimal investment differs across sectors). Irrespective of the particular shape of the carbon price, it remains the case that before the steady state, emissions are positive, $\lambda_t = 0$, and (1.37) and (1.38) can be integrated so as to express optimal investment as a function of the carbon price μ_t as:

$$\forall t \leq T,$$
$$c'(x_t) = \int_t^T \mu_\theta e^{-(\delta+r)(\theta-t)}\, d\theta + \int_T^\infty (r+\delta)\, c'\left(\delta e_{ref}\right)\, e^{-(\delta+r)(\theta-t)}\, d\theta \tag{1.40}$$

In particular, Prop. 2 holds (as does Coroll. 2).

Yet another equivalent problem is the following, where a social planner (or any equivalent decentralized procedure) faces an exogenous carbon price μ_t on unabated emissions:

$$\min_{x_t} \int_0^\infty e^{-rt}\left(c(x_t) + \mu_t(e_{ref} - a_t)\right) dt \tag{1.41}$$
$$\text{subject to} \quad \dot{a}_t = x_t - \delta a_t \qquad (\nu_t)$$
$$a_t \leq e_{ref} \qquad (\lambda_t)$$

This problem also leads to optimal marginal abatement investment costs to be valued at the carbon price before the steady state, and at the replacement cost of abatement capital after the steady state — that is, (1.40) and Prop. 2 (and Coroll. 2) all remain true.

C Proof of the expression of the LCCC ℓ_t

Let h be a marginal physical investment in abatement capital made at time t in sector i (expressed in tCO_2/yr per year). It generates an infinitesimal abatement flux that starts at h at time t and decreases exponentially at rate δ_i, leading to discounted abatement ΔA (expressed in tCO_2):

$$\Delta A = \int_{\theta=t}^\infty e^{r(\theta-t)} h\, e^{-\delta_i(\theta-t)}\, d\theta = \frac{h}{r+\delta} \tag{1.42}$$

This additional investment h brings current investment from x_t to $(x_t + h)$. The additional cost ΔC (expressed in \$) that it brings reads:

$$\Delta C = c(x_t + h) - c(x_t) \underset{h \to 0}{=} h\, c'(x_t) \tag{1.43}$$

The levelized cost of conserved carbon ℓ_t is the ratio of additional costs by additional discounted abatement:

$$\ell_t = \frac{\Delta C}{\Delta A} \tag{1.44}$$

$$\ell_t = (r + \delta)\, c'(x_t) \tag{1.45}$$

D An alternative understanding of the marginal implicit rental cost of abatement capital

From an existing investment pathway (x_t) leading to an abatement pathway (a_t), the social planner may increase investment by one unit at time θ and immediately reduce investment by $1 - \delta\, d\theta$ at the next period $\theta + d\theta$. The resulting investment schedule $(\tilde{x}_t)$ leads to an abatement pathway $(\tilde{a}_t)$ that abates one supplementary unit of GHG between θ and $\theta + d\theta$ (Fig. 1.5). Moving from (x_t) to $(\tilde{x}_t)$ costs:

$$\mathcal{P} = \frac{1}{d\theta} \left[c'(x_\theta) - \frac{(1 - \delta\, d\theta)}{(1 + r\, d\theta)}\, c'(x_{\theta + d\theta}) \right] \tag{1.46}$$

For marginal time lapses, this tends to :

$$\mathcal{P} \xrightarrow[d\theta \to 0]{} (r + \delta)\, c'(x_\theta) - \frac{dc'(x_\theta)}{d\theta} \tag{1.47}$$

$\mathcal{P}$ tends to the cost of renting one unit of abatement capital at θ.

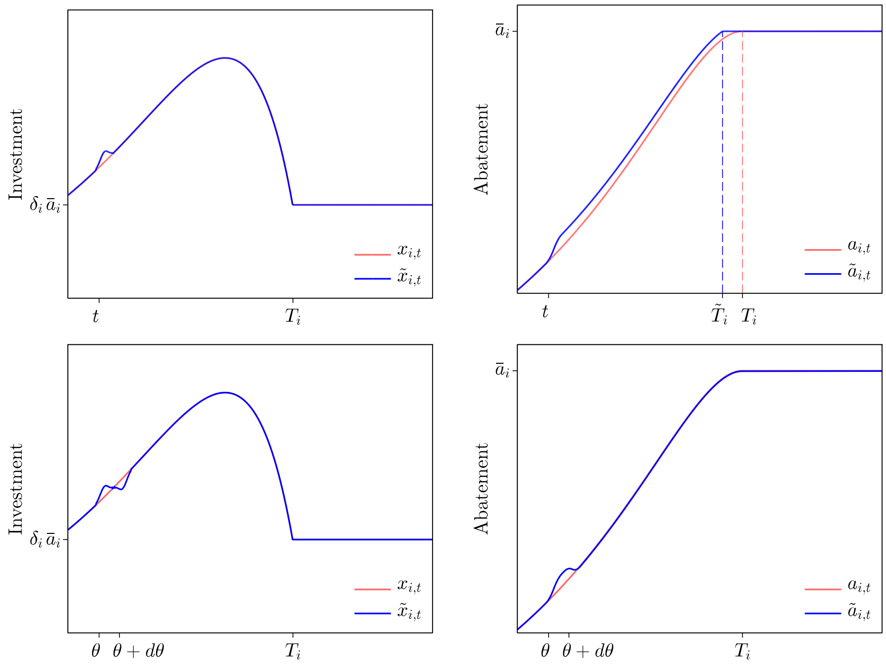


Figure 1.5: Top row: from a given investment pathway (x_t) leading to the abatement pathway (a_t), one additional unit of investment at time θ has two effects: it saves GHG, and brings forward the date when the maximum potential e_{ref} is reached $(T \to \tilde{T})$. Bottom row: saving one more unit of GHG at a date θ without changing the rest of the abatement pathway, as in $(\tilde{a}_t)$, requires to invest one more unit at θ and $(1 - \delta\, d\theta)$ less at $\theta + d\theta$, as $(\tilde{x}_t)$ does.

E Optimal allocation of abatement investment

The Hamiltonian associated with (1.12) reads:

$$H(x_{i,t}, a_{i,t}, m_t) = e^{-rt} \Bigg(\sum_i c_i(x_{i,t}) + \sum_i \lambda_{i,t} \left(a_{i,t} - \bar{a}_i\right) + \sum_i \nu_{i,t} \left(\delta_i a_{i,t} - x_t\right) \\ + \mu_t \sum_i \left(\bar{a}_i - a_{i,t}\right) + \phi_t \left(m_t - B\right) \Bigg) \tag{1.48}$$

The first order conditions read $\forall(i,t)$:

$$c_i{}'(x_{i,t}) = \nu_{i,t} \qquad (\partial x_{i,t}) \qquad (1.49)$$

$$\dot{\nu}_{i,t} - (\delta_i + r)\nu_{i,t} = \lambda_{i,t} - \mu_t \qquad (\partial a_{i,t}) \qquad (1.50)$$

$$\dot{\mu}_t - r\mu_t = -\phi_t \qquad (\partial m_t) \qquad (1.51)$$

Where $\nu_{i,t}$ is the present value of investment in low carbon capital, μ is the present cost of carbon, and $\lambda_{i,t}$ is the social cost of the sectoral potential. The steady state is reached at a date T_m when the carbon budget is reached. After this date, emission are null in every sector and investment is used to counterbalance depreciation:

$$\dot{m}_t = 0 \implies \forall i, a_{i,t} = \bar{a}_i \implies x_{i,t} = \delta_i \bar{a}_i \qquad (1.52)$$

Denoting T_i the date when all emissions in sector i are capped ($\forall i \geq T_i, a_{i,t} = \bar{a}_i$), it is easy to establish that $T_m = \max_i(T_i)$ (adapting the resolution from A). The complementary slackness conditions mean that the carbon price grows at the discount rate before the steady state:

$$\forall t < T_m, \quad m_t < B \quad \text{and} \quad \phi_t = 0 \qquad (1.53)$$

$$\implies \mu_t = \mu e^{rt} \qquad (1.54)$$

and the social costs of the sectoral potentials are null before the respective dates T_i:

$$\forall t < T_i, \quad a_{i,t} < \bar{a}_i \quad \text{and} \quad \lambda_{i,t} = 0 \qquad (1.55)$$

The first order conditions can be re-arranged as:

$$\forall (i,t), \quad (r + \delta_i)\, c_i{}'(x_{i,t}) - \frac{dc_i{}'(x_{i,t})}{dt} = \mu e^{rt} - \lambda_{i,t} \qquad (1.56)$$

Following the demonstration for the case of one single sector (A) yields:

$$c_i{}'(x_{i,t}) = \mu e^{rt} \int_t^{T_i} e^{-\delta_i(\theta-t)}\, d\theta + e^{-(\delta+r)(T_i-t)}\, c_i'\left(\delta_i \bar{a}_i\right) \tag{1.57}$$

$$= \int_t^{T_i} \mu e^{r\theta} e^{-(\delta_i+r)(\theta-t)}\, d\theta + \int_{T_i}^{\infty} \left(r+\delta_i\right) c_i'\left(\delta_i \bar{a}_i\right)\, e^{-(\delta_i+r)(\theta-t)}\, d\theta \tag{1.58}$$

The fact that the dates T_i differ across sectors is easily derived from the demonstrations of the corollaries in the next subsection.

E.a Proof of Coroll. 1

Here we demonstrate Coroll. 1. We first show that two investment profiles cannot cross before one of the sector has reached its maximum potential. One is therefore always higher than the other. We then show that the highest investment profile corresponds to the most expensive sector, or the one with higher abatement potential.

As a lemma, note that the Euler equation

$$\forall i, \forall t < T_i, \quad \frac{dc_i{}'(x_{i,t})}{dt} = (r+\delta_i)c_i{}'(x_{i,t}) - \mu e^{rt} \tag{1.59}$$

implies that if two sectors have the same depreciation rate δ_i, if their investment trajectories meet before one of the sectors is decarbonized, then they must be equal for all times before one of the sector is decarbonized:

$$\forall (i,j),\, \delta_i = \delta_j \text{ and } \exists t^\times \leq \min(T_i, T_j) \text{ s.t. } c_i'(x_{i,t^\times}) = c_j'(x_{j,t^\times}) \tag{1.60}$$

$$\implies \forall t \leq \min(T_i, T_j), \quad c_i'(x_{i,t}) = c_j'(x_{j,t}) \tag{1.61}$$

This means that the only possibility for two optimal investment trajectories — corresponding to two sectors with the same depreciation rate — to cross at one point in time is after one has reached its maximum abatement potential (Fig. 1.6).

Let us prove Coroll. 1(i):

Proof. Let two sectors $\{1,2\}$ be such that they exhibit the same investment cost function, the same depreciation rate, but different abatement

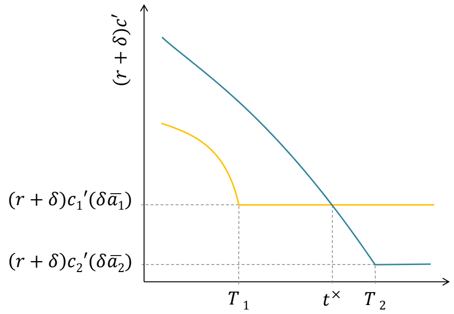


Figure 1.6: Two different investment trajectories corresponding to two sectors with the same depreciation rate crossing after one has reached its maximum abatement potential.

potentials:

$$\forall x > 0,\ c_1'(x) = c_2'(x),\ \delta_1 = \delta_2 = \delta,\ \bar{a}_1 > \bar{a}_2$$

In the long term, the largest sector is above the small one:

$$\forall t \geq \max(T_1, T_2), \quad (r+\delta)c_1'(\delta\bar{a}_1) > (r+\delta)c_2'(\delta\bar{a}_2) \tag{1.62}$$

Suppose that the two investment pathways cross at $t^\times \in [T_1, T_2]$,[19] such that (Fig. 1.6):

$$\begin{cases} \forall t < t^\times, & c_1'(x_{1,t}) \leq c_2'(x_{2,t}) \\ \forall t > t^\times, & c_1'(x_{1,t}) > c_2'(x_{2,t}) \end{cases} \tag{1.63}$$

$$\implies \forall t < T_1, \quad x_{1,t} \leq x_{2,t}$$

$$\implies \int_0^{T_1} x_{1,t}\, e^{-\delta(T_2-t)} dt = \bar{a}_1 < \int_0^{T_1} x_{2,t}\, e^{-\delta(T_2-t)} dt = a_{2,T_1}$$

which is incompatible with the constraint that $a_{2,T_2} \leq \bar{a}_2$ and the assumption that $\bar{a}_1 < \bar{a}_2$. As a result, it is impossible that $c_1'(x_{1,t})$ and $c_2'(x_{2,t})$ cross, and:

$$\forall t,\ c_1'(x_{1,t}) > c_2'(x_{2,t}) \tag{1.64}$$

[19]Because $\frac{dc_i{}'(x_{i,t})}{dt} < 0$ in the vicinity of T_i, $T_1 > T_2$ is not possible if the curves cross (Fig. 1.6)

$\square$

Coroll. 1(ii) tackles the similar case of two sectors differing only for the cost of their abatement capital:

$$\forall x > 0,\ c_1'(x) < c_2'(x) \quad (\text{while } \bar{a}_1 = \bar{a}_2 \text{ and } \delta_1 = \delta_2)$$

The proof is similar: (1.62) holds and (1.63) would imply that $\bar{a}_2 = a_{2,T_2} > \bar{a}_1 = \bar{a}_2$.

Note that Coroll. 1 does not prevent any two optimal sectoral investment pathways to cross: the situation pictured in Fig. 1.6 may happen for two sectors which differ in cost *and* abatement potential in different directions ($c_1' > c_2'$ and $\bar{a}_1 < \bar{a}_2$) and for sectors for which the depreciation rate of abatement capital differs ($\delta_1 \neq \delta_2$).

F A perfectly-credible carbon price can decentralize the optimal abatement strategy

Take the point of view of the owner of one polluting equipment in a sector i, facing the credibly announced carbon price μe^{rt}. One question for this owner is when should the equipment be retrofitted or replaced with zero-carbon capital. The following corollary illustrates that the question is easily answered if agents correctly anticipate the prices of carbon and abatement capital:

Corollary 3. *Along the optimal pathway, individual forward-looking agents in each sector i are indifferent between investing in abatement capital at any time before T_i.*

Proof. Let τ be the date when the agent invests in abatement capital. Before τ, the agent pays the carbon price. At τ, she invests in one unit of abatement capital at the price $c_i'(x_{i,\tau})$. At each time period t after τ, she has to maintain its abatement capital, which costs $\delta_i c_i'(x_{i,t})$. The total discounted cost $V_i(\tau)$ of this strategy reads:

$$V_i(\tau) = \mu\tau + e^{-r\tau} c_i'(x_{i,\tau}) + \int_\tau^\infty e^{-rt} \delta_i c_i'(x_{i,t}) dt \tag{1.65}$$

Let us derivative the cost V with respect to the decision variable τ:

$$\begin{aligned} V_i'(\tau) &= \mu + e^{-r\tau}\left(c_i'(x_{i,\tau}) - r\frac{d}{d\tau}c_i'(x_{i,\tau})\right) - e^{-r\tau}\delta_i c_i'(x_{i,\tau}) \\ &= (r+\delta_i)\, c_i'(x_{i,\tau}) - \frac{d}{d\tau}c_i'(x_{i,\tau}) - \mu e^{r\tau} \\ V_i'(\tau) &= \lambda_{i,\tau} && \text{(from eq. 1.56)} \end{aligned}$$

This last equations means that $V_i'(\tau)$ is null for any $\tau \leq T_i$, and positive afterward (1.55). □ □

Coroll. 3 means that the optimal investment pathways can be decentralized to a market equilibrium by imposing a perfectly credible carbon price path μe^{rt} to forward-looking investors.

G Overview of the abatement-cost-curve model

Since the seminal contribution by Nordhaus (1991), a frequent approach to derive the optimal timing of mitigation strategies is to use an abatement cost curve. In this section we find that in this framework the optimal timing and cost of GHG reductions is essentially the same thing as the exponentially-increasing carbon price.

G.a An abatement cost curve model

The cost of emission abatement at time t is linked to the abatement a_t through an abatement cost curve γ. The function γ is classically convex, positive and twice differentiable:

$$\begin{aligned} \forall a_t, \quad \gamma''(a_t) &> 0 \\ \gamma'(a_t) &> 0 \\ \gamma(a_t) &> 0 \end{aligned} \tag{1.66}$$

The basic idea behind the abatement cost curve is that some potentials for emission reductions are cheap (e.g. building insulation pays for itself thanks to subsequent savings), while other are more expensive (e.g. upgrading power plants with carbon capture and storage). If potentials are exploited in the merit order — from the cheapest to the most expensive — the marginal cost of doing so $\gamma'(a_t)$ is increasing in a_t, and $\gamma(a_t)$ is convex.

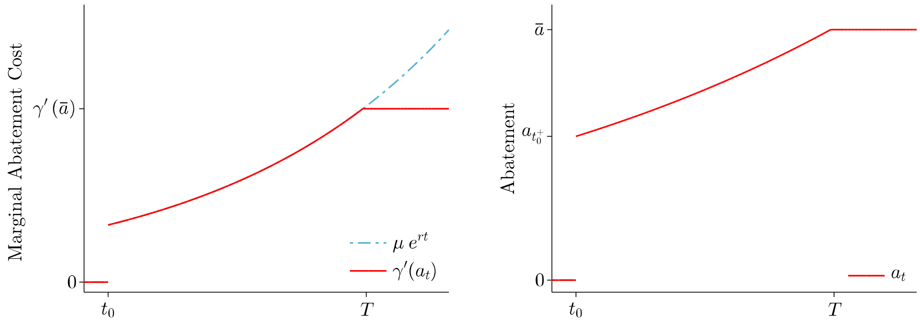


Figure 1.7: Optimal timing and costs of abatement in the abatement-cost-curve framework. Left: Before the potential is reached, abatement efforts are equal to the carbon price and grow over time. Right: When the social planner imposes a carbon price at t_0, the level of abatement "jumps".

A social planner determines when to abate in order to minimize abatement costs discounted at a given rate r, under the constraints set by the abatement potential and the carbon budget:

$$\min_{a_t} \int_0^\infty e^{-rt}\,\gamma\,(a_t)\,dt \tag{1.67}$$

$$\begin{aligned} \text{subject to} \quad & a_t \leq e_{ref} && (\lambda_t) \\ & \dot{m}_t = e_{ref} - a_t && (\mu_t) \\ & m_t \leq B && (\phi_t) \end{aligned}$$

We denoted in parentheses the co-state variables and Lagrangian multipliers.

G.b Result in the abatement cost curve framework

In the abatement cost curve framework, the optimal abatement cost strategy is to implement abatement options such that the marginal abatement cost is equal to the carbon price μe^{rt} at each point in time, until the potential e_{ref} is reached at a date T (G.c):

$$\gamma'(a_t) = \begin{cases} 0 & t \leq t_0 \\ \mu e^{rt} & t_0 < t < T \\ \gamma'(e_{ref}) & t \geq T \end{cases} \tag{1.68}$$

Where t_0 is the date when the social planner implements the carbon price (Fig. 1.7).

Many contributions based on abatement cost curves and numerical optimization factor in some climate change dynamics and damages from climate change, including the DICE model and its extensions discussed in footnote 1, without changing these general results.

In the abatement cost curve framework, both the optimal abatement efforts $\gamma(a_t)$ and the abatement level a_t thus increase over time. Moreover, abatement decisions can be made at each time step independently, based only on the current carbon price μe^{rt} and the abatement cost curve γ. In particular, the level of abatement jumps when the carbon price is implemented (Fig. 1.7). Such jumps are common in the literature on the optimal timing of mitigation. For instance, the last version of DICE finds that the least-cost pathway to reach 2°C starting a policy in 2010 is to jump to 35% of emission reductions in five years, between 2010 and 2015 — see Figure 9 in Nordhaus et Sztorc (2013); and Schwoon et Tol (2006) allow explicitly for such jumps, in a model that would otherwise be close to the abatement investment model presented in section 1.

The (implicit) assumption that abatement can be decided independently at each time step is only valid in cases where abatement action is paid for and delivers emission reduction at the same time, such as driving less or reducing air conditioning. In many cases, such as upgrading to more efficient vehicles or retrofitting buildings, costs are mainly paid when the action is undertaken, while annual emissions are reduced over several decades. These actions are better modeled as abatement investment.

G.c Detailed resolution

The Hamiltonian associated with (1.67) reads:

$$H(a_t, m_t) = e^{-rt} \left(\gamma(a_t) + \lambda_t \left(a_t - e_{ref} \right) + \mu_t \left(e_{ref} - a_t \right) + \phi_t \left(m_t - B \right) \right) \tag{1.69}$$

The first order conditions are:

$$(\partial a_t) \qquad \gamma'(a_t) = (\mu_t - \lambda_t) \tag{1.70}$$

$$(\partial m_t) \qquad \dot{\mu}_t - r\mu_t = -\phi_t \tag{1.71}$$

The steady state is reached at a date T when $\dot{m}_t = 0$, that is when the abatement potential e_{ref} is reached, such that:

$$\forall t < T,\ a_t < e_{ref} \text{ and } m_t < B$$
$$\forall t \geq T,\ a_t = e_{ref} \text{ and } m_t = B$$

As the associated Lagrangian multiplier, ϕ_t is null before the carbon budget is reached (complementary slackness condition):

$$\begin{aligned} &\forall t, \quad \phi_t \cdot (m_t - B) = 0 \\ \implies &\forall t < T, \quad \phi_t = 0 \end{aligned} \tag{1.72}$$

This means that the present value of carbon μ_t is constant while the carbon budget has not been reached (1.71):

$$\forall t < T, \quad \mu_t = \mu e^{rt} \tag{1.73}$$

For the same reason, λ_t is null before the sectoral potential becomes binding:

$$\begin{aligned} &\forall t, \quad \lambda_t \cdot (a_t - e_{ref}) = 0 \\ \implies &\forall t < T, \quad \lambda_t = 0 \end{aligned} \tag{1.74}$$

Combining (1.70), (1.73), and (1.74), one gets (1.68).

2

Optimal transition from coal to gas and renewable energy under capacity constraints and adjustment costs

MANY governments aim at stabilizing climate change to avoid important climate damages, which requires reaching near-zero greenhouse gas (GHG) emissions in the long term (Steinacher et al., 2013; IPCC, 2014c). Abating GHG emissions from power generation is key to reach this goal, as the power sector is currently responsible for nearly 40% of carbon emissions worldwide, and fuel switching to clean electricity is a major technical option to reduce emissions from other sectors (Williams et al., 2012; Audoly et al., 2014).

Two important features of the electricity sector are that (i) it depends on long-lived capital that, in general, is tied to a specific fuel, and (ii) today's power production predominantly relies on polluting fossil fuels such as coal (IEA, 2014b). Several alternatives are available to abate GHG emissions from electricity production. Emissions may be reduced by replacing coal plants by new gas power plants, [1] or by more-expensive but almost-carbon-free options such as renewable power. In addition, decision makers can either wait for existing plants to reach their natural lifetime, or decide to decommission them earlier in order to switch faster to cleaner energy sources.

This paper analyzes the optimal transition from coal to gas and renewable energy under capacity constraints and a carbon budget. We model different types of nonrenewable resources, *à la* Chakravorty et al. (2008) (cheap coal and more expensive gas), and an expensive renewable source. All energy sources are subject to capacity constraints: consuming more energy first requires investment in coal, gas, or renewable power plants. Finally, investment is irreversible and bears *adjustment costs*. Adjustment costs are convex investment costs capturing the increasing opportunity cost to use scarce resources to build and deploy new capital faster (Lucas, 1967; Gould, 1968; Mussa, 1977).

We find that optimal investment in renewable can start early, that is before coal and gas are phased out. The reason is that smoothing investment over time reduces adjustment costs. Loosely speaking, the availability of appropriate resources (skilled workers, production lines) sets an optimal speed at which to deploy renewable power. This speed, combined with the ultimate goal of achieving carbon neutrality (to comply with the carbon budget), sets an optimal date to start investment in renewable power plants. We also find that transient investment in new gas plants can be used to reduce (but not necessarily cancel) the need for investment in expensive renewable energy in the short term. But new gas-fired capital needs to be decommissioned eventually and give room to more carbon-free energy.

More generally, the transition from coal to gas and renewable energy can exhibit three different profiles. First, the social planner can sequentially switch from coal to gas, and only after from gas to renewable power. Numerical simulations suggest that this occurs for lax carbon budgets and low adjustment costs, giving time to switch entirely to gas before starting to invest in renewable power and reducing the need to smooth investment in renewable energy. Second, for inter-

[1] This paper assumes gas is a low-carbon substitute for coal. The relative carbon content of gas and coal may actually depend on the type of gas and coal and on the particular processes used for extracting and transporting the fuels (e.g., Alvarez et al., 2012). The relative merits of coal and gas also depend on factors disregarded here, such as impact on energy security (see the review in Guivarch et al., 2015) or impact on local pollution (e.g., Shindell, 2015).

mediate adjustment costs and carbon budgets, the transition can start with investment in gas, and continue with investment in renewable before coal has been phased out. In the third type of transition profile, for stricter carbon budget and larger adjustment costs, investment in renewable power starts as soon as possible.

We illustrate and quantify these findings in a numerical simulation of the European Commission's Energy Roadmap (EU, 2011), whose aim is to fully decarbonize the European power sector by mid-century. According to our simulations, the ambitious goal of the European Commission implies that the optimal transition starts with investment in renewable power, except if adjustment costs are small and the cost of renewable energy is significantly higher than suggested by available data. With our reference calibration, it is optimal to start with investment in both renewable and gas. Optimal short-term investment in renewable capacity is comparable to actual figures. New gas power plants are built until 2040, to reduce the need for renewable power plants in the short-term, but electricity generation from gas is then phased out within the next 15 years. These results shed light on technical choices (e.g. investors can consider gas plants with short scheduled lifetimes) as well as policy decisions (when setting milestones for carbon-free power generation capacity).

This paper relates to two different strands of the analytical literature. The first one studies the optimal usage of different fossil fuels under an environmental constraint, through the lens of nonrenewable resources theory (Hotelling, 1931; Herfindahl, 1967), with little attention to the dynamics of capital accumulation (e.g., Chakravorty et al., 2008; van der Ploeg et Withagen, 2012). In this literature, renewable energy is modeled as a *clean backstop*, a technology that can immediately produce arbitrary quantities of energy at some fixed marginal costs. With these assumptions, renewable energy should never be used early, that is before fossil fuel consumption stops. We expand this literature by studying the effect of capacity constraints and adjustment costs limiting the extraction of all types of energies. We find that to reduce adjustment costs, it makes sense to start investing in renewable and gas power plants early, and to use several energy types at the same time.

The other strand of the literature studies optimal investment in clean capital under adjustment costs, with little attention to fossil fuel resources, and neglecting intermediate alternatives to perfectly clean capital (such as switching from coal to gas). Fischer et al. (2004), Williams (2010) and Slechten (2013) all stress that to reduce adjustment costs, the optimal strategy is to smooth investment in clean capacity, anticipating future carbon prices. Vogt-Schilb et al. (2014b) compare abatement investment across sectors, and find that the abatement potential in each sector should also be anticipated: the same carbon price translates into more short-term investment in sectors with larger abatement potential. Here, we confirm that smoothing investment and anticipating future prices is critical. In particular we find that more investment should go to renewable power, which is built to last, than to gas power, which is only an intermediate technology. Finally, Rozenberg et al. (2014) analyze the trade-off between early-scrapping existing dirty capital and investing in clean capital. They find that early-scraping part of the dirty capital, built before climate policies are announced, is optimal for achieving stringent climate targets.[2] Here, we find that it can also be optimal to build gas-fired capital after climate policies are implemented, knowing that it will subsequently be underused, to move efforts from the short to the middle term.

Last but not least, other authors have previously investigated optimal capital accumulation and resource extraction under a single model. In a recent working paper, Amigues et al. (2013) study the extraction of a renewable and a non-renewable energy source, taking into account that the extraction of the renewable source requires to first invest in appropriate capital (renewable power plants) and pay for adjustment costs. They also find that optimal investment in renewable may start early, before fossil resources are exhausted. [3] But they model a single fossil resource, and they leave environmental constraints and capacity constraints limiting the extraction of fossil fuels for further research. This paper thus proposes the first analytical model able to assess the optimal transition from coal to gas and renewable power plants, taking

[2]We focus on the analytical literature. Early decommissioning of existing coal power plants has also been studied using numerical models (e.g., IEA, 2014b; Johnson et al., 2014).

[3]A whole literature started by Kemp et Long (1980) has established that if the extraction rate of an expensive energy source is constrained by an *exogenous* factor, it may be optimal to use that source simultaneously with cheaper alternatives (e.g., Amigues et al., 1998; Holland, 2003). Amigues et al. (2013) confirm this result for *endogenous* constraints.

Other reasons for not extracting resources according to a strict Herfindahl sequence include time to build (Winkler, 2008), imperfect substitution (Smulders et Van Der Werf, 2008), heterogeneity of producers, heterogeneity of consumers and transportation costs – Gaudet et Salant (2014) provide a review.

into account capacity constraints on all energy sources and an environmental constraint.[4]

The remainder of the paper is structured as follows. Section 1 details the model. section 2 solves the model for the carbon and fossil energy costs (2.1), the optimal value of capacities and the cost of building new ones (2.2), the electricity price and capacity rents (2.3), and optimal investment trajectories (2.4). Section 2.5 discusses the optimal ordering of investment and possible transition profiles. Section 3 provides numerical simulations calibrated with data from the European electricity sector. Section 4 discusses limitations of this paper and concludes.

1 Model

A social planner controls the supply of electricity, using and investing in three different technologies: an existing high-carbon technology (h, coal power), a fossil-fueled low-carbon technology (ℓ, gas), and an inexhaustible zero-carbon technology (z, renewable power).

At each time t, the social planner chooses a positive amount of physical investment $x_{i,t}$ in technology i. Investment adds to the installed capacity k_t, that depreciates at the constant rate δ (dotted variables denote temporal derivatives):[5]

[4] The interaction of investment and natural resources extraction is also the subject of the theory of the mine (e.g., Campbell, 1980; Gaudet, 1983; Lasserre, 1985), in which installed capital similarly limits the extraction rate of (a single type of) minerals. After reviewing this literature, Cairns (1998) notes that "*there can be three phases in the exploitation of the mine, namely (1) a period of positive investment after time $t = 0$, in which production is at full capacity, then (2) a period in which investment is zero and production is at full capacity, and finally (3) a period of declining production*". This paper is different, as we model several resources and an environmental constraint; we find, however, a similar trajectory for exploitation of gas resources.

In addition, Dasgupta et Heal (1974), Solow (1974) and Stiglitz (1974) have started a literature that studies the impact of resource exhaustiblity on growth, in *green Ramsey models* that feature both capital accumulation and resource extraction (e.g., van der Ploeg et Withagen, 1991, 2014). This literature also focuses on a single type of capital and a single fossil resource while we model several resources and resource-specific capital.

[5] Throughout this paper, *capacity* is to be understood as equivalent capacity, e.g., in kWh/yr, unless otherwise specified. For instance if 2 kW of windmills are required to provide as much output per year as 1 kW of coal, then 2 kW of windmills are accounted as 1 kW_{eq}.

$$\dot{k}_{i,t} = x_{i,t} - \delta k_t, \quad \forall i \tag{2.1}$$

$$x_{i,t} \geq 0 \tag{2.2}$$

Without loss of generality, we assume low-carbon and zero-carbon capacities to be nil at the beginning ($k_{\ell,t_0} = k_{z,t_0} = 0$).[6]

The constraint that investment is positive implies that once a power plant has been built, it cannot be unbuilt to retrieve its costs. For instance, once the workforce and cement have been used to build a gas power plant, the plant cannot be transformed back to manpower and raw cement to build something else. Other authors have referred to such constraints as *irreversible investment* (Arrow et Kurz, 1970), or *putty-clay capital* (Arltesou, 1999; Wei, 2003).[7]

Physical investment is made at a positive, increasing and convex cost c_i:

$$c_i(x) > 0,\ c_i'(x) > 0,\ c_i''(x) > 0, \quad \forall x \tag{2.3}$$

This convexity captures the increasing opportunity cost to use scarce resources (skilled workers and appropriate capital) in order to build and deploy capacities faster. It has been labeled *adjustment costs* in the theory of the firm (Lucas, 1967; Gould, 1968). In general, the words *adjustment costs* cover many factors limiting the speed at which individual firms can adjust their stock of capital to new prices, such as the cost to purchase capital or to install it. In the literature on resource extraction (e.g., Gaudet, 1983; Amigues et al., 2013), including this paper, adjustment costs are best understood as the production costs for the industries that manufacture each type of power plants — Mussa (1977) calls these *external* adjustment costs. [8]

[6]The reason why this assumption does not result in a loss of generality is that our model studies the transition from the existing situation to cleaner and to clean power, as done in Section 3.

[7]As the irreversibility constraint is on the *building* process of power plants, it does not prevent private agents who own a power plant to sell it to other private agents at any moment. During the analytical resolution of the problem, it will be useful to interpret some terms as the resale value of existing capacities.

[8]In this paper, *investment* refer to the building of new power plants. When private owners of power plants sell an existing plant to another electricity production

A practical consequence of adjustment costs is that the faster the social planner builds new windmills or new gas plants, the higher are their marginal costs. In order to minimize the costs of the transition, the social planner will smooth investment over time.

We assume that, when both are built at the same pace, low-carbon capacity is cheaper than zero-carbon capacity:

$$c'_\ell(x) < c'_z(x), \quad \forall x \tag{2.4}$$

In general, we do not assume that $c'_i(0) = 0$; the strictly positive $c'_i(0)$ are the minimum costs at which power plants i may be built. [9]

The social planner also chooses how much output to produce with each technology. We assume production exhibits constant returns to scale: two gas plants can produce twice as much electricity as one gas plant.[10] The positive production ${c_i}'(x_{i,t})$ with technology i cannot exceed the installed capacity k_t:

$$0 \leq {c_i}'(x_{i,t}), \quad \forall i \tag{2.5}$$

$${c_i}'(x_{i,t}) \leq k_t \tag{2.6}$$

For simplicity, we assume the existing carbon-intensive capital is over-abundant, such that (2.6) is not binding for coal; this assumption is relaxed and confirmed in the numerical application.

Let F_i be the carbon intensity (or emission factor) of technology i. The high-carbon technology is more carbon-intensive than the low-carbon technology:

firm, that latter firm is also performing investment. But at the social level, such investment is a transfer, not a net accumulation of new capital.

[9] Some readers may prefer to think of our marginal investment costs $c'(x)$ as the sum of some "pure" investment costs $c'(0)$ and some "pure" adjustment costs $c'(x) - c'(0)$.

[10] We are neglecting any complementarity or imperfect substitution between gas and renewable plants that comes from their respective cost structures (in terms of fixed versus variable costs) and from the intermittency of renewable power availability. We are implicitly assuming that such considerations have more impact on the optimal electricity mix *at* the equilibrium than on the optimal transition from the existing state *to* that equilibrium, which is the focus of the paper.

$$F_h > F_\ell > F_z = 0 \tag{2.7}$$

The social planner is constrained by an exogenous carbon budget (or emission ceiling), that is cumulative emissions cannot exceed a given ceiling B:

$$m_t \leq B, \quad \forall t \tag{2.8}$$

where cumulative emissions m_t grow with emissions $F_i\, q_{j,t}$:

$$\dot{m}_t = \sum_i F_i\, q_{j,t} \tag{2.9}$$

Cumulative emissions have been found to be a good proxy for global warming (Allen et al., 2009; Matthews et al., 2009a; IPCC, 2014c). Some policy instruments, such as an emission trading scheme with unlimited banking and borrowing, set a similar constraint on firms (Slechten, 2013).

Using fossil fuel (gas or coal) requires to extract exhaustible resource from an initial stock, such that the current stock $S_{i,t}$ satisfies:

$$\begin{aligned} &S_{i,t_0} \text{ given} \\ &\dot{S}_{i,t} = -{c_i}'(x_{i,t}) \\ &S_{i,t} \geq 0 \end{aligned} \tag{2.10}$$

We assume that the zero carbon technology is renewable: $S_{z,t_0} = \infty$. While it is convenient to use the general notations introduced above (indexed by i), parts of the analytical resolution will focus on the case where coal is overabundant ($S_{h,t_0} = \infty$). In these cases the carbon budget is more stringent than the scarcity of coal resources (as in van der Ploeg et Withagen, 2012).

Consumers derive utility $u\left(\sum_i {c_i}'(x_{i,t})\right)$ from electricity consumption, where u satisfies Inada conditions and is sufficiently smooth. The program of the social planner consists of determining the trajectories of investment $x_{i,t}$ and production ${c_i}'(x_{i,t})$ that maximize discounted utility net of investment costs while complying with the carbon budget B and the various constraints:

$$
\begin{aligned}
&\max_{x_{i,t}, c_i'(x_{i,t})} \int_0^\infty e^{-rt} \left[u\left(\sum_i c_i'(x_{i,t})\right) - \sum_i c_i(x_{i,t})\right] dt && (2.11)\\
&\text{s.t. } \dot{k}_{i,t} = x_{i,t} - \delta k_t && (\nu_t)\\
&\qquad q_{j,t} \leq k_{j,t} && (\gamma_{i,t})\\
&\qquad q_{j,t} \geq 0 && (\lambda_{i,t})\\
&\qquad x_{i,t} \geq 0 && (\xi_{i,t})\\
&\qquad \dot{m}_t = \sum_i F_i\, q_{j,t} && (\mu_t)\\
&\qquad m_t \leq B && (\eta_t)\\
&\qquad \dot{S}_{i,t} = -c_i'(x_{i,t}) && (\alpha_{i,t})\\
&\qquad S_{i,t} \geq 0 && (\beta_{i,t})
\end{aligned}
$$

Where r is the constant discount rate and the Greek letters in parentheses denote the costate variables and Lagrange multipliers (all chosen such as to be positive). A few of them play a key role in the analytical resolution: ν_t, the shadow value of new power plants; $\gamma_{i,t}$, the social costs of the capacity constraint, which can also be interpreted as the shadow rental costs of power plants; μ_t, the shadow carbon price; and $\alpha_{i,t}$, the shadow price of resource i (all notations are gathered in Tab. 2.5).

2 Analytical resolution

2.1 Hotelling rents, carbon prices and energy costs

The transition from coal to gas and renewable power is driven by the increase of three prices: the price of coal $\alpha_{h,t}$, the price of gas $\alpha_{\ell,t}$, and the price of carbon emissions μ_t. (In the following, we frequently omit the term "shadow" when referring to co-state variables and Lagrangian multipliers. We also freely switch between the social planner's perspective and the equivalent point of view of private agents facing optimal energy and carbon prices.) All three prices correspond to scarcity rents, and follow the Hotelling rule (see the appendix for the full set of efficiency conditions), that is they grow over time at the interest rate:

$$\alpha_{h,t} = \alpha_h \, e^{rt}, \ \alpha_{\ell,t} = \alpha_\ell \, e^{rt}, \ \mu_t = \mu e^{rt} \tag{2.12}$$

As there are no extraction costs in this model, $\alpha_{h,t}$, $\alpha_{\ell,t}$, and μ_t are non-zero only when the respective exhaustibility constraint for coal, gas, and the carbon budget is binding. Under the assumption that coal reserves are not binding, $\alpha_h = 0$; in addition, if there is more carbon contained in gas reserves underground than the carbon budget allows to emit into the atmosphere, then $\alpha_{\ell,t} = 0$.

In the following, we continue the analytical resolution of the model using $\alpha_{h,t}$ and $\alpha_{\ell,t}$ — without substituting. With this more general notation, the resolution also holds for cases with positive extraction, transformation and transportation costs that would be encompassed in the energy costs $\alpha_{h,t}$ and $\alpha_{\ell,t}$; or more generally for any exogenous energy price trajectory $\alpha_{h,t}$ and $\alpha_{\ell,t}$ — as will be used in section 3.

2.2 Capacity rents, capacity value, and construction costs

This subsection clarifies the link between capacity rents $\gamma_{i,t}$, capacity value ν_t, and construction costs ${c_i}'(x_{i,t})$. Such clarification is essential to the rest of the resolution.

After deriving the first order conditions (see appendix), we find that along the optimal path, the costs of building new capacities ${c_i}'(x_{i,t})$ equals the shadow value of capacities ν_t plus the shadow costs of the irreversibility constraint $\xi_{i,t}$, that is ${c_i}'(x_{i,t}) = \nu_t + \xi_{i,t}$. According to when the value of a power plant ν_t is higher than the minimal costs $c_i'(0)$ of constructing the same power plant from scratch, power plants are built up to the pace at which the building costs equal the value of power plants, and the irreversibility constraint is not binding ($\xi_{i,t} = 0$):

$$\nu_t > c_i'(0) \iff {c_i}'(x_{i,t}) = \nu_t \iff x_{i,t} > 0 \tag{2.13}$$

For values ν_t lower than $c_i'(0)$, it would be desirable to deconstruct the power plants back into raw resources, but the irreversibility constraint prevents that. First order conditions also show that the value of capacity ν_t is linked to the shadow cost of the capacity constraint $\gamma_{i,t}$ by the following relation:

$$\gamma_{i,t} = (\delta + r) \, \nu_t - \dot{\nu}_t, \quad \forall t \tag{2.14}$$

This is a well-known equation in the theory of investment. It means that $\gamma_{i,t}$ is what Jorgenson (1967) calls the *implicit rental costs of capital*. It is the rental price that ensures agents are indifferent between buying capacity at ν_t and renting capacity at $\gamma_{i,t}$. As pointed by Jorgenson (1967), the relation expresses the absence of arbitrage opportunities between the two following strategies: (i) buy a power plant at t at a costs ν_t, rent it out during one period dt at the rental price $\gamma_{i,t}$, then sell the depreciated (δ) capacities at $t + dt$ at a price $\nu_t + \dot{\nu}_t dt$ or (ii) simply lend money at the interest rate r. In other words, the current price of capital, ν_t, comes from the rent derived from the capital today, $\gamma_{i,t}$, and from future price changes $\dot{\nu}_t$.

Combining (2.13) and (2.14), we find that when power plants are being built, the building costs and the rental costs of a given type of power plant are linked in a similar way:

$$x_{i,t} > 0 \iff \gamma_{i,t} = (\delta + r)\, c_i{}'(x_{i,t}) - \frac{d}{dt} c_i{}'(x_{i,t}) \tag{2.15}$$

This relation means that on the optimal path, there are no arbitrage opportunities between using a stock of money for building power plants in order to rent them, and simply lending money at the interest rate r.

In section 2.4, we show how integrating (2.15) yields an equation analogous to $c_i{}'(x_{i,t}) = \int e^{-(r+\delta)t} \gamma_{i,t}\, dt$: power plants are built up to the pace for which the construction cost equals the discounted sum of future rental revenues from the depreciating marginal capacity. Before that, the next subsection studies the capacity rents $\gamma_{i,t}$.

2.3 Electricity prices, Hotelling and capacity rents

We continue the resolution with the equilibrium conditions between Hotelling rents, capacity rents, and electricity prices at each point in time. When power plants are being used, the first-order conditions simplify to (see appendix):

$$c_i{}'(x_{i,t}) > 0 \iff u'_t = \gamma_{i,t} + \alpha_{i,t} + \mu_t\, F_i \tag{2.16}$$

On the left hand side, u'_t is the competitive electricity price — u'_t stands for $u'\left(\sum_i c_i{}'(x_{i,t})\right)$. On the right hand side, $\gamma_{i,t}$ is the capacity rent, $\alpha_{i,t}$ are the fuel costs, F_i the carbon intensity of technology i, and μ_t is the carbon price. Equation 2.16 implies that, if a technology is used at time t, the full costs of producing electricity with that technology must be equal to the electricity price.

In addition, the capacity rent $\gamma_{i,t}$, as the Lagrange multiplier associated with the capacity constraint, is null when capacity i is underused (equation 2.45 in the appendix):

$$c_i{}'(x_{i,t}) < k_t \implies \gamma_{i,t} = 0 \tag{2.17}$$

Taken together, the last two equations imply that (in general), at any time, only one type of power plant is used at full capacity. Indeed, if two technologies i and j are both used under full capacity at time t, then the costs of fuel and carbon for these two technologies are equal:

$$0 < c_i{}'(x_{i,t}) < k_t \;\&\; 0 < q_{j,t} < k_{j,t} \implies u_t' = \alpha_{i,t} + F_i\,\mu_t = \alpha_{j,t} + F_j\,\mu_t \tag{2.18}$$

The occurrence of such a situation requires a very specific set of parameters linking available coal resources, gas resources, and the carbon budget. As a consequence, we neglect this case for the rest of the paper.

The previous results suggest the following natural definitions, and an immediate proposition, both illustrated in Fig. 2.2:

Definition 1. *1. We call the sum of fuel prices and carbon prices of technology i:* $\alpha_{i,t} + F_i\,\mu_t$ variable production costs*.*

2. We call the used capacity with the highest variable production costs at time t the marginal power plant at time t*.*

Following these definitions, equation 2.16 allows to characterize the electricity price at each point in time t, contingent on the marginal power plant:

Proposition 1. *At each point in time t, the electricity price u_t' is given by the variable costs of the marginal power plant, and a capacity rent which is strictly positive only when capacities are fully used. In particular:*

1. If coal capacities are used at less than full capacity, the electricity price equals variable costs from coal generation:

$$0 < q_{h,t} < k_{h,t} \implies u_t' = \alpha_{h,t} + F_h\,\mu_t \tag{2.19}$$

2. *If gas capacities are used at less than full capacity, the electricity price equals variable costs from gas generation:*

$$0 < q_{\ell,t} < k_{\ell,t} \implies u'_t = \alpha_{\ell,t} + F_\ell \, \mu_t \tag{2.20}$$

3. *If all capacities are either used at full capacity or not used at all, rental costs adjust such that the production costs, including the rental costs of capacities, is equal across technologies.*

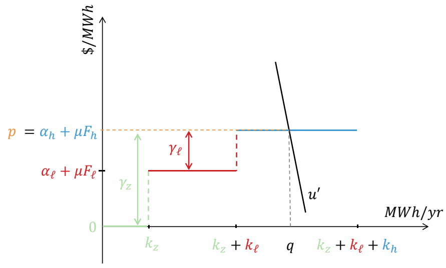
$$c_i{}'(x_{i,t}) = k_t \implies \quad \gamma_{i,t} > 0 \quad \textit{and} \quad u'_t = \gamma_{i,t} + \alpha_{i,t} + \mu_t \, F_i \tag{2.21}$$

Proof. Straightforward implication of equations (2.16),(2.17) and (2.18). □
□

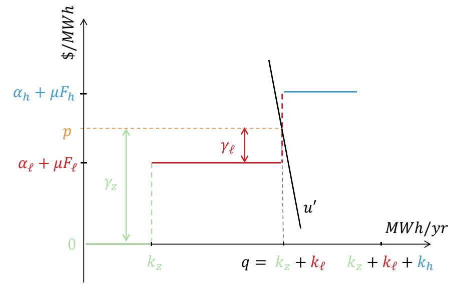
Fig. 2.1 and 2.2 illustrate this proposition. Fig. 2.1 shows the marginal costs of energy and the electricity price of electricity as a function of the installed capacity at time t, as well as the downward sloping electricity demand. Installed capacities are ranked along their *merit order*, that is according to variable production costs — again, excluding capacity rents. Price and total quantities are set where the demand function intersects the merit order curve. The various panels represent different phases in the transition, and different cases of Proposition 1.

Fig. 2.1 also illustrates how fully-used capacities receive a capacity rent γ_i. Capacity rents provide incentives to invest and increase infra-marginal capacity. They also allow the market to clear when marginal capacities are fully used (Fig. 2.1b and Fig. 2.1d), and finance the maintenance of renewable capacities when all production comes from renewable power (Fig. 2.1d). Positive capacity rents are possible even in the absence of market imperfections (other than the unrelated GHG externality) because adjustment costs prevent total capacities to adjust immediately to a point where capacity rents would be null. [11]

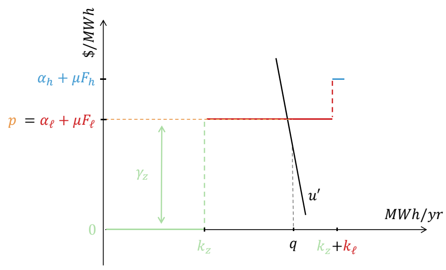
[11] It is well-known that infra-marginal capacity rents allow power producers to finance investment (e.g., **?**Boiteux, 1960; Biggar et Hesamzadeh, 2014). At the best of our knowledge, this paper is the first to propose that adjustment costs allow explicit (and parsimonious) modeling of the link between infra-marginal rents and investment decisions. Indeed, the most frequent practice to take into account the limited ability to switch quickly from high- to low-carbon capital is to use exogenous maximum investment speeds (see footnote 3 and Seebregts et al., 2002; Loulou, 2008; Wilson et al., 2013; Iyer et al., 2015; Vogt-Schilb et al., 2014a).



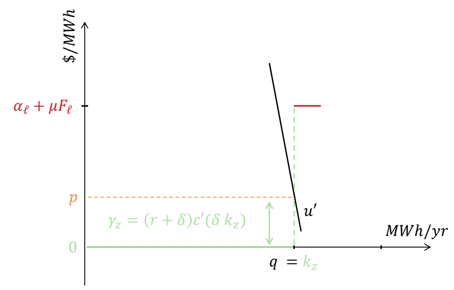
(a) A case where coal is the marginal power plant, and is used under full capacity



(b) A case where gas is the marginal power plant and is used at full capacity



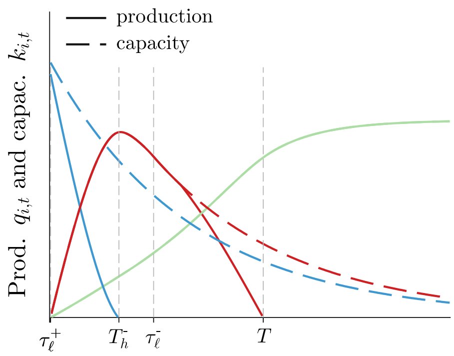
(c) A case where gas is the marginal power plant, and is used under full capacity



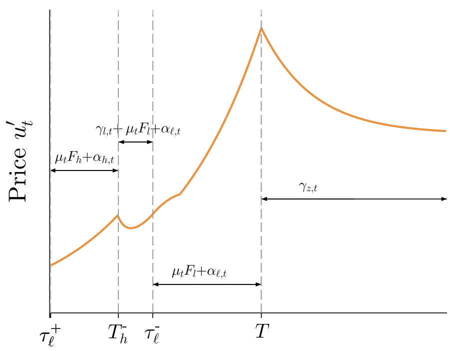
(d) The steady state, when all production comes from renewable power

Figure 2.1: Examples of the merit-order curve at different points of the transition from coal to gas and renewable power

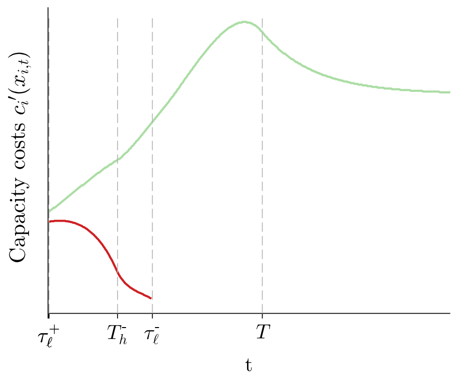
Note: The horizontal axis shows the installed capacity for renewable power (z), gas (ℓ) and coal (h) at one given point in time. The vertical axis shows the marginal costs and the price of electricity. The production technologies are ranked according to their *variable production costs*, excluding capacity rents (in other words, accounting only for the resource costs α_i plus the cost of emissions μF_i). The price p and quantity q are set by the intersection of the demand curve u' and the merit-order curve. Such intersection can lead to only one type of power plants to be used, but under full capacity: the marginal capacity. All technologies used at full capacity receive a capacity rent $\gamma_i = p - \alpha_i - \mu F_i$.



(a) Production and capacity



(b) Electricity price



(c) Marginal investment cost

Figure 2.2: Capacity, production, electricity price and investment in one possible transition from coal to gas and renewable power

As discussed in section 2.5, the ordering of investment in gas and renewable power may vary. Fig. 2.2 shows one particular situation where investment in both renewable and gas power start at the beginning of the time horizon. Fig. 2.2a plots capacity and production against time, while Fig. 2.2b shows the electricity price. In a first phase, coal is progressively replaced by both renewable and gas, coal capacity is underused and the price of electricity is determined by the variable cost of coal (as in Fig. 2.1a). During this phase, the electricity price increases, as the cost of coal and the cost of carbon emissions increase.

When coal is entirely phased, a phase follows during which renewable power progressively replaces gas. During this phase, gas is used at full capacity, and the electricity price includes a rent for gas capacity (as in Fig. 2.1b). Investment in renewable and gas power first increases both renewable and gas capacity, reducing capacity rents, and decreasing the price of electricity. At some point, future rents for gas plants become too low to make new gas capacities profitable, and investment in gas stops. During the later part of this second phase, total capacity decreases and electricity prices increase again. [12]

In a third phase, gas plants are used under full capacity, the price is set by the variable costs of gas, and the price increases over time (as in Fig. 2.1c). During the final phase, gas plants are entirely phased out, carbon-free capacity receives a decreasing rent (and the electricity price decreases) until the point where capacity rents compensate exactly depreciation of carbon-free capacity, and the system has reached a steady state (as in Fig. 2.1d).

2.4 Valuing investment in gas and renewable power plants

In this section, we study optimal investment decisions. As clarified in section 2.2, the anticipation of all future prices and resulting capacity rents $\gamma_{i,t}$ translates into a value ν_t for current capacity. If that value is higher than the cost of building new capacities $\nu_t > c_i'(0)$, investment in type capacity i is desirable (and undertaken by well-functioning markets facing the right carbon price).

The case of renewable power plants is the simplest one. Because

[12]Fig. 2.1b shows that when gas is used at full capacity, the increasing cost of carbon and gas fuel (which translates into an increasing height for the red rectangle) cannot be passed to the consumer through the electricity price; while the changes of wind and gas capacity (modifying the width of the green and red rectangles) do change capacity rents and resulting electricity prices.

they bare no variable costs, existing renewable power plants are always used and always receive a rent equal to the electricity price : $\gamma_{z,t} = u'_t$. The value of renewable power plants is the solution of the differential equation (2.14):

$$\nu_{z,t} = \int_t^{\infty} e^{-(r+\delta)(\theta-t)} u'_\theta \, d\theta, \quad \forall t \tag{2.22}$$

It is equal to the present value of all future revenues from selling the electricity (u'_θ) produced by the depreciated marginal unit of capacity ($e^{-(r+\delta)(t-\theta)}$). We denote the date when investment in renewable power starts by τ_z^+ ; following (2.13):

$$c'_z(x_{z,t}) = \int_t^{\infty} e^{-(r+\delta)(\theta-t)} u'_\theta \, d\theta, \quad \forall t \geq \tau_z^+ \tag{2.23}$$

Equation 2.23 says that when windmills are built, they are built up to the pace where the marginal costs of producing windmills equal their discounted future revenues.

The case of gas capacity is more complex. As we have shown in the previous subsection, gas capacity may be underused during the optimal transition from coal to gas and renewable power. We denote by T_γ the date when gas is underused. Gas capacities receive a rent only when they are fully used ($t > T_\gamma \implies \gamma_{\ell,t} = 0$), leading to the following value for gas capacities:

$$\nu_{\ell,t} = \int_t^{T_\gamma} e^{-(r+\delta)(\theta-t)} (u'_\theta - \mu_\theta \, F_\ell - \alpha_{\ell,\theta}) d\theta \tag{2.24}$$

The value of gas power plants is the discounted sum of the electricity price net of production costs over the period when gas power plants are used at full capacity. Investment in gas power plants is optimal when the value of gas plants exceeds the minimal value of producing a gas plant $\nu_{\ell,t} > c'_\ell(0)$. [13]

[13]Note that investment in gas stops at τ_ℓ^- when future revenues are lower than the minimal building cost, such that:

$$\int_{\tau_\ell^-}^{T_\gamma} e^{-(r+\delta)(\theta-\tau_\ell^-)} (u'_\theta - \mu_\theta \, F_i - \alpha_{i,\theta}) d\theta = c'_\ell(0) \tag{2.25}$$

Comparing equations 2.23 and 2.24 reveals that renewable power plants are more valuable than gas power plants:

$$\nu_{z,t} - \nu_{\ell,t} = \underbrace{\int_t^{T_\gamma} e^{-(r+\delta)(\theta-t)} \left(\mu_\theta\, F_\ell + \alpha_{\ell,\theta}\right) d\theta}_{\Delta\gamma} + \underbrace{c'_z(x_{z,T_\gamma}) e^{(r+\delta)(t-T_\gamma)}}_{\Delta\nu} \geq 0 \tag{2.26}$$

The difference in the values of renewable and gas power plants breaks down into:

- $\Delta\gamma$, the discounted value of emissions and fossil fuels that the marginal renewable capacity built at time t saves before τ_ℓ^-, when compared to a marginal gas capacity built at the same time; and

- $\Delta\nu$, the difference between the discounted values of the capacities at T_γ. Indeed, after T_γ, gas plants are underused and receive no rents, such that their value is null; while renewable power plants have a positive value $\nu_{z,t} = c'_z(x_{z,T_\gamma})$.

While the value of renewable plants are higher than the value of gas power plants, gas plants are cheaper to build than windmills. As a result, the optimal ordering of investment in both types of power plants is not trivial, as discussed in the next subsection.

2.5 Ordering investment in low- and zero-carbon capacity

Three dates are of particular importance to classify transition profiles from coal to gas and renewable power: the date τ_z^+ when investment in renewable starts, the date τ_ℓ^+ when investment in gas power plants starts and the date T_h^- when coal production is phased out.

In general, three given dates can be ordered in six different ways. Two cases ($T_h^- < \tau_z^+ \leq \tau_\ell^+$ and $T_h^- < \tau_\ell^+ \leq \tau_z^+$) are never optimal with standard utility functions, because they imply that coal is phased out before investment in renewable or gas have started, so that energy consumption tends to 0 when t tends to T_h^-. This leaves four relevant cases, as stated in the following proposition:

In particular, if $c'_\ell(0) = 0$ then $\tau_\ell^- = T_\gamma$ (this is the case in Fig. 2.2).

Proposition 2. *Depending on the parameters, investment phases may be ordered in three different ways:*

1. *Two successive transitions ($\tau_\ell^+ \leq T_h^- < \tau_z^+$). Gas first completely replaces coal, then renewable power replaces gas. In this case, investment in renewable power starts after coal is phased out, but before gas is phased out (Fig. 2.3a).*

2. *Gas and wind simultaneously replace coal, starting with investment in gas ($\tau_\ell^+ \leq \tau_z^+ \leq T_h^-$). In this case, investment in renewable starts before production from any fossil resources is phased-out (Fig. 2.3b).*

3. *Starting with investment in renewable power, either using some gas ($\tau_z^+ \leq \tau_\ell^+ \leq T_h^-$, as in Fig. 2.2) or without using any gas ($\tau_z^+ \leq T_h^- \leq \tau_\ell^+$, Fig. 2.3c).*

Proof. See text before the proposition. □ □

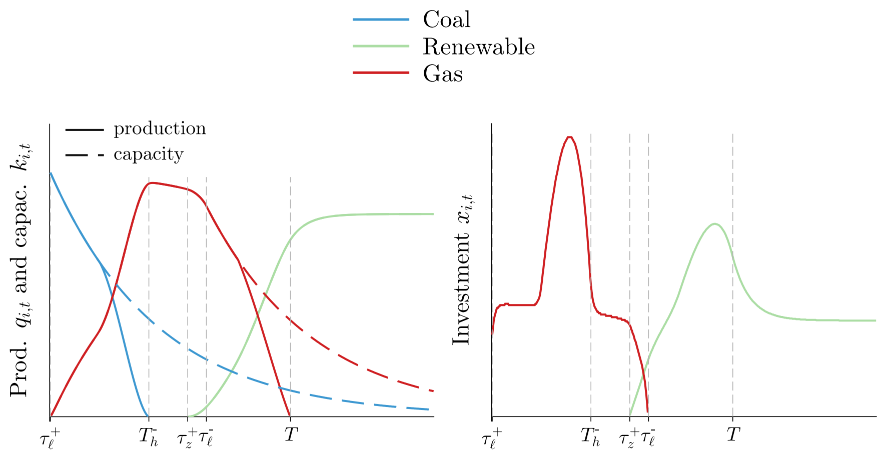
We use numerical simulations to investigate how the stringency of the carbon budget and the adjustment costs lead to different transitions profiles. To quantify the stringency of adjustment costs, we write the cost functions as:

$$c_i(x_{i,t}) = C_i \times \left((1 - A)\, x_{i,t} + \frac{1}{2} A x_{i,t}^2 \right) \tag{2.27}$$

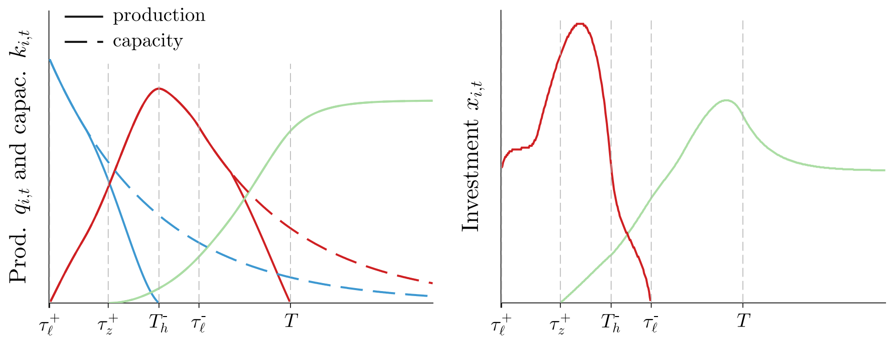
$$\implies c_i{}'(x_{i,t}) = C_i \times ((1 - A) + A x_{i,t}) \tag{2.28}$$

where $A \in (0, 1)$ is a measure of adjustment costs, which for simplicity is equal across technologies, and C_i is a scaling parameter ($C_z > C_\ell$ as renewable capacity is more expensive than gas capacity). When $A = 0$, i.e. marginal investment costs are constant, there are no adjustment costs, and optimal investment pathways may exhibit jumps. When $A = 1$, the full cost is purely quadratic, marginal costs are linear, capacity accumulated at very low speed is almost free ($\lim_{x_{i,t}\to 0; A=0}\ c_i{}'(x_{i,t}) = 0$), and the cost of new capacity doubles when the investment pace doubles. For intermediate value $A \in (0, 1)$, new capacity is always costly, and the marginal costs of new capacity increase with the pace of investment.

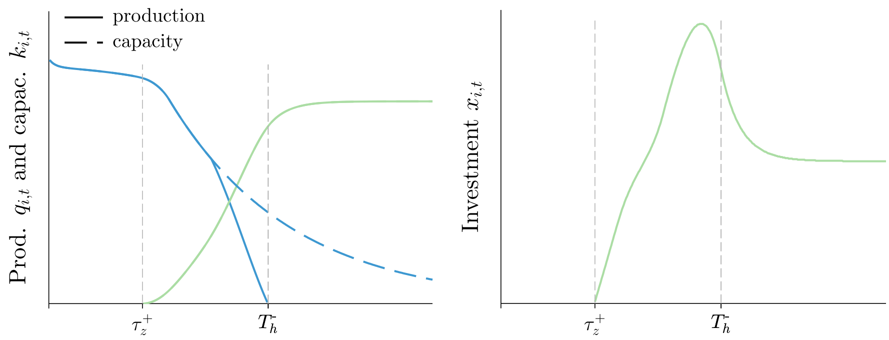
Results are displayed in Fig. 2.4. The first case discussed in Prop. 2 is similar to an Herfindahl sequence, where energy sources are used one after the other (Fig. 2.3a). The sensitivity analysis reveals that



(a) Two successive transitions



(b) Gas and wind simultaneously replace coal



(c) Wind alone replaces coal

Figure 2.3: Numerical simulations of three possible transition profiles.

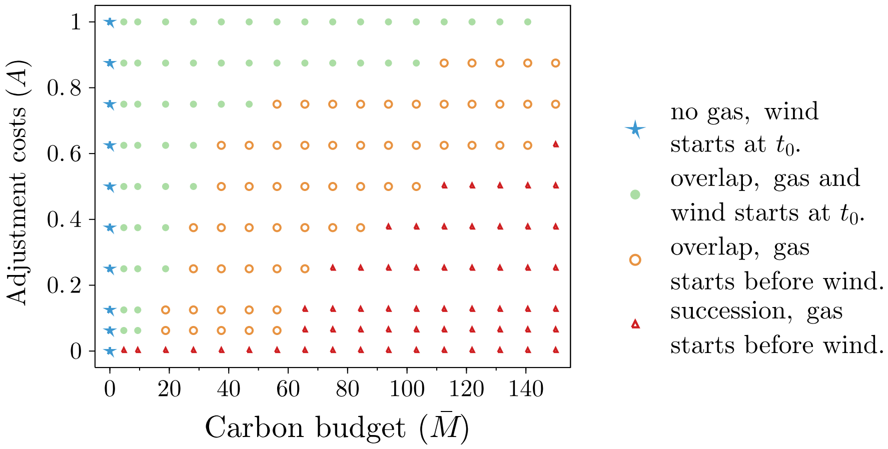


Figure 2.4: How transition profiles depend on the stringency of the carbon budget and the adjustment costs.

this case requires a large carbon budget—which "gives time" to switch entirely to gas before starting to invest in renewable power, and low adjustment costs—making it cheap to invest in each of the transitions (red triangles in Fig. 2.4). In the limiting case without adjustment costs, the optimal strategy is to replace all coal with gas overnight at a date $T_{h\ell} = T_h^- = \tau_\ell^+$, and then replace all gas with renewable at some later date $T_{\ell z} = T_\gamma = \tau_z^+$.

The second case happens with any non-zero carbon budget, provided adjustment costs are large enough, but not too large (orange circles in Fig. 2.4). In this case, renewable power enters early to smooth investment and reduce adjustment costs. In addition, transient investment in gas allows for reducing investment in expensive renewable power plants in the short term, moving some efforts to the medium term, when gas power is under-used and replaced by renewable power (Fig. 2.3b).

With even higher adjustment costs, it becomes even more profitable to smooth investment in renewable power, and investment in renewable power starts as soon as possible. In this case, investment in gas and wind start simultaneously at the beginning of the transition ($\tau_z^+ = \tau_\ell^+ = t_0 \leq T_h^-$, green dots in Fig. 2.4). This case corresponds to the third one in Prop. 2, as the transition begins with investment in renewable power. Finally, for very low carbon budgets, investment still starts with renewable power, but gas is not even used as intermediary technology

(Fig. 2.3c and blue stars in Fig. 2.4). [14]

3 Numerical application to the European electricity sector

3.1 Functional forms, data and calibration

We calibrate the model with raw data from the European power sector, as described in the European 2050 Energy Roadmap (EU, 2011). In this numerical application, efficient gas power plants (the low-carbon technology) and onshore wind (the zero-carbon technology) are used to phase out the existing polluting capacities represented by the average legacy thermal production mix (composed of coal, oil and gas Tab. 2.1).

We modify the model from section 1 to take into account that Europe is price-taker for fossil resources. We assume exogenous fossil fuel costs $\alpha_{i,t}$, calibrated from the European 2050 Roadmap — $\alpha_{h,t}$ is computed as the weighted average of the price of coal, gas and oil (Tab. 2.2). The new social planner program reads:

$$\max_{x_{i,t}, c_i'(x_{i,t})} \int_0^\infty e^{-rt} \left[u\left(\sum_i c_i'(x_{i,t}) \right) - \sum_i \left(c_i(x_{i,t}) + c_i'(x_{i,t})\alpha_{i,t} \right) \right] dt \tag{2.29}$$

$$\begin{aligned}
\text{s.t. } \dot{k}_{i,t} &= x_{i,t} - \delta k_t && (\nu_t)\\
q_{j,t} &\leq k_{j,t} && (\gamma_{i,t})\\
q_{j,t} &\geq 0 && (\lambda_{i,t})\\
x_{i,t} &\geq 0 && (\xi_{i,t})\\
\dot{m}_t &= \sum_i F_i\, q_{j,t} && (\mu_t)\\
m_t &\leq B && (\eta_t)
\end{aligned}$$

Problem 2.29 has the same first order conditions and economic interpretation as problem 2.11 exposed in section 1.

For the utility function, we start from a demand function calibrated

[14] In the limit case with no adjustment costs, and very low carbon budgets, switching overnight from coal to gas at $T_{h\ell}$ and then overnight to renewable at $T_{\ell z}$ would not be optimal, because the time span during which gas power plants would operate $T_{\ell z} - T_{h\ell}$ would be too short for the initial investment to be profitable. This case, mentioned for the sake of completeness, is not distinguishable from the case of a 0 carbon budget in Fig. 2.4.

Table 2.1: Technology sets considered in the numerical model

Set	Abbreviation	Composition
High carbon technology	Legacy	Average thermal production mix in 2008: 40% gas, 50% coal, 10% oil
Low carbon technology	Gas	Efficient gas
Zero carbon technology	Wind	Onshore wind

Source: ENERDATA (2012)

Table 2.2: Fuel price trajectories of the fossil technology sets in $/MWh

	2008	2025	2035	2050
Legacy	40	43	45	37
Gas	58	68	67	54

Source: EU (2011)

Table 2.3: Technology-specific data used in the numerical application

	Description	Unit	Legacy	Gas	Wind	Source
C_i^m	Nominal investment costs	$/kW	2 100	1 400	2 500	EU (2011); IEA (2010)
X_i	Average annual new capacity in Europe	GW/yr	4.2	11	10	ENERDATA (2012)
H_i	Average annual operating hours	h/yr	7 500	7 500	2 000	EU (2011); IEA (2010)
F_i	Carbon intensity	gCO_2/kWh	530	330	0	ENERDATA (2012); Trotignon et Delbosc (2008)

Table 2.4: General parameter values used in the numerical application

	Description	Unit	Value	Source
r	Discount rate	%/yr	5	
B	Carbon budget (central value)	$G\,tCO_2$	22	UE (2011)
D_0	Electricity demand in 2008	TWh/y	1 940	ENERDATA (2012); EU (2011)
G	Annual growth of demand	TWh/y	16.5	EU (2011)
P	Average electricity price in 2008	\$/MWh	90	Eurostat (2014)
e	Short term linear price elasticity of electricity demand	(TWh/y)/(\$/MWh)	0.1	Eurostat (2014)
δ	Depreciation rate	%/yr	3.33	IEA (2010)
A	Convexity parameter (central value)	·	1	

against D_t, the projected demand in the Roadmap. We assume this demand corresponds to a reference price P, taken as the average electricity price to households in all European countries $P = 90\$/\text{MWh}$ (Eurostat, 2014). We then assume a short-term linear elasticity $e = .1$, meaning that increases of 10% of the electricity price above this reference level would lead demand to be reduced by 1% compared to the reference demand D_t (Labandeira et al., 2012). The demand function reads:

$$q(p) = D_t - e \cdot (p - P) \tag{2.30}$$

Substituting the price p for $u_t'(q)$ yields:

$$u(q) = \left(P + \frac{D_t}{e}\right) q - \frac{q^2}{2e} \tag{2.31}$$

The reference electricity consumption point D_0 is calibrated to match the reference fossil energy production (from coal, oil and gas) in 2008, that is $D_0 = 1\,940\,\text{TWh/yr}$ (ENERDATA, 2012). The central scenario of the Roadmap envisages that electricity demand will increase by 700 TWh/yr between 2008 and 2050. We model this by a linear growth of $G = 16.5\,\text{TWh/yr}^2$:

$$D_t = D_0 + t \cdot G \tag{2.32}$$

To better fit the data, we express installed capacity k_t in peak capacity (GW), and production ${c_i}'(x_{i,t})$ in GWh/yr. Production is constrained by a maximum number of operating hours per year H_i (Tab. 2.3). For instance, a given windmill produces electricity only when it is windy, which happens only a given number of hours per year in expectation. We thus ignore *unpredicted* intermittency issues, which add a cost to renewable sources, and are a rationale to use back-up generation along with renewable power (Ambec et Crampes, 2012). [15]

The initial capacity of wind and gas are by assumption zero, and we calibrate the initial capacity of the legacy technology to match the level of capacity needed to produce the initial reference electricity con-

[15] Alternatively, our renewable technology may be interpreted as a mix of intermittent renewable and carbon-free back-up, as provided for instance, by large hydro, nuclear or biomass.

sumption point D_0 at the given capacity factor:

$$k_{z,0} = k_{l,0} = 0; \quad k_{h,0} = \frac{D_0}{H_h}$$

To calibrate the cost functions, we assume that when investment equals the actual average annual investment flow in Europe between 2009 and 2011 (X_i), the marginal investment cost C_i^m is equal to the OECD average value for 2010 (Tab. 2.3). We thus re-write the cost function used in the previous section as:

$$c_i(x_{i,t}) = C_i^m \cdot X_i \cdot \left((1 - A) \frac{x_{i,t}}{X_i} + \frac{A}{2} \left(\frac{x_{i,t}}{X_i} \right)^2 \right) \tag{2.33}$$

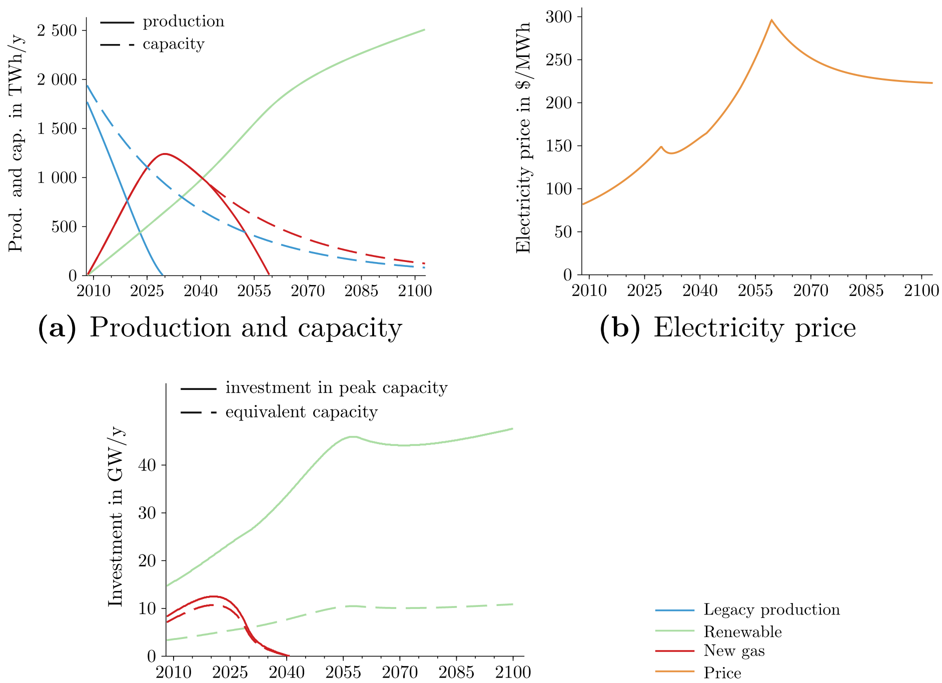
$$\Longrightarrow c_i'(X_i) = C_i^m \tag{2.34}$$

According to Trotignon et Delbosc (2008), emission allowances allocated to the power sector in 2008 amounted to $e_{ref,t} = 1.03\,\mathrm{GtCO_2/yr}$, leading to a reference carbon intensity of $F_h = 530\ \mathrm{tCO_2/GWh}$. A linear decrease of these emissions until 2050, as planned in the Roadmap, yields a carbon budget of $B = 22\,\mathrm{GtCO_2}$. (A sensitivity analysis on B is performed later.) The carbon intensity of gas is taken to be equal to $F_l = 330\ \mathrm{tCO_2/GWh}$.

We use $r = 5$ %/yr for the social discount rate. We assume for simplicity that all technologies have the same depreciation rate δ, calibrated as $\delta = 1/\text{lifetime}$ assuming a lifetime of 30 years (IEA, 2010).

3.2 Results

Fig. 2.5 shows production, investment and the electricity price obtained in the numerical application. For the carbon budget to be consistent with the roadmap, the social planner does not invest in the legacy capacity. Moreover, existing legacy plants start being decommissioned as soon as the climate policy is implemented (Fig. 2.5a). In this simulation, legacy fossil-fueled plants are entirely phased out in 2028. With our technology assumptions, the carbon budget is slightly too loose to justify a complete decarbonization by 2050, as it is the European Commission's objective; production from fossil fuel is phased out by



(a) Production and capacity

(b) Electricity price

(c) Investment

Figure 2.5: Numerical application to the European electricity sector

2059 instead.[16] The carbon price consistent with the carbon budget is 108 \$/tCO_2.[17] Electricity prices start at 90\$/MWh (close to the actual average EU level), increase with the carbon price to 300 \$/MWh by the end of the transition in 2059, and decrease again to reach a plateau around 220 \$/MWh by the end of the century.

Investment in renewable power starts as soon as possible (Fig. 2.5c), and grows over time, until all production is generated by renewable power plants (Fig. 2.5a). Optimal investment in renewable rises from 15 to 18 GW/yr between 2008 and 2013. These figures are close to actual numbers, as investment in renewable capacity in Europe fluctuated between 15 to 34 GW/yr during this same period (EWEA, 2014).[18]

Investment in new gas plants also start as soon as possible, smoothing the need for more expensive investment in renewable in the short term (Fig. 2.5c). But new gas plants play a transient role. In 2040, investment in gas stops and gas capacities start being underused, allowing gas to be replaced faster by renewable power. In this simulation, up to 80 GW of gas power plants (or the capacity to produce 600 TWh/y) are underused during the simulation.

We perform various sensitivity analyses to investigate under which conditions it would be optimal to wait before building renewable power in Europe. A first one varying adjustment costs A and the carbon budget B reveal that for any carbon budget lower than 45 GtCO_2 (twice the budget implied in the Roadmap), and for any adjustment costs, it is optimal to start building renewable power as soon as possible.

We then perform another sensitivity analysis, holding the carbon budget constant and varying adjustment costs and nominal investment costs for renewable power (Fig. 2.6). For high adjustment costs ($A > 0.5$), it is optimal to start with renewable power even if investment costs were as high as 10\$/W (four times our estimation of actual costs). For low adjustment costs ($A = .125$), it is optimal to delay investment in clean electricity if costs are higher than 4\$/W, that is 60% more expensive than our reference calibration. Finally, if adjust-

[16] Note that we ignored technical progress reducing the cost of renewable energy in the future, which could be a rationale to accelerate decarbonization.

[17] This is much higher than the current carbon price in the EU-ETS. Note that the European governments currently rely on other policies — feed-in-tariffs, mandates and auctioned pilot projects — to encourage investment in renewable power.

[18] All these figures are expressed in peak capacity; Fig. 2.5c also reports investment in equivalent capacity, taking into account that renewable power can be used less hours per year.

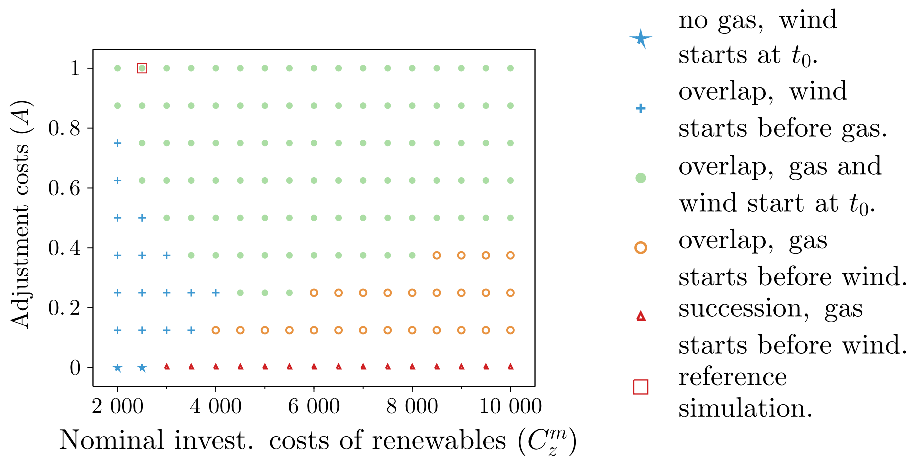


Figure 2.6: Transition types for different values of the cost of renewables and the adjustment costs.

ment costs are entirely absent, the optimal strategy is to first replace existing capacity with gas, and only to later replace all gas power with renewable power overnight.

4 Conclusion

Our results should be interpreted cautiously, as our analysis makes several simplifications. Among them, we did not account for knowledge accumulation and directed technical change, which have been found to play a key role in the optimal transition from fossil to renewable energy (Tahvonen et Salo, 2001; Acemoglu et al., 2012; André et Smulders, 2014; Gerlagh et al., 2014). Knowledge spillovers would tend to increase the short-term gap between optimal investment in renewable and gas energy (Rosendahl, 2004b; Bramoullé et Olson, 2005; del Rio Gonzalez, 2008), adding to the effect of adjustment costs studied here.

We also disregarded uncertainty, known to play a key role in optimal accumulation of capital (Pindyck, 1991), optimal emission reduction pathways (Ha-Duong et al., 1997), and optimal extraction of several energy sources (Gaudet et Lasserre, 2011). While it is well known that uncertainty provides a strong rationale for avoiding irreversible activities, the net effect of uncertainty is not trivial in our setting. Indeed, extracting exhaustible resources, releasing long-lived GHG in the atmosphere, investing in carbon-intensive power plants, and investing in expensive renewable capacities are all irreversible activities. Moreover, in the presence of adjustment costs, waiting makes subsequent investment more expensive. We leave the question of uncertainty for further research.

Another limitation is that, we did not explicitly model the intermittency of renewable sources, which may require to keep flexible gas turbines (or other flexible but carbon-free options such as large hydro or biomass-fueled plants) in operation. Finally, we disregarded the possibility to retrofit existing plants (notably with carbon capture and storage), and the possibility to use cleaner fuels (in particular derived from biomass) in existing power plants.

Notwithstanding these limitations, our parsimonious model suggests that capacity constraints and adjustment costs play an essential role in the transition from coal to gas and renewable energy. Our results stand in contrast to those derived from "pure" Hotelling models, where capital accumulation and adjustment costs are neglected (or that focus on generic capital that can be fueled with any type of energy). In particular, we find that it makes sense to start investment in, and usage of, renewable energy before coal and gas resources are phased out, even if renewable energy first appears to be more expensive.

We also find that the transition to carbon-free energy may benefit from temporary investment in intermediate technologies such as gas, to decrease (but not necessarily cancel) the need for costlier renewables in the short term. The resulting plants would however need to be subsequently decommissioned, to give room to more carbon-free energy in the medium term.

Our results shed light on technical choices (e.g., investors can consider gas plants with shorter scheduled lifetimes or an option to retrofit) as well as policy decisions (when setting milestones for carbon-free power). Finally, while we used power generation as an obvious illustration, our paper more broadly informs on the ordering and assessment of investment in polluting fossil-fueled and clean capital. Its results could be extended to other capital- and energy-intensive sectors, such as buildings and transportation.

Appendices

A Efficiency conditions

The Hamiltonian associated with Problem 2.11 reads:

$$\begin{aligned}\mathcal{H} = e^{-rt} \Bigg[& u\left(\sum_i {c_i}'(x_{i,t})\right) - \sum_i c_i(x_{i,t}) - \sum_i \nu_t\,(\delta\, k_t - x_{i,t}) \\ & - \mu_t \sum_i F_i\, q_{j,t} - \eta_t\,(m_t - B) - \sum_i (\alpha_{i,t}\, {c_i}'(x_{i,t}) - \beta_{i,t}\, S_{i,t}) \\ & - \sum_i \gamma_{i,t}\,(q_{j,t} - k_{j,t}) + \sum_i \lambda_{i,t}\, q_{j,t} + \sum_i \xi_{i,t}\, x_{i,t} \Bigg]\end{aligned} \tag{2.35}$$

The first-order conditions are:

$$\frac{\partial \mathcal{H}}{\partial x_i} = 0 \iff {c_i}'(x_{i,t}) = \nu_t + \xi_{i,t} \tag{2.36}$$

$$\frac{\partial \mathcal{H}}{\partial q_i} = 0 \iff \lambda_{i,t} - \mu_t R_i - \alpha_{i,t} + u_t' = \gamma_{i,t} \tag{2.37}$$

$$\frac{\partial \mathcal{H}}{\partial k_i} = \frac{-d\,(e^{-rt}\nu_t)}{dt} \iff (\delta + r)\,\nu_t - \dot{\nu}_t = \gamma_{i,t} \tag{2.38}$$

$$\frac{\partial \mathcal{H}}{\partial m_t} = \frac{-d\,(e^{-rt}\mu_t)}{dt} \iff \dot{\mu}_t - r\,\mu_t = -\eta_t \tag{2.39}$$

$$\frac{\partial \mathcal{H}}{\partial S_i} = \frac{-d\,(e^{-rt}\alpha_{i,t})}{dt} \iff \dot{\alpha}_i - r\,\alpha_{i,t} = -\beta_{i,t} \tag{2.40}$$

The complementary slackness conditions are:

$$\forall i,t,\quad \xi_{i,t} \geq 0,\quad x_{i,t} \geq 0 \quad \text{and} \quad \xi_{i,t}\, x_{i,t} = 0 \tag{2.41}$$

$$\forall i,t,\quad \lambda_{i,t} \geq 0,\quad {c_i}'(x_{i,t}) \geq 0 \quad \text{and} \quad \lambda_{i,t}\, {c_i}'(x_{i,t}) = 0 \tag{2.42}$$

$$\forall i,t,\quad \eta_t \geq 0,\quad B - m_t \geq 0 \quad \text{and} \quad \eta_t\ (B - m_t) = 0 \tag{2.43}$$

$$\forall i,t,\quad \beta_{i,t} \geq 0,\quad S_{i,t} \geq 0 \quad \text{and} \quad \beta_{i,t}\, S_{i,t} = 0 \tag{2.44}$$

$$\forall i,t,\quad \gamma_{i,t} \geq 0,\quad k_t - {c_i}'(x_{i,t}) \geq 0 \quad \text{and} \quad \gamma_{i,t}\ (k_t - {c_i}'(x_{i,t})) = 0 \tag{2.45}$$

The transversality condition is replaced by the terminal condition that at some point the atmospheric carbon reaches its ceiling (2.8).

B Scarcity rents of the exhaustible resources and the carbon budget

From (2.43) and (2.44), we see that while the carbon budget and the resource stocks are not exhausted, their non-negativity dual variable η_t and $\beta_{i,t}$ are zero. From (2.39) (2.40), we then get the classic Hotelling rule:

$$\alpha_{h,t} = \alpha_h \, e^{rt}$$
$$\alpha_{\ell,t} = \alpha_\ell \, e^{rt}$$
$$\mu_t = \mu e^{rt}$$

Table 2.5: Variables and parameters notations used in the model.

	Description	Dimension
i	technology index	
h	coal (high-carbon technology,h)	
l	gas (low-carbon technology, ℓ)	
z	renewables (zero-carbon technology, z)	
k_t	capacity of technology i at time t	GW
${c_i}'(x_{i,t})$	production with technology i at time t	GW
$x_{i,t}$	physical investment in technology i at time t	GW/yr
$c_i(x_{i,t})$	cost of investment in technology i at time t	\$/yr
ν_t	shadow price of capacity k_t	\$/GW
μ_t	shadow cost of emissions (carbon price)	\$/ tCO_2
$\alpha_{i,t}$	shadow cost of resource used by technology i (fuel price)	\$/GWh
$\gamma_{i,t}$	shadow rental cost of existing capacity i	\$/(GW$\cdot$ yr)
u'_t	shadow electricity price (or willingness to pay)	\$/GWh
m_t	stock of atmospheric carbon	tCO_2
δ	depreciation rate	yr^{-1}
r	discount rate	yr^{-1}
F_i	emission rate of technology i	tCO_2/GWh
D_t	demand level at time t	GW
B	carbon budget	tCO_2
$u\left(\sum_i {c_i}'(x_{i,t})\right)$	consumer utility	\$/yr

3

Pathways toward Zero-Carbon Electricity Required for Climate Stabilization

POWER generation plays an important role in global warming, for at least two reasons. First, it is responsible for a large share of anthropogenic greenhouse gas (GHG) emissions: today's electricity accounts for 12 $GtCO_2$/yr, about 28% of total annual greenhouse gas emissions. Reducing the carbon content of electricity would thus decrease significantly global GHG emissions. Second, electricity can be used as a substitute for carbon-intensive fossil fuels in many cases. For instance, today's road transportation and housing sectors account together for about 16% of total emissions; and industrial energy consumption, mainly used to produce heat or motion, accounts for an additional 18% (IEA, 2012; WRI, 2015). Technologies such as electric vehicles, heat pumps, electric furnaces, industrial motors and other electric equipment can in part replace fossil-fuel based counterparts in these sectors, reducing indirectly GHG emissions.

A well-established result from integrated assessment models (IAM) is that both *decarbonization* of electricity supply and *electrification* of the energy system play a decisive role in reaching climate stabilization (e.g., Luderer et al., 2012; Sugiyama, 2012; Williams et al., 2012; IEA, 2014a; IPCC, 2014b; Krey et al., 2014; McCollum et al., 2014; Sachs et al., 2014).[1] Indeed, stabilizing climate change to *any* level (e.g. 2, 3 or 4°C) requires reducing global emissions to near-zero levels (Collins et al., 2013; IPCC, 2013). Moreover, switching from fossil fuel to low-carbon electricity is one of the only technical options to drastically reduce GHG emissions in energy-intensive sectors such as industry, transportation and buildings.

Despite this consensus and its importance to inform the policy debate, cost-effective pathways of the future carbon content of electricity are not available to decision-makers, researchers in other disciplines, or the general public — in particular, none of the above-mentioned studies provides any pathway of the carbon content of electricity under climate stabilization targets. To fill this gap, we compute and report the carbon content of electricity in a set of existing prospective scenarios.

We focus on a set of 55 pathways generated with 10 different integrated assessment models (IAM) for the purpose of a recent IAM comparison study: AMPERE (Riahi et al., 2015).[2] IAMs compute cost-effective pathways of the socio-economic and energy systems under the constraint set by climate targets. They factor in a wide range of parameters, such as long-term demographic evolution; availability of natural resources; countries' participation to emission-reduction efforts. Technology costs and maximum penetration rates, in particular, are calibrated using a mix of historical uptake rates and assumptions on learning by doing and autonomous technical progress (Wilson et al., 2013; Iyer et al., 2015). IAMs are regularly peer-reviewed in comparison exercises (Clarke et al., 2009; van Vuuren et al., 2009; Edenhofer et al., 2010; Kriegler et al., 2015, 2014) and occasionally evaluated against historical data (Guivarch et al., 2009; Wilson et al., 2013).

Unsurprisingly, the pathways of the carbon content of electricity from AMPERE confirm the above-mentioned consensus. Specifically, the pathways show that (1) near-zero-carbon electricity is necessary

[1]These and other studies offer in-depth analysis of the interlinked dynamics of electrification and decarbonization of electricity, and cover topics out of the scope of this paper, such as economic implications and the role of different technologies to produce zero-carbon electricity.

[2]We chose this study as it is freely available online (IIASA, 2014), other recent studies such as EMF27 (Kriegler et al., 2014) are of similar scope, use a broader variety of models and assumptions, and reach qualitatively and quantitatively similar results, but are unfortunately not publicly available online at the moment.

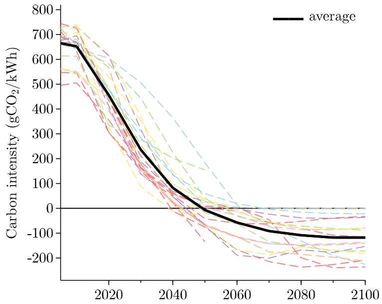
to reach concentrations consistent with global warming anywhere from 2°C to 3°C; (2) near-zero-carbon electricity can be achieved even if some of the key low-carbon technologies (nuclear, carbon capture and storage, or renewable power) turn out to be unavailable; and (3) near-zero-carbon electricity can and should occur in every major country or region of the world.

We report pathways at the global level and the country/region level for China, the EU, India and the US, under a variety of assumptions concerning the state of technology and long-term climate targets. These pathways may be useful to planners and policymakers designing climate mitigation strategies. First, they provide a reference on the speed at which decarbonization of the power sector should happen to meet a given climate target in a cost-effective way. They may thus be used to benchmark existing milestones, such as the ones proposed by the European Commission's energy roadmap (UE, 2011) and the Clean Power Plan currently under discussion in the US; or inform new measures in other countries or jurisdictions.

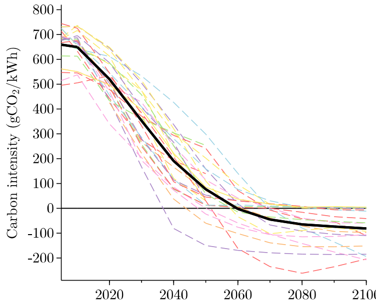
Second, such pathways of the carbon content of electricity are useful to assess the desirability of specific electrification technologies. Indeed, existing studies have focused on the impact of electrification on *today*'s GHG emissions, and concluded that it depends on the carbon intensity of power generation at the specific location where it takes place. For instance, electric vehicles may emit more GHG than conventional vehicles if they are charged in places where or at time of the days when electricity is produced from coal (Sioshansi et Denholm, 2009; Hawkins et al., 2012a,b; Richardson, 2013; Graff Zivin et al., 2014).[3] However, since climate stabilization eventually requires near-zero carbon electricity, the relevant question for policymakers is not whether to electrify, but when to do it. The pathways reported make it possible to investigate this question, using what Hertwich et al. (2014) recently called an *integrated life cycle analysis*.[4]

[3]Such studies have been interpreted as showing that electrification is to be avoided (e.g., BBC, 2012). Similar results have been reported by Thomson et al. (2000) on industrial electric furnaces, and Gustavsson et Joelsson (2010), Zabalza Bribián et al. (2009) and Ramesh et al. (2010) on buildings.

[4]As mentioned before, IAMs are sometimes used to assess optimal electrification of the economy. The pathways provided here can nonetheless be used by scholars outside the IAM community, for instance to evaluate the impact on GHG emissions of a technology or industrial process too specific to be explicitly represented in an IAM.



(a) 450 ppm — all carbon-free technologies



(b) 550 ppm — all carbon-free technologies

Figure 3.1: Carbon content of electricity at the global scale in two scenarios: (a) stringent GHG concentration target (consistent with 2°C); (b) less stringent GHG concentration target (consistent with 3°C). Each thin line corresponds to the pathway simulated by one integrated assessment model (the reported carbon intensity for 2005 and 2010 varies among IAMs because they use different scopes and sources of historical data for calibration). In both cases, bio-energy with carbon capture and storage (BECCS) allows to reduce the carbon content of electricity to below-zero levels by the end of the century.

The remainder of the paper is structured as follows. Section 1 reports pathways of the carbon content of electricity in the most technology-optimistic scenarios, where bio-energy combined with carbon capture and storage (CCS) allows for producing electricity with negative carbon emissions. Section 2 reports pathways in scenarios where either (i) both nuclear and CCS or (ii) renewable power are constrained. In both cases, the carbon content of electricity still decreases to near-zero levels. Section 3 and B detail pathways at the country/region level, for China, the EU, India and the US. They illustrate that the decrease to near-zero level can happen in every region of the world under a wide range of assumptions concerning technology availability, and is part of cost-effective strategies toward a range of different climate targets. Section 4 concludes.

1 Biomass combined with CCS could provide electricty with negative carbon content

During AMPERE, IAMs were run under the constraint that final GHG atmospheric concentration should not exceed 450 ppm CO_2-eq —

Meinshausen et al. (2009b) estimate such concentration leads to 63-92% probability of remaining below +2°C by 2100. Fig. 3.1a presents the projected carbon intensity of the global electricity generation in this scenario. It shows that all models project a drastic decrease in carbon intensity by the end of the century.

Most trajectories in this scenario even fall below zero-carbon electricity. Indeed, this scenario assumes the technologies able to generate low-carbon electricity are widely available — these technologies include mainly wind, solar, hydro, biomass, nuclear and carbon capture and storage (Smith et al., 2009). Among them, bio-energy with carbon capture and storage (BECCS), the burning of biomass in power plants associated to the long-term storage of resulting CO_2, allows to produce electricity with negative net GHG emissions (Tavoni et Socolow, 2013; Kriegler et al., 2014).[5] When BECCS is available, the least-cost strategy to achieve global carbon neutrality is to produce negative-emission electricity and offset emissions from sectors of the economy that are more difficult to decarbonize.[6]

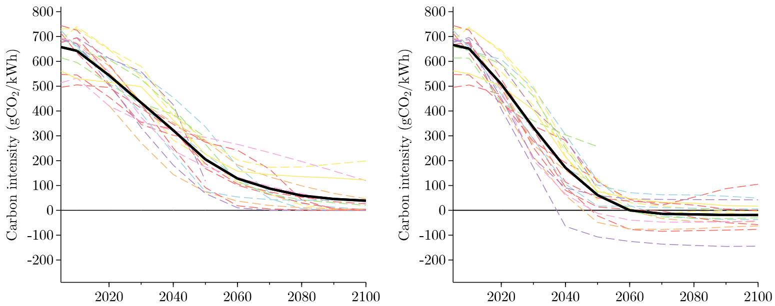
However, stabilizing GHG concentration around 450 ppm would require a fast intergovernmental coordination that may be difficult to achieve in time (Guivarch et Hallegatte, 2013; Stocker, 2013; Luderer et al., 2013b). AMPERE considered the effect of a less stringent concentration target: 550 ppm CO_2-eq — generally admitted to be consistent with a 3°C warming, and still 15–51% probability of remaining below 2°C according to Meinshausen et al. (2009b). If low-carbon technologies are still assumed to be widely available, pathways to this easier climate target also entail a decrease of the global carbon intensity to negative levels (Fig. 3.1b).

2 Near-zero-carbon electricity does not require all carbon-free technologies to be available

A third scenario in AMPERE sets a 550 ppmCO_2-eq stabilization target and assumes no further deployment of nuclear power after existing plants are decommissioned (for instance for social acceptability reasons) and assuming CCS never reaches market deployment. The

[5] "Plants" extract carbon dioxide from the atmosphere as they grow.

[6] However, the large-scale feasibility and desirability of BECCs is controversial, given their potential impact on land use, food production, freshwater availability, and the uncertain availability of suitable geological storage sites — see Guivarch et Hallegatte (2013) for an overview.



(a) 550 ppm — No nuclear, no CCS

(b) 550 ppm — Low renewable

Figure 3.2: Decarbonization of global electricity in two 550 ppm scenarios (consistent with 3°C): (a) without new nuclear or carbon capture; (b) with low potential for renewable power. In both cases, the carbon content of electricity is reduced to near-zero levels by the end of the century.

decrease in carbon intensity of electricity holds under these assumptions (Fig. 3.2a). The trajectories in this sample exhibit an average of more than 95% reduction in carbon intensity, reaching less than 25 gCO_2/kWh by 2100, while the most conservative pathway falls below 75 gCO_2/kWh.

Even in this scenario, decarbonization of power supply is sufficient to justify electrification. For instance, a conservative estimate of electric vehicles' (EV) consumption is 25 kWh/100km from the power plant to the wheel, that is accounting for losses when transmitting electricity over long distances and charging the battery.[7] In this case, electric vehicles, or hybrid vehicles running on electricity, would emit between 0 and 19 gCO_2/km by 2100. For comparison, the European target for new passenger vehicles sold in 2015 is 130 gCO_2/km on average, and the proposed objective for vehicles sold in 2021 is 95 gCO_2/km (ICCT, 2014).

AMPERE also explored scenarios where CCS and nuclear are widely available, but biomass, wind and photovoltaic power are constrained. Fig. 3.2b reports the pathways of the carbon content of electricity in this case — they can still decrease to near-zero or negative levels by

[7] For instance, today's most sold electric car, the Nissan Leaf is rated between 18 and 21kWh/100km (battery to the wheel) by the US Environmental Protection Agency; and 20% is an accepted upper bound for transmission, distribution, and recharging losses.

the end of the century.

3 Every major country or region of the world can and should decarbonize its electricity

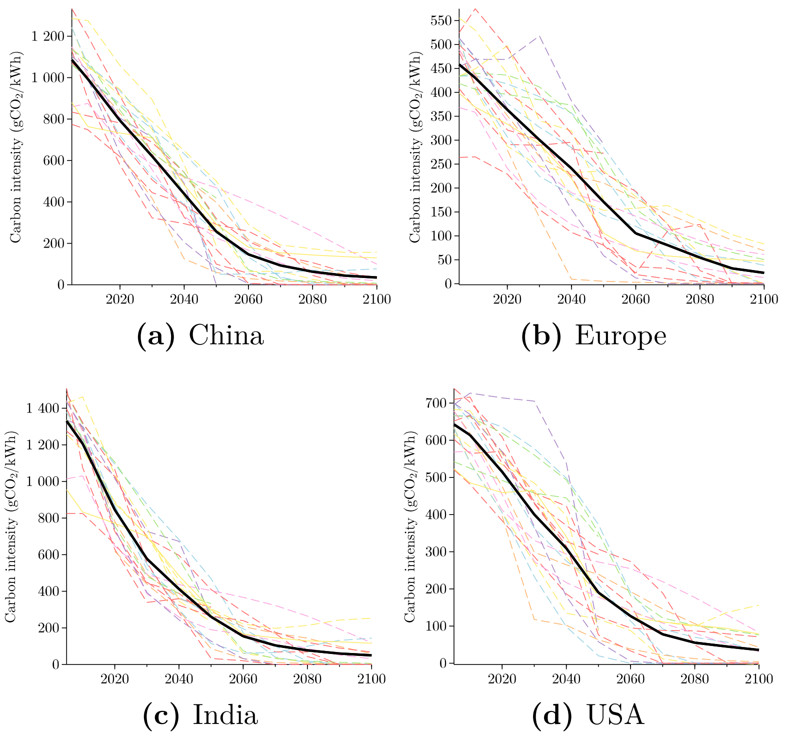


Figure 3.3: Carbon intensity in China, Europe, India and the US in AMPERE's 550 ppm (consistent with +3°C), technology-pessimistic (no nuclear, no CCS) scenario.

Finally, according to AMPERE, the decrease in the carbon content of electricity is feasible in every region of the world. Fig. 3.3 reports the pathways towards carbon free electricity as simulated in AMPERE for China and India, two countries with high initial emissions from power generation, and for the EU and US, where electricity is less carbon-intensive. We consider the less favorable scenario both in terms of the concentration target (550 ppm) and in terms of technology availability (no replacement of nuclear capacities and no CCS allowed) — detailed pathways for these regions with different technology portfolios are displayed in the appendix (Fig. 3.4, Fig. 3.6, Fig. 3.7, and Fig. 3.5). In every region, the average carbon intensity decreases steadily during the 21st century, and falls below 100 gCO2/kWh in 2100 in every simulation.

These figures suggest that electrification is an effective option to reduce long-term emissions in every region. In other words, the policy-relevant question is not whether to electrify, but when to do it. For instance, indirect emissions from driving an electric vehicle would reach 100 gCO_2/km between 2030-2060 in China, 2010-2030 in Europe, 2030-2055 in India and 2020-2050 in the US; and would drop below 50 gCO_2/km between 2045-2065 in China, 2045-2060 in Europe, 2050-2070 in India and 2035-2060 in the US.

4 Conclusion

The work reported here has several limitations. We only analyzed scenarios where all countries participate in climate policies. In regions that do not participate or delay their participation in climate policies, the reduction in carbon intensity of power generation would not necessarily happen, or would be delayed (Kriegler et al., 2015). Also, our analysis may overestimate the speed and/or potential of carbon intensity reduction in power generation. Indeed, IAMs may imperfectly represent real-world barriers that may hinder power generation decarbonization. A further discusses these limitations. Finally, the IAM comparison studied here does not investigate the consequences of simultaneous shortage of all the key low-carbon power generation technologies — CCS, nuclear, biomass and intermittent renewable.[8] In that case, stabilizing the climate would be made much more difficult, and would require a drastic reduction in global energy consumption.

The pathways towards clean electricity reported here should be interpreted cautiously. In particular, they do not entail any normative prescription of the level of efforts that any specific country should affect to climate change mitigation. What they show is a consensus among state-of-the-art integrated assessment models: cost-effective climate stabilization requires near-zero carbon electricity in every major country/region of the world. This very robust finding is a technical one, which disregards any consideration of the burden sharing of emission reductions: independently of who is or should be paying for it, the

[8]During AMPERE, IAMs explored the consequences of limited availability of renewable, limited availability of nuclear, and limited availability of CCS *separately* (as reported in B); in all these cases, the carbon intensity still decreases drastically in every region, sometimes to below-zero levels.

cheapest strategy to achieve climate stabilization includes decarbonization of the power supply.

The pathways of the carbon content of electricity that we report can be used outside the community of integrated assessment, for instance when assessing the relevance of electric vehicles as a means to reduce greenhouse gas emissions; or to benchmark policies aiming at reducing carbon emissions from power plants. Further work could report pathways for other countries or regions of the world, and extend this approach to sectors other than power supply.

Appendices

A Methods

Data

We reanalyzed a set of 55 IAM pathways from AMPERE, a study for which CO_2 emissions for electricity are reported separately, thus allowing to recover the projected carbon intensity at each point (2005, 2010 and then every 10 years up to 2100).

We retain *final energy* as our measure of electricity production, that is, the total electric energy consumed by end-users, excluding that used by the power supply sector itself for transformation, transportation and distribution (including these losses would result in lower carbon intensities). As electricity-related emissions at a given point in time are readily available in our sample, computing cumulative emissions is straightforward.

Limitations

The limitations in our analysis are of two kinds. First, we restricted our study to a subset of IAM trajectories by selecting only results reported in a recent model comparison study. This may introduce a selection bias. Second, IAMs may imperfectly represent real-life barriers to power generation decarbonization. We may therefore overestimate the speed and/or potential of power generation carbon intensity reductions.

Bias

We restricted our study to the results of a recent IAM comparison exercise, AMPERE, because the data are available online.

We are not aware of any published scenario that would reach a low or moderate atmospheric concentration target without featuring a decreasing carbon-intensity trajectory similar to the consensus highlighted here. However, reducing the study sample can always introduce biases. In particular, the studies presented here do not explore the case where all renewable energies, carbon capture and storage, nuclear and bio-energies turn out not to be widely available.

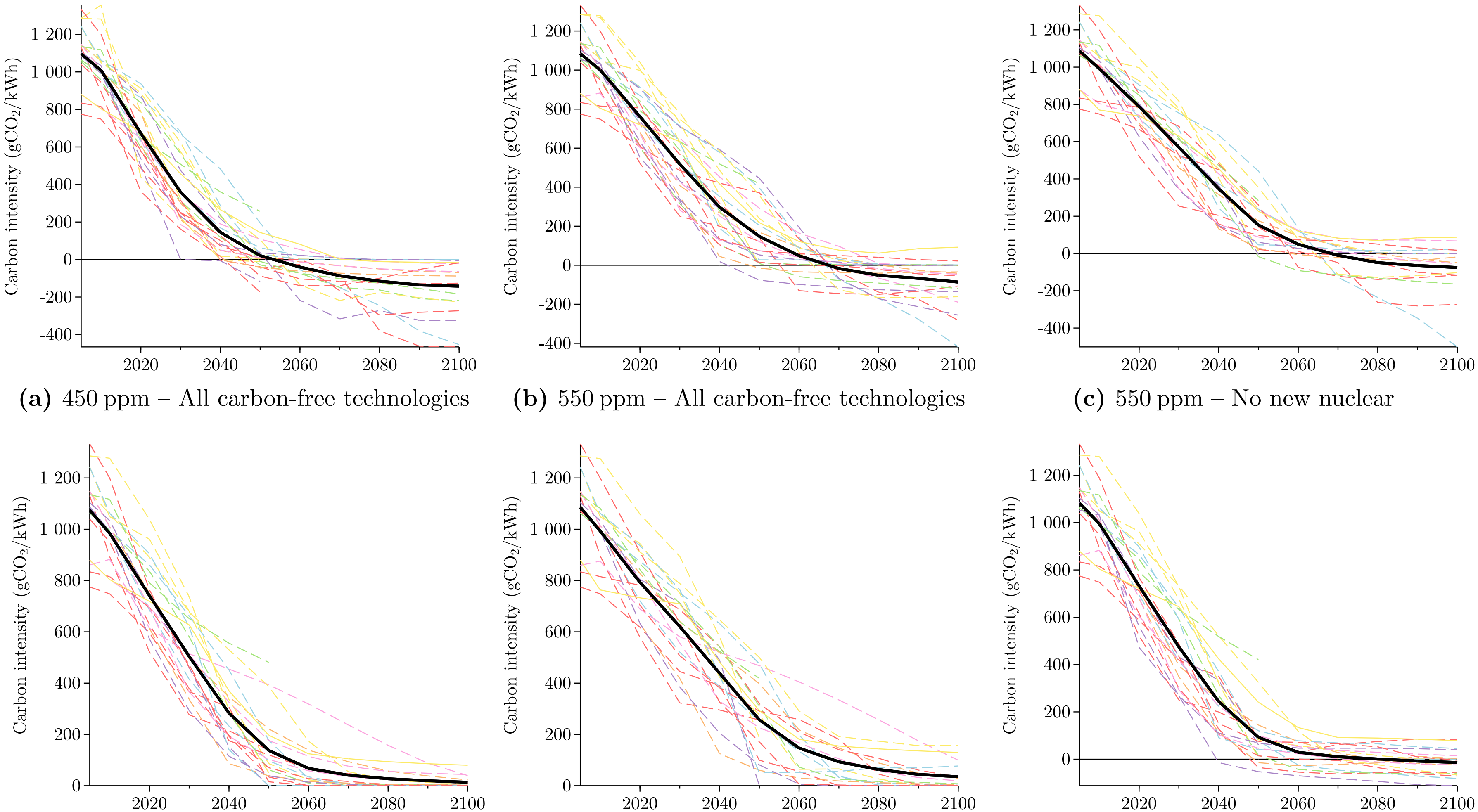
Moreover, previous studies have documented the risk of selection bias in IAM reviews, as results are not always reported when targets are unachievable (Tavoni et Tol, 2010). Our sample of trajectories may be affected by selection bias, given some models might not report their results with some generation technologies unavailable. When availability of some technologies is restricted, such as CCS and nuclear, the number of reported paths decreased, in particular when targeting 450 ppm CO_2-eq (this effect is mitigated with the looser 550 ppm CO_2-eq constraint).[9] This hints at the potential difficulty of reaching a stringent climatic target if the development of BECCS is constrained (Tavoni et Socolow, 2013; Bibas et Méjean, 2014; Rose et al., 2014).

Barriers to the decarbonization of power generation

IAMs might imperfectly account for several barriers to the decarbonization of power generation (Iyer et al., 2015). For instance, the capacity credit – the contribution of a given technology to meeting the demand – tends to be lower for intermittent renewable energy (mainly solar and wind) than for fossil fuel, nuclear, and bio-energy, due to potential mismatches between resource availability and demand peaks (Sims et al., 2003). Also, some low-carbon technologies may require to build wider distribution and transmission networks to connect remote energy sources or production locations to end-users (renewable energies and nuclear) and transportation infrastructure to carbon sequestration sites (CCS).

B Additional figures

[9]Such evidence should be taken with caution, as participants were not required to run every scenario (scenarios were ranked as required, recommended, or optional). A smaller number of trajectories does not necessarily reflect selection.



(a) 450 ppm – All carbon-free technologies

(b) 550 ppm – All carbon-free technologies

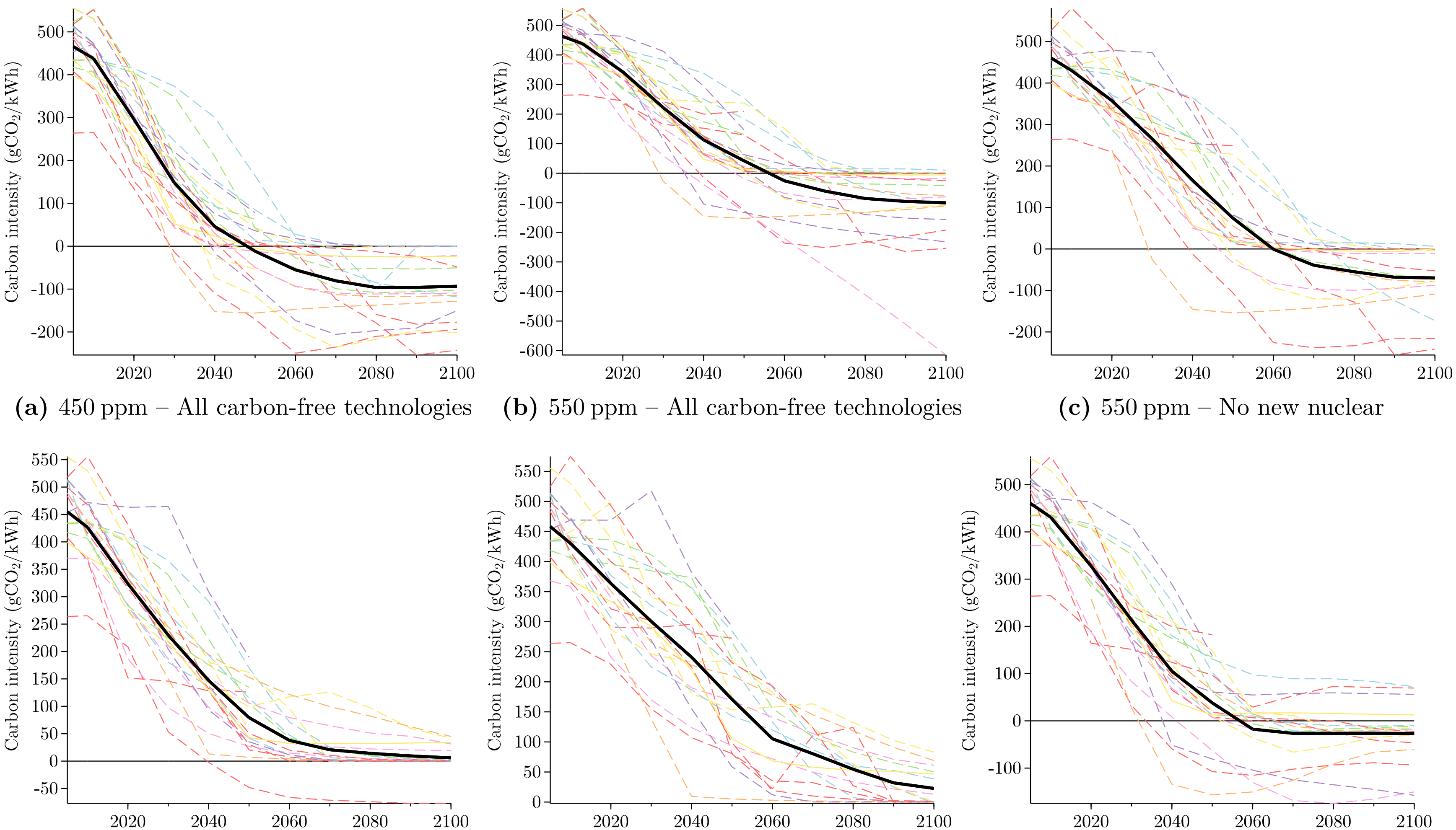
(c) 550 ppm – No new nuclear

(d) 550 ppm – No CCS

(e) 550 ppm – No new nuclear and no CCS

(f) 550 ppm – Low renewable

Figure 3.4: Carbon content of electricity in China.



(a) 450 ppm – All carbon-free technologies

(b) 550 ppm – All carbon-free technologies

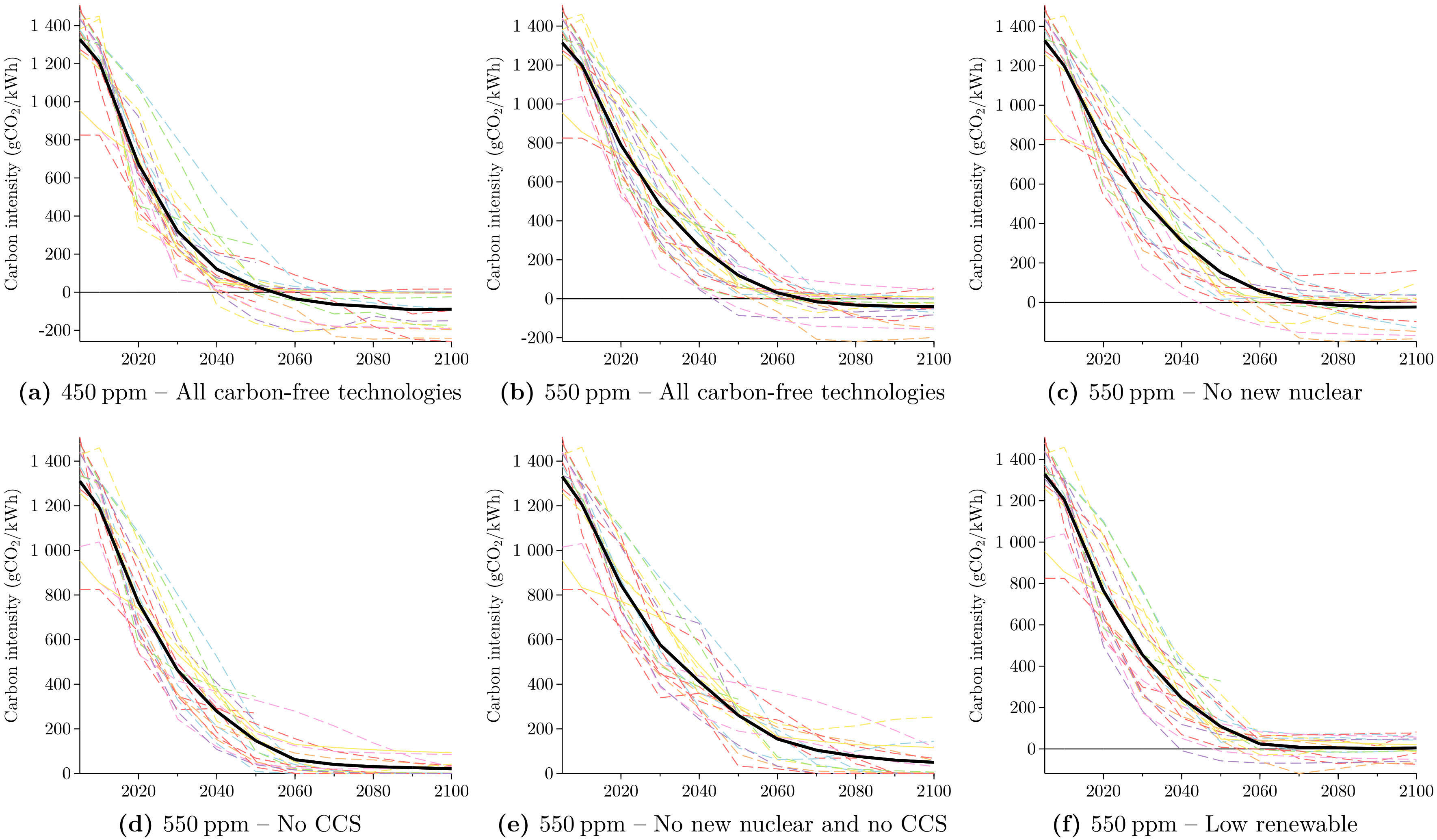
(c) 550 ppm – No new nuclear

(d) 550 ppm – No CCS

(e) 550 ppm – No new nuclear and no CCS

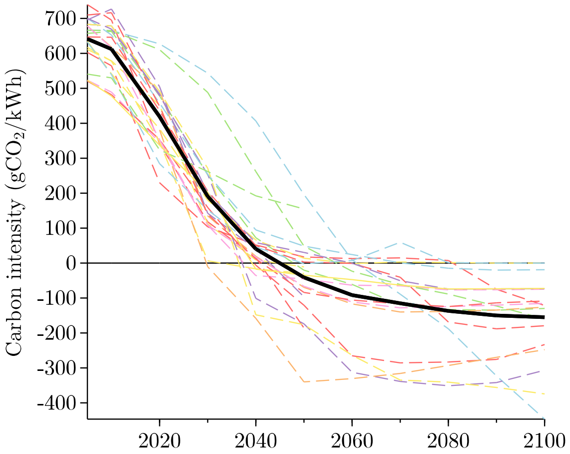
(f) 550 ppm – Low renewable

Figure 3.5: Carbon content of electricity in the EU.

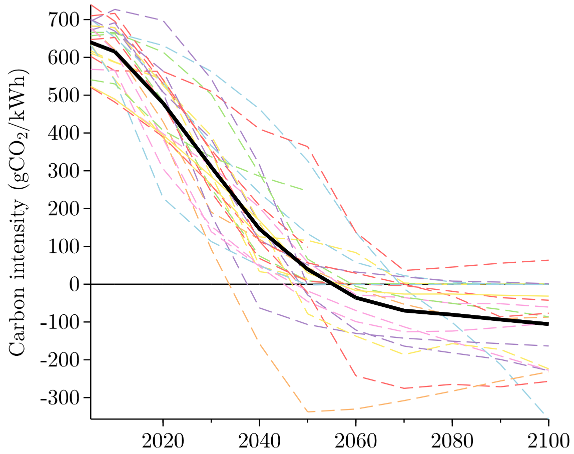


(a) 450 ppm – All carbon-free technologies
(b) 550 ppm – All carbon-free technologies
(c) 550 ppm – No new nuclear
(d) 550 ppm – No CCS
(e) 550 ppm – No new nuclear and no CCS
(f) 550 ppm – Low renewable

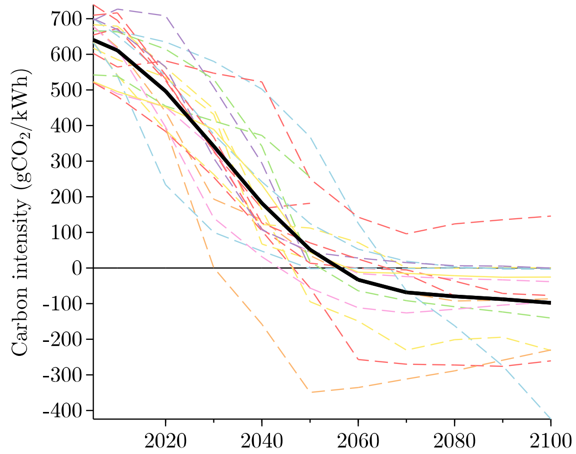
Figure 3.6: Carbon content of electricity in India.



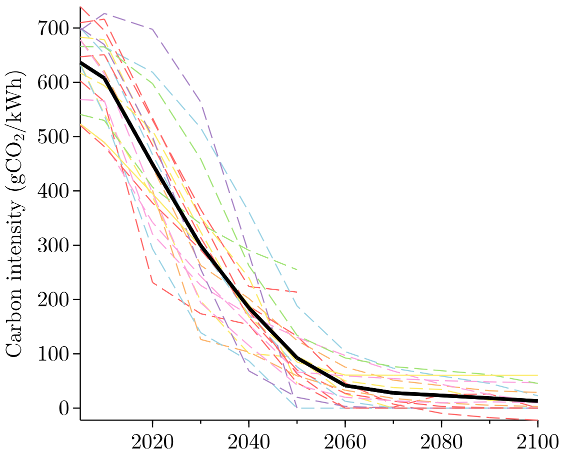
(a) 450 ppm – All carbon-free technologies



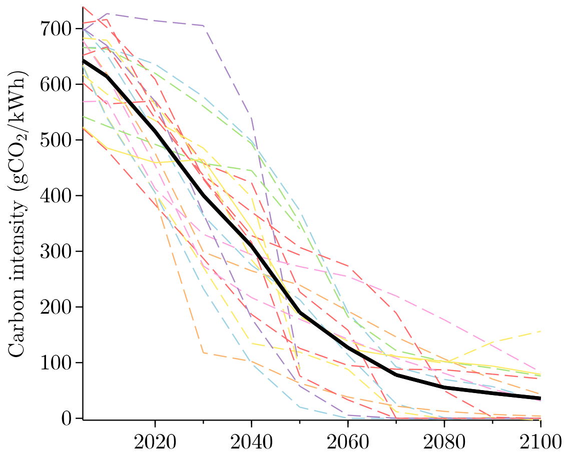
(b) 550 ppm – All carbon-free technologies



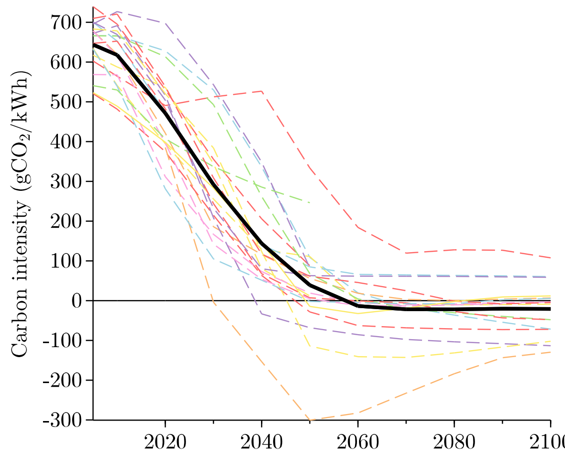
(c) 550 ppm – No new nuclear



(d) 550 ppm – No CCS

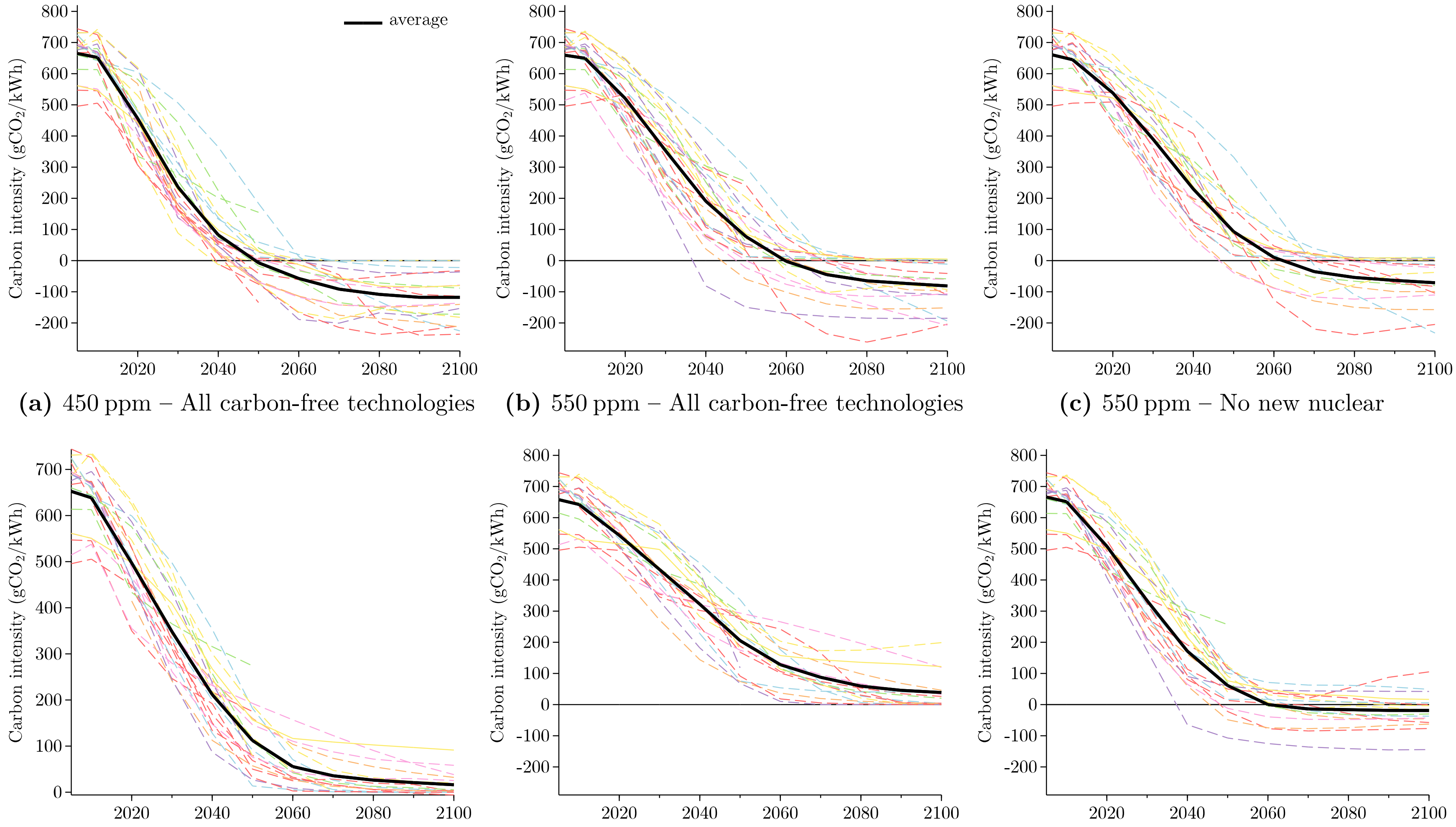


(e) 550 ppm – No new nuclear and no CCS



(f) 550 ppm – Low renewable

Figure 3.7: Carbon content of electricity in the US.



(a) 450 ppm – All carbon-free technologies

(b) 550 ppm – All carbon-free technologies

(c) 550 ppm – No new nuclear

(d) 550 ppm – No CCS

(e) 550 ppm – No new nuclear and no CCS

(f) 550 ppm – Low renewable

Figure 3.8: Carbon intensity of electricity at the global level.

4

Marginal abatement cost curves and the optimal timing of mitigation measures

To design the best policies to cope with climate change, decision-makers need information about the options for reducing greenhouse gas (GHG) emissions. Such information has been provided in many ways, including through measure-explicit marginal abatement cost curves (MACCs). We call *measure-explicit MACCs* the curves that represent information on abatement costs and potentials for a set of mitigation measures. Measures include changing technologies, notably in the transport, housing and power sectors, but also non-technological options such as waste recycling and management of land use and forest. These MACCs are usually constructed for a specific country or region, and for a specific date. They report abatement potentials as a function of the abatement cost, ranking mitigation options from the least to the most expensive (Fig. 4.1).

Decision makers who face an emission-reduction target need to decide which abatement options to implement, and following which schedule. They can misinterpret measure-explicit MAC curves as abatement supply curves. According to this interpretation, the optimal behavior

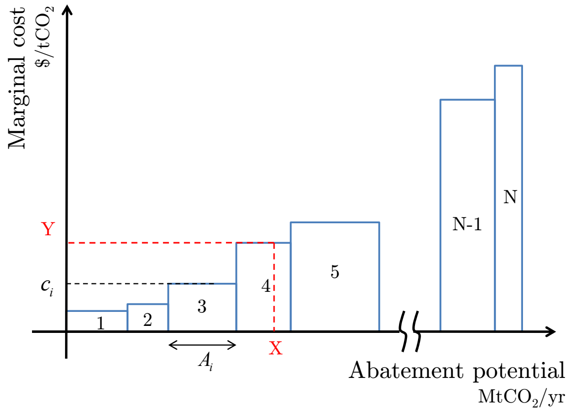


Figure 4.1: A measure-explicit MACC exhibits N abatement options ranked from the least to the most expensive. Each option i is characterized by their abatement potential A_i and their marginal abatement cost c_i. This curves stands for a given date T. We explain why the optimal mitigation strategy to reach a target X at T is not necessarily to implement exclusively the measures 1 to 4 cheaper than Y (where Y is the marginal abatement cost corresponding to X on the curve).

to meet an abatement target (e.g, bringing back GHG emissions at their 1990 level by 2020) is to build a MAC curve for this date, and implement only the cheapest options that allow the target to be met (e.g., DECC, 2011, Fig 17, p. 52).

In this paper, we explain why decision makers need to distinguish available abatement measures using their costs, abating potential, and the time it takes to implement them. Indeed, the high-abating potential options required to meet ambitious emission-reduction targets cannot be implemented overnight. Therefore, the optimal set of measures to reach a short-term target depends on the measures required to meet longer-term targets and on the speed at which these measures can take effect.

We thus propose a new way for reporting information on emission-reduction options to the general public and decision-makers. Reports could display assessments of the cost of each option, the abating potential or carbon intensity of each option, and the speed at which each option can be implemented – taking into account the required accumulation of human and physical capital. While some MACCs factor in all this information, none provides data on these three dimensions separately.

We first contribute a classification of existing MAC curves (Section 1). Then, we build a simple model that can compute the optimal timing of GHG emissions reductions (choice across time) along with the optimal dispatch of the reduction burden (choice across abatement measures) from this three dimensions (Section 2). We use it in Section 3 with an objective in terms of cumulative emissions over a long period, a so-called *carbon budget*, reportedly a good proxy for climate change. We show that it make sense to implement the more expensive options before exhausting the whole potential of the cheapest options. We turn in Section 4 to objectives expressed in terms of aggregate abatement at one point in time, closer to the actual practices. In that case, it can be preferable to start implementing the most expensive options before cheap ones, if their potential is large and their inertia is great (Section 4.1). Finally, we explain in Section 4.2 how the optimal short-term strategy depends on the long-term emission objective. This means that MACCs should not be used as supply curves when choosing the optimal strategy to reach short-term emission targets.

1 Overview of existing marginal abatement cost curves

The term "MAC curve" refers in the literature to various curves, constructed in various ways. Here, we distinguish *continuous* MAC curves and *measure-explicit* MAC curves. We then distinguish *full-potential* measure-explicit MACCs and *achievable-potential* measure-explicit MACCs.

1.1 Continuous *vs.* measure-explicit MAC curves

Continuous MAC curves depict the aggregate shadow cost of an emission target against the stringency of this target. They do not depict particular mitigation measures. The existing literature builds this type of MACCs from Integrated Assessment Models (IAM). It has for instance emphasized that the cost of reducing GHG emissions inside an economy depends on external factors such as energy prices or climate policies decided abroad (Klepper et Peterson, 2006; Kuik et al., 2009; Morris et al., 2011).

In this paper we take the perspective of a decision maker who faces an exogenous abatement target and needs to decide which emission-reduction options to implement, and in which order. Continuous MACCs are out of the scope of this paper. We focus on measure-explicit MAC curves that represent information on abatement costs and potentials for a set of mitigation measures (Fig. 4.1).

Measure-explicit MACCs have recently reached a wide public, when McKinsey and Company published an assessment of the cost and potentials in the United States (Enkvist et al., 2007) and at the global scale (McKinsey, 2009). These curves are increasingly used to inform policymakers: McKinsey currently lists 15 MAC curves in its website, the World Bank has assessed reduction potentials in many countries in the form of MACCs (ESMAP, 2012), and Sweeney et Weyant (2008) have proposed such a MACC for California. Other examples include the MACCs developed by the Wuppertal Institute for Climate, Environment and Energy (2006), and by Bloomberg (2010). Their usage goes beyond climate mitigation: for instance, similar depictions have been used to describe available options to reduce energy consumption (e.g., Jackson, 1991), waste production (Beaumont et Tinch, 2004) and water consumption (McKinsey, 2009).

Recent research has identified – and proposed solutions for – methodological issues when *building* measure-explicit MAC curves (Kesicki et Ekins, 2012); this has allowed to enhance the reporting of abatement costs and potentials. A first issue relates to uncertainty when assessing future costs – it can be addressed by presenting ranges of costs and potentials instead of best-guest estimates (IPCC, 2007, SPM6 p.11). A second issue is that MACCs do not depict the interaction between different measures (e.g, promoting electric vehicles and green electricity together would allow to save more GHG than the sum of the two isolated abatement measures), even if they are built taking these interactions into account (Kesicki, 2012b). Kesicki et Ekins (2012) identify other shortcomings, like the fact that MACCs frequently assess project or technological costs only, excluding institutional barriers, transaction costs and non-monetary costs. In contrast, we focus in this paper on how to *use* MAC curves, that is on how they can help to design optimal emission-reduction strategies.

1.2 Full potential vs. achievable potential measure-explicit MAC curves

While similar in appearance, two types of measure-explicit MAC curves should be distinguished, depending on their implicit definition of the abating potential of a measure.

The *full-potential* approach gives information on how much GHG could be saved if the measure was used at his technical maximum. It is calculated against a reference or baseline technology, taking into account the carbon intensity and imperfect substitutability of different technologies. For instance, this approach takes into account that an Electric Vehicle (EV) does not emit any GHG (e.g. saves 140 gCO_2/km compared to the average new vehicle sold in Europe in 2010) but that all passenger vehicles cannot be replaced by EVs due to limited driving range. This approach does not take into account any dynamic aspect.

Among others, Rubin et al. (1992) used this approach. For instance, they assess the potential of nuclear power (in the US) as the quantity of GHG that would be saved if nuclear replaced *all* the fossil fuel capacity that was used for base load and intermediate load operation in 1989, and find 1 500 $MtCO_2$/yr (Rubin et al., 1992, Table 3, footnote j). More recently, Wächter (2013) built a MAC curve for Austria based on the same approach, using 2008 data.

We call the other approach the *achievable-potential* approach. It seems to have been popularized by McKinsey. Achievable-potential measure-explicit MAC curves have a prospective dimension, as they are built for a date in the future. This approach takes into account that large-scale diffusion of new technologies can take up to decades (Grübler et al., 1999). In this context, the abating potential of a technology assesses the abatement that could be achieved with such a technology if it was implemented at a given speed (McKinsey, 2009, Exhibit 1). For instance, this approach takes into account that even ambitious fiscal incentives in favor of electric vehicles would induce a limited increase of EV sales, resulting in a limited share of EVs by 2020 or 2030. The achievable-potential by a given date mixes the information on the full potential and the slow diffusion process, and is therefore lower than the full potential described above.

A MACC built this way is the one by Sweeney et Weyant (2008): they find for instance that solar photovoltaic power can only save 0.8 $MtCO_2$/yr in California by 2020. They also distinguish the abating potential of industrial combined heat and power achievable thanks to price incentives and the potential that can be reached after an "aggressive growth" (Table 11 page 50). As IAMs account for slow technological diffusion (Wilson et al., 2013), they can be used to produce achievable-potential measure-explicit MACCs. One example is the MACC built by Kesicki (2012a) for the UK transport sector by 2030.

In the following we show the value of combining the two approaches, i.e. how the full-potential and the implementation speed, reported separately, can be used to decide which options to implement, and in which order, to comply with exogenous emission targets. We propose a methodology to do so, based on three information pieces per measure – its cost, full potential, and implementation speed – and a simple intertemporal optimization model.

2 Model

A social planner controls GHG abatement from an emission baseline, by spending money and time on a set of options described by their cost, full abatement potential, and implementation speed. We do not incorporate more realistic but complex dynamics, such as sectoral interactions or crowding-out effects on investment.

2.1 GHG emissions

There are N abatement options, indexed by i. The model is run on a period that goes from 2000 to 2050 with a time step, Δt, of 3 months. At each time step t, emissions are computed from the baseline emissions E_t^{ref} and the abatement $a_{i,t}$ achieved with each measure i at time t.

$$e_t = E_t^{ref} - \sum_{i=1}^{N} a_{i,t} \tag{4.1}$$

The cumulative emissions M_t are then computed as the sum of emissions.

$$M_t = e_t \cdot \Delta t + M_{t-\Delta t} \tag{4.2}$$

2.2 Potentials, costs and inertia

Each measure is described by three figures. First, each measure i has a maximum abating potential A_i, expressed in avoided annual emissions, in $MtCO_2/yr$. For instance, switching to more efficient thermal engines for passenger vehicles may not save more than a fraction of GHG emissions associated with private mobility. In *full-potential measure-explicit* MACCs, this potential is represented by the width of the rectangles (see Fig. 4.1).

$$a_{i,t} \leq A_i \tag{4.3}$$

Second, each measure i is qualified with a constant abatement cost c_i — the heights in Fig. 4.1. Here, we also assume that abatement costs are independent of cumulative abatement and time.[1] Abatement $a_{i,t}$ achieved thanks to measure i at time t has a cost $I_{i,t}$ which reads.

$$I_{i,t} = a_{i,t} \cdot c_i \tag{4.4}$$

Third, a given amount of abatement requires a non-negative amount of time for its implementation. This is modeled as a constant maximum speed v_i, (in $\mathrm{MtCO_2/yr/yr}$), assumed to be independent of the financial cost of the measure[2]: achievable abatement at time t directly depend on already achieved abatement at time $t - \Delta t$.[3]

$$a_{i,t} \leq a_{i,t-\Delta t} + v_i \cdot \Delta t \tag{4.5}$$

These growth constraints may come from any bottleneck such as (i) availability of skilled workers, (ii) availability of productive capacities, (iii) incompressible institutional requirements, (iv) emissions being embedded in long-lived capital, or (v) requirement for knowledge accumulation before technologies spread.

Issues (i) and (ii) could be overcome by training workers or redirecting unemployed workers and unused capital; but training and redirecting are measures *per se* and cannot be done overnight either. The issue of institutional or organizational delays is well documented (World Bank et International Finance Corporation, 2013). Reducing them is also a measure *per se*, and takes time. The fourth point is related to capital vintages and turnover: if one sees emissions as embedded in capital (Davis et al., 2010; Guivarch et Hallegatte, 2011), decarbonization cannot be faster than capital turnover, except by wasting valuable productive capital through premature replacement (Lecocq et al., 1998; Lecuyer et Vogt-Schilb, 2014; Rozenberg et al., 2014). Concerning (v),

[1] On the effect of learning-by-doing, see del Rio Gonzalez (2008) and Meunier et Finon (2013).

[2] Note that abatement is expressed in $\mathrm{MtCO_2/yr}$.

[3] The initial abatement is assumed to be null ($a_{i,0} = 0$). This is done without loss of generality: if the initial abatement is not null, a new abating potential A'_i can be redefined as the potential beyond what is already achieved $A'_i = A_i - a_{i,0}$.

Mansfield (1998), and Agarwal et Bayus (2002) have found that research and development is typically carried out from several years to few decades before new technologies experience market uptake.

As noted in section 1.2, MAC curves built for a date in the future T frequently provide an achievable potential, not a full potential. In our framework, the achievable potential $\tilde{A}_i$ is linked to the full potential A_i and the implementation speed v_i.

$$\tilde{A}_i = \min\left(v_i \cdot T, A_i\right) \tag{4.6}$$

We can also define the implementation time as A_i/v_i, the ratio of the abatement potentials over the maximum speed.

2.3 Social planner objectives

The objective is to achieve a climate-related target while minimizing abatement costs. The decision maker minimizes C, the total present cost of abatement, discounted at rate r over the period.

$$C = \sum_{t=T_0}^{T} \sum_{i=1}^{N} \frac{I_{i,t}}{(1+r)^{t \cdot \Delta t}} \tag{4.7}$$

Theoretically, a benevolent social planner can control GHG emissions in order to equalize the marginal costs of mitigation and adaptation in a cost-benefit approach. Because of uncertainty surrounding both climate response to a change in GHG emissions and adaptation costs, and because decisions are made at national instead of global scale, it is common to adopt a cost-effectiveness approach (Ambrosi et al., 2003). In our model, this can be done by constraining cumulative emissions M_t to remain below a given carbon budget M_{obj}.

$$M_t \leq M_{obj} \tag{4.8}$$

Cumulative emissions can be used as proxies for climate change (Allen et al., 2009; Matthews et al., 2009b).

In practice, however, governments and other public agencies frequently provide objectives for given points in time. For instance, the EU has the objective of cutting its emissions by 20% of 1990 levels by 2020.[4] In our model, these objectives can be implemented by defining a

[4]It is also common to adopt intensity objectives, as the efficiency standards in

			Cheap	Deep
Marginal Abatement Cost	c	$\$/tCO_2$	30	60
Full potential	A	$GtCO_2/yr$	1.5	3.5
Speed	v	$MtCO_2/yr^2$	60	50

Table 4.1: Numerical assumptions

set of milestones indexed by m, and by constraining emissions at each milestone.

$$e_{t_m} \leq E_m^{obj} \tag{4.9}$$

2.4 Numerical values

For illustrative purpose, we assume a MAC containing only two contrasted measures ($N = 2$), labeled *cheap* and *deep*. *Cheap* has a lower abatement cost than *deep*, but also a lower abatement potential (Table 4.1). *Cheap* could represent for instance the measure of switching energy sources in buildings, and *deep* could represent the retrofitting of these buildings. In the auto industry, *cheap* could represent the energy efficiency gains in the internal combustion engines and *deep* switching to other energy sources, such as electricity or hydrogen.

In the absence of reliable data, we assume that it takes 70 years to implement the whole potential of *deep*, while *cheap* only requires 25 years. They lead to values for v of respectively $50\,MtCO_2/yr^2$ and $60\,MtCO_2/yr^2$. We use $r = 5\%/yr$ as the discount rate. These values are not meant to represent accurately concrete sectors of the economy, even though they do not differ much from the two sectors modeled by Lecocq et al. (1998). We assume constant baseline emissions, that is $E_t^{ref} = 5\,GtCO_2/yr$ (close to contemporaneous European GHG emissions). We use these values to carry out illustrative experiments, which help draw more general conclusions.

We solve this simple model using a linear programing algorithm provided by GAMS (Brook et al., 1988). The source code also uses Scilab (Scilab Consortium, 2011). Code and data are available on the corresponding author's web page. Results may be verified using the

the auto industry. Our model may be used with existing intensity MACCs (IEA, 2009, p. 37).

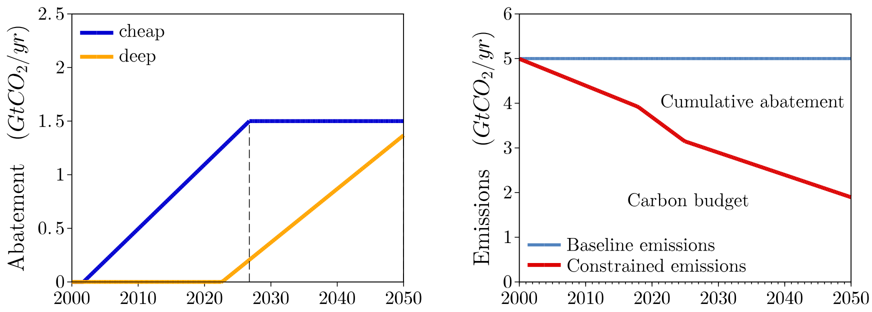


Figure 4.2: Left: Optimal abatement strategy to limit cumulative emissions below 175 $GtCO_2$ between 2000 and 2050. Inertia and discounting mean that *deep* has to enter before the potential of *cheap* has been exhausted. Right: curves represent emissions in the baseline and in the constrained simulation; in-between areas represent the cumulative abatement and the carbon budget in the constrained simulation.

spreadsheet model provided on the corresponding author's web page.

3 Optimal schedule under a cumulative carbon budget

In this section, we investigate the optimal abatement pathway when using a carbon budget, i.e. with full flexibility on when to reduce emissions (Eq. 4.8). We test a range of carbon budgets (M_{obj}), and assess the consequence on the optimal reduction pathway.

3.1 Using expensive options before exhausting the potential of cheap ones

Figure 4.2 shows the optimal strategy for maintaining cumulative emission below 175 $GtCO_2$ over the 2000-2050 period. This value is used for illustrative purpose, and will allow us to make some comparisons with subsequent simulations (in Section 4).

The abatement paths (figure 4.2, left panel) have triangular or trapezoidal shapes; this shows that one of the inertia (Eq. 4.5) or maximum potential (Eq. 4.3) constraint is always binding. The cumulative abatement corresponds to the area between baseline emissions and emissions in the constrained run (figure 4.2, right panel). In this case, the intuitive ranking of abatement measures is respected: the social planner starts by implementing *cheap* before *deep*. However, she does not use

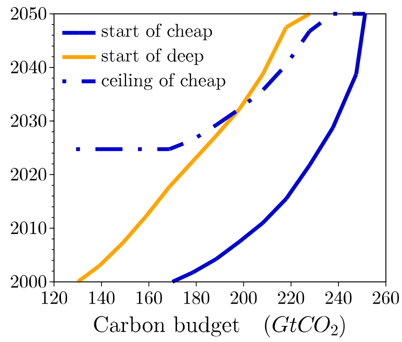


Figure 4.3: Entry date and ceiling date of each abatement measure as a function of the carbon budget. Lower carbon budgets, on the left, correspond to tighter climate objectives and require more abatement. *Start of deep/cheap* is the date when the respective measure begins to be implemented; the *ceiling date* is the date when the abating potential is exhausted.

the whole potential of *cheap* before starting using *deep*. *Deep* enters in 2023 while *cheap* does not reach its full potential before 2027. A more stringent objective would force *deep* to start even earlier (see below).

The optimal implementation strategy does not follow a merit order in which the whole potential of the cheapest solutions is used before more expensive solutions are introduced.

A more systematic analysis using a range of carbon budgets (Fig. 4.3) confirms that for any objective it is never preferable to implement the expensive *deep* before *cheap*. It also shows that if the objective is stringent enough (about 195 $GtCO_2$), *deep* has to begin before the whole potential of *cheap* has been exploited — the implementation is not sequential. And if the carbon budget is even more stringent (about 130 $GtCO_2$), *deep* is forced to start in 2000, at the same time as *cheap*.

3.2 Expensive options may be useful even when cheaper ones appear sufficient

Let us analyze a case in which the carbon budget is not very stringent, e.g. 210 $GtCO_2$. This translates into cumulative abatement of 45 $GtCO_2$ over the period.[5] *Cheap* has a cumulative abatement poten-

[5]Cumulative emissions in the baseline amount to 5 Gt/yr during 51 years, that is 255 Gt.

tial of more than 55 $GtCO_2$.[6] It is then possible to achieve the abatement objective by implementing only *cheap*. An intuitive strategy could be to focus on *cheap* and to not implement *deep*. Our simulations show that this is not the optimal strategy, because there is a trade-off between (i) implementing only the cheapest solutions, but starting early to give them enough time to reach the objective; (ii) delaying abatement in order to save present value (thanks to the discounting), but undertaking both *cheap* and *deep* to be more aggressive later and reach the objective in spite of the delayed action.

In our simulations (Fig. 4.3), the optimal strategy to meet a (lax) 210 $GtCO_2$ carbon budget is to implement *deep* from year 2040, which makes it possible not to implement *cheap* before 2011 (for a strategy starting in 2000). The additional cost of using *deep* is more than compensated by the delay on implementing *cheap*. In other words, the optimal strategy uses an expensive measure even when a cheaper measure is sufficient to reach the objective.

4 Optimal abatement pathways with annual emission targets

Commitments in terms of carbon budget are difficult to enforce: there is an incentive for decision-makers to delay investments and efforts beyond their mandate. Alternative policies include the definition of emission targets at one or several points in time. In the next two sections, we assume that commitments are made in terms of abatement levels at different points in time.

The cumulative-emissions constraint (Eq. 4.8) is thus excluded from the model, and we include the emission constraint with a single milestone ($m \in \{1\}$, $t_1 = 2050$) and test various emission objectives (E_1^{obj} in Eq. 4.9). We find that the shape of the optimal mitigation strategy depends on the stringency of the emission target.

4.1 Implementing expensive options before cheap ones

Figure 4.4 shows the optimal abatement pathway for achieving an ambitious reduction of 75% of emissions in 2050. In this case, the

[6] Its annual abatement potential is 1.5 Gt/yr and takes 25 years to implement in full (see Table 4.1); adding the cumulated potential during the take-off phase (25 yr $\times$ 1.5 Gt/yr)/2 and the potential when annual abatement have reached their maximum value 25 yr$\times$1.5 Gt/yr gives a total of 56.25 Gt.

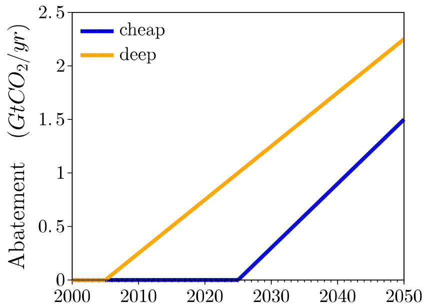


Figure 4.4: Optimal abatement pathways to achieve ambitious abatement (3.75 $GtCO_2$/yr) in 2050. The expensive option with large abatement potential is implemented before the cheaper option.

optimal strategy is to start by implementing the most expensive option before the cheapest (i.e., *deep* starts before *cheap*).

Indeed, the emission objective translates to 3.75 $GtCO_2$/yr abated in 2050, which cannot be achieved by implementing *cheap* alone. The cheapest way to achieve this objective in 2050 is to use *cheap* to abate as much GHG emissions as possible, i.e. 1.5 $GtCO_2$/yr. Because *cheap* cannot penetrate faster than 60 $MtCO_2/yr^2$, it has to enter in 2026. Then 2.25 $GtCO_2$/yr remain to be abated with *deep* by 2050. To do so, *deep* has to enter as soon as 2006, 20 years before *cheap*.

The 75% reduction in emissions leads to cumulative emissions of 175 $GtCO_2$, and is thus comparable to the simulation proposed in Section 3.1.[7] Compared to the carbon-budget simulation, this emission-targets simulation leads to start *cheap* later and *deep* sooner. Short-term abatement are lower — in 2020, they amount to 750 $MtCO_2$/yr under an emission target, against 1.3 $GtCO_2$/yr under a carbon budget — but long-term abatement are higher.

The loss of when-flexibility eventually raises the present cost of abatement, from 390 G\$ to 630 G\$ when the carbon budget is replaced by an emission target.[8] Compared to emission objectives, carbon budgets are more flexible and allow the social planner to reach the same climate target at lower cost.

[7] Since cumulative emissions are good proxies for climate change, both simulations would lead to comparable climate change impacts.

[8] In other words, 390 G\$ is the lowest possible cost to reach the carbon budget constraint, while 630G\$ is the lowest cost for reaching the same carbon budget through one aggregate emission target in 2050.

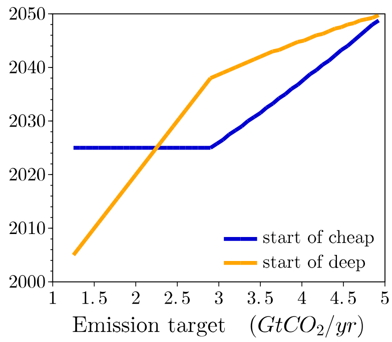
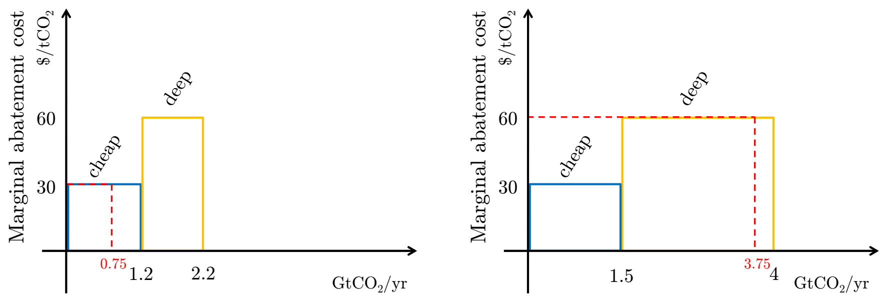


Figure 4.5: Entry date of each measure as a function of emission objective for 2050. For ambitious emission targets (below 2.25 $GtCO_2$/yr), the expensive option with large abatement potential is implemented before the cheaper option.

A more systematic analysis is presented in Fig. 4.5. It gives the optimal entry dates of both measures (*cheap* and *deep*), as a function of the 2050 emission target. It shows that below a threshold emission target, the optimal strategy starts to implement the expensive, inert and high-abating potential measure before the cheap one. In our example, this happens when the emission target is lower than 2.25 $GtCO_2$/yr — i.e. when the abatement objective is higher than 2.75 $GtCO_2$/yr.

The optimal strategy to achieve an emission target is not to set a growing carbon price and to implement sequentially the abatement options that show an abatement cost below this carbon price.[9] However, if the government cannot credibly commit to long-term carbon prices (Kydland et Prescott, 1977; Dixit et Lambertini, 2003), investors may be left with only current prices to take their decisions. In this case, a carbon price of 60 \$/tCO_2 would be necessary in 2006 to trigger the entry of *deep* (Fig. 4.4). This high carbon price would also trigger the implementation of *cheap* (because its abatement cost, 30 \$/tCO_2, is lower than the signal) in 2006, i.e. too soon, leading to a suboptimal abatement pathway. In the conclusion we discuss possible solutions to this problem.

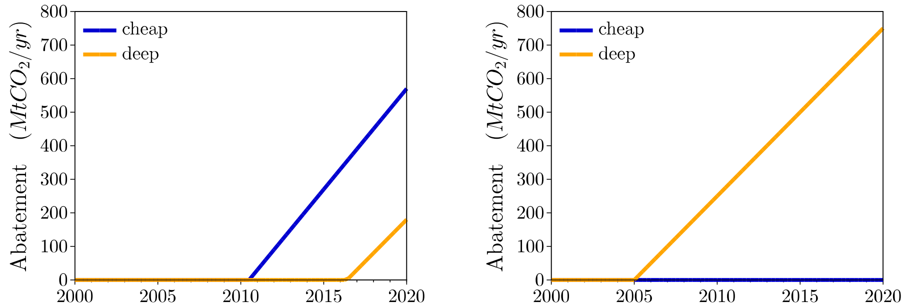


(a) Abatement potential by 2020

(b) Abatement potential by 2050

			Cheap	Deep
Time Horizon	t_1	yr	20	
Achievable potential	$\tilde{A}$	$GtCO_2/yr$	1.2	1.0
Time Horizon	t_2	yr	50	
Achievable potential	$\tilde{A}$	$GtCO_2/yr$	1.5	2.5

Figure 4.6: MACCs derived from our numerical values, using the achievable-potential approach. We explain why the 2020 target should not be reached by implementing only *cheap*.



(a) Short-term Only

(b) Short-term and Long-term objs

Figure 4.7: Comparison of optimal abatement strategies to reach the same target for 2020, disregarding or taking into account the longer-term 2050 objective (respectively SO and S&L). The best strategy to reach the 2020 target depends on whether this target is the ultimate objective (SO) or only a milestone towards a longer-term target (SL).

4.2 The influence of long-term objectives on short-term strategies

Actual policies include shorter-term emission objectives, such as the 2020 target in the EU. They are milestones toward a more ambitious climate target in the long run, as the -75% by 2050 objective in Europe. In this section, we find that it is dangerous to use only information on costs and achievable potential to decide which measures to implement in order to achieve an intermediate target (Fig 4.6), because it can make the long term target impossible to reach.

We compare two simulations. The first simulation, labeled SO (Short-term Only), has a short-term constraint but no long-term constraint.

$$E_1^{obj} = E(2020) = 4.25\ \mathrm{GtCO_2/yr} \tag{4.10}$$

This target corresponds to 750 $\mathrm{MtCO_2/yr}$ abated in 2020, that is exactly the abatement achieved in 2020 in the optimal pathway to a -75% in 2050 target according to our model (Fig. 4.4).

The second simulation, S&L (Short-term and Long-term objectives),

[9] This corroborates previous findings that in presence of inertia, efforts to reduce emissions should not be equal to the carbon price at each point in time (Vogt-Schilb et al., 2014b; Rozenberg et al., 2014).

has the same short-term constraint for 2020, but takes into account the longer-term target: a reduction by 75% of GHG emissions in 2050. In this simulation, there are thus two emission milestones (see Eq. 4.9).

$$E_1^{obj} = E(2020) = 4.25\,\mathrm{GtCO_2/yr} \tag{4.11}$$

$$E_2^{obj} = E(2050) = 1.25\,\mathrm{GtCO_2/yr} \tag{4.12}$$

Our objective is to assess the difference over the short-term between a strategy aiming at a short-term target and a strategy aiming at both short-term and long-term targets. We find that long-term objectives impact strongly the short-term strategy.

Figure 4.7 compares the optimal abatement strategies from 2000 to 2020 in the two cases. With both the 2020 and the 2050 objectives (simulation S&L, panel a), the social planner starts by implementing *deep* in 2006, and does not implement *cheap* before 2020 (as in Section 4.1). In contrast, when the 2050 milestone is disregarded (simulation SO, panel b), the social planner starts abating later (in 2010 vs 2006) and uses cheaper and lower-potential options, namely *cheap* and *deep* instead of *deep* only. The discounted expenditures in abatement measures amounts to 28 G$ against 112 G$ when the 2050 objective is taken into account: the optimal short-term financial effort is much higher if the long-term target is taken into account, even though the abatement in $\mathrm{MtCO_2}$ is the same.

If the 2050 target was not taken into account before 2020, it may then appear extremely costly or even impossible to achieve. In this illustrative example, the 75% reduction in emissions becomes indeed impossible to achieve in 2050.[10]

Despite short-term aggregate emissions being reduced to the same level in SO and in S&L by 2020, the SO strategy produces a lock-in in a carbon intensive pathway that cannot be reversed in the second period. In other words, the optimal strategy to reach the 2020 target is different (it uses more expensive options) if it's a milestone to a 2050 target than if it is the ultimate target. With an ambitious long-term objective, the short-term target needs to be achieved implementing the options with the largest potentials and the greatest inertia, not with

[10] *Cheap* has entered in 2006. It would reach its full potential (1.5 Gt/yr) in 2030. If *deep* enters in 2021, it would also reach abatement of 1.5 Gt/yr in 2050, 30 years after (30 yr × 50 $\mathrm{MtCO_2}$/yr). The total would be abatement of 3 Gt/yr in 2050, when the target is 3.75 Gt/yr.

the cheapest solutions.

In the previous subsection, we concluded that a unique price instrument may not be the best approach to trigger the right investments in emission-reduction measures, provided that actors may not rely on long-term signals. The same warning applies to aggregate emission targets.

Short-term targets are *a priori* relevant, because there is visibility over the short term on technology availability, macroeconomics trends and institutional frameworks. For instance, they can be enforced with tradable emissions permits, such as the EU ETS system. However, if decision makers omit the longer-term target when deciding which measures can be implemented to reach the short-term target, they will focus on the cheapest available options (Fig. 4.6a and 4.7a).

It is therefore a good practice to announce long-term objectives along with short-term binding policies. An example are the existing carbon-intensity or fuel-efficiency standards for new passenger vehicles (ICCT, 2012): governments have enacted short-term standards (e.g. 130 g/km in 2015 in Europe), and also enacted or proposed longer-term ones (95 g/km in 2020 in Europe).

This result also sheds a new light on sector-specific mitigation targets, such as energy-efficiency standards in the automobile sector or the 20% renewable power in the European Union. This kind of sectoral short-term targets in favor of expensive but high-potential technologies may be a way to ensure that aggregate targets (the 20% reductions of greenhouse gas emissions) are not reached using only the cheapest options (as coal-to-gas switch).

5 Conclusion

This paper investigates the design of optimal abatement strategies using information on the cost, the abating potential and the implementation speed of a set of available measures.

Optimal abatement strategies may (i) implement expensive options before the whole potential of cheaper measures has been exploited; (ii) use expensive options even when cheap ones appear sufficient to meet the climate target; or (iii) start to implement some expensive options before cheaper ones. If the climate objective is stringent and inertia is large, the optimal strategy would be to start implementing at the same time a set of measures covering a wide range of abatement costs.

Our results have policy and methodological implications. In the European Union, there was a debate on whether aggregate GHG emissions should be abated by 20% or 30% in the short-term (i.e. 2020). This question on when to abate GHG emissions should not be separated from the question on how these abatement have to be done (i.e., in which sector and with which measures). Economic actors might otherwise focus on cheap and fast-to-implement solutions to reach the short-term target, neglecting high-potential but high-inertia options required to meet an ambitious objective in 2050 (see also Rose et al., 1999; Sandén et Azar, 2005; Narain et Veld, 2008; del Rio Gonzalez, 2008).

The optimal approach to achieve an emission target is not to set a growing carbon price and to implement sequentially the abatement options that show an abatement cost below this carbon price. Decision makers need assessments of the speed at which various measures to curb greenhouse gas emissions can be implemented, and they should be informed of long-term objectives in advance. Further research could investigate how policies targeted at high-potential but long-to-implement options, such as urban planing or deployment of low-carbon technologies, may complement a carbon price in the absence of perfect foresight or long-term policy credibility.

There is of course a balance to maintain (Azar et Sandén, 2011): sectoral policies should be targeted enough to distinguish differences in inertia, but broad enough to let economic agents select the best options and technologies to reach them (this may be the case, for instance, of existing fuel economy standards in the auto industry). Because of information asymmetry and the risk of rent-seeking behavior, micro-managing mitigation by defining over-targeted objectives can be counter-productive (Laffont, 1999). Also, objectives need to be updated when new information is available (Rodrik, 2008); for instance if one measure turns out to be more expensive, or turns out to save less GHG, than expected. Finally, if sectoral policies overlap, they may come with additional costs (Braathen, 2007; Böhringer et Rosendahl, 2010) or benefits (Fischer et Preonas, 2010; Lecuyer et Quirion, 2013) that should be analyzed carefully and taken into account (Hallegatte et al., 2013).

Our results are based on illustrative examples. The main conclusion is methodological: we reinforce the need to account for sector-specific inertia when designing climate policies. To date, the literature has focused on cross-sector differences on knowledge spillovers (e.g. Manne et Richels, 2004; Rosendahl, 2004b). While some numerical studies (Lecocq et al., 1998; Schwoon et Tol, 2006; Jaccard et Rivers, 2007) and integrated assessment models (Wilson et al., 2013) factor this type of differentiated inertias, the optimal timing and cost of emission reduction taking into account differentiated inertias is the object of only few theoretical contributions (e.g, Vogt-Schilb et al., 2014b; Lecuyer et Vogt-Schilb, 2014).

Measure-explicit marginal abatement cost curves have proved extremely effective in communicating some results from the economics of climate mitigation to decision makers and the general public. For instance, by reporting the cost and potential of a list of mitigation measures, MACCs illustrate in a simple way why energy-efficiency is a key option: it can save significant amounts of GHG at a low or negative cost. Existing MAC curves, however, do not explain why more expensive options, such as carbon capture and storage or renewable power, should receive significant attention today. Our answer is that these options can abate large amounts of GHG in the future, and that they need time to be implemented (Grübler et al., 1999). The reporting currently carried out by MAC curves could be enhanced by supplying assessments of the cost, potential, and implementation speed of each option.

With this information, the optimal implementation schedule of the various existing abating options could be assessed in a simple, transparent and accessible process, for instance using linear models like the one proposed in this paper. Such a model certainly is less sophisticated than state-of-the-art integrated assessment models, but can prove nonetheless useful for researchers from other fields, decision makers, and the general public. This process would also provide figures to debate new or existing sectoral policies, such as the objective of 20% of renewable energies in Europe by 2020, the fuel economy standards in the auto industry, or proposed changes in land-use planning, building norms and infrastructure design.

5

Long-Term Mitigation Strategies and Marginal Abatement Cost Curves: A Case Study on Brazil

Various options are available to reduce greenhouse gas (GHG) emissions: fuel switching in the power sector, renewable power, electric vehicles, energy efficiency improvements in combustion engines, waste recycling, forest management, etc. Policy makers have to compare and assess these different options to design a comprehensive mitigation strategy and decide the scheduling of various actions (i.e. decide what measures need to be introduced and when). This is especially true concerning the emission-reduction measures that require government action (e.g., energy-efficiency standards, public investment, public planning).

Marginal abatement cost (MAC) curves are largely and increasingly used in the policy debate to compare mitigation actions (Kesicki et Ekins, 2012; ESMAP, 2012; Kolstad et al., 2014). A MAC curve provides information on abatement costs and abatement potentials for a set of mitigation measures. They can serve as powerful tools to communicate that large amounts of emission reductions are technically possible. They also show that some emission reductions can pay for themselves

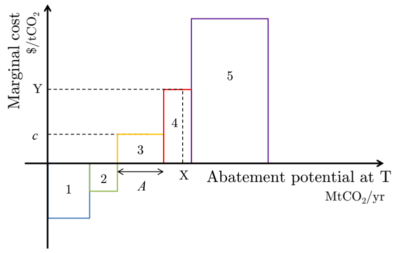


Figure 5.1: A measure-explicit marginal abatement cost curve. The general appearance of the curve makes it easy to misinterpret it as an abatement supply curve, leading to the misguided conclusion that the "abatement demand" X should be met with measures 1 to 4 only (possibly using the carbon price Y).

due to co-benefits such as energy efficiency gains or positive impact on health, and that many others will be inexpensive (in terms of net present social value). This information can help governments decide how ambitious their mitigation strategy will be, and make informed domestic and international commitments (in the UNFCCC context, for instance). It is also helpful for policy makers searching for synergies and co-benefits, for instance between emission reduction and economic development.

The academic literature on MAC curves has extensively discussed the plausibility of energy efficiency options that would reduce emissions at net negative costs. In general, MAC curves do not factor in implementation barriers on these options, such as split incentives, lack of information, behavioral failures, or lack of resources (Allcott et Greenstone, 2012; Kesicki et Ekins, 2012).[1] According to this literature, overcoming such barriers may be costly enough to reduce significantly the economic benefits from energy savings. To date, identifying specific barriers and cost-effective ways of working around them remains a policy-relevant challenge (e.g., Giraudet et Houde, 2014).

The issue discussed here is different. Because they rank options according to their cost — from the least to the most expensive — MAC curves look like abatement supply curves (Fig. 5.1), and are frequently interpreted as such (e.g. Haab, 2007; DECC, 2011). According to this interpretation, the optimal emission-reduction strategy would

[1]The *investor's MAC curves* commissioned by the EBRD are noticeable exceptions, as they factor energy subsidies, the high cost of capital that the private sector faces, and positive transaction costs in their assessment of the abatement cost of each option (NERA, 2011b, 2012, 2011a).

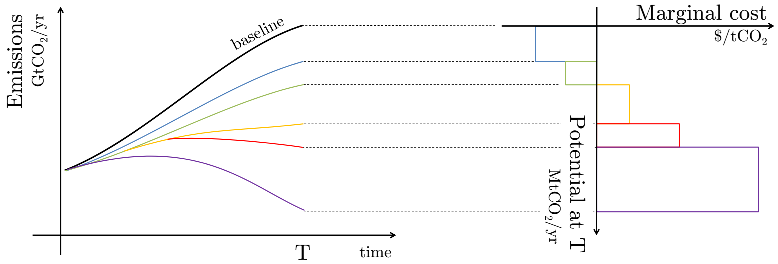
be to "*implement the cheapest measure first, preferring measures with a lower total saving potential but more cost-effective than those with a higher GHG saving potential in absolute terms*" (Wächter, 2013). In this paper we show why this strategy is not the optimal one, we propose a new graphical representation of MAC curves that avoid this misinterpretation, and we derive broader policy implications on the design of climate mitigation strategies.

In addition to the cost and potential, a key parameter of emission reduction options is the speed at which they can be implemented. Speed is limited by factors such as (1) long capital turnover, (2) slow technological diffusion, (3) availability of skilled workers, (4) availability of relevant specific capital, such as production lines, (5) availability of funds or (6) institutional constraints.[2] As a consequence, some high-abatement-potential measures, such as switching to renewable power or retrofitting existing energy-inefficient buildings, may take decades to implement. While the cost and potential displayed in a MAC curve are frequently assessed with such maximum speed in mind, the diffusion speed itself is almost never displayed in the MAC curve or generally disclosed to decision-makers.

With a simple theoretical model, Ha-Duong et al. (1997) find that this *technical inertia* (using the wording by Grubb et al., 1995) means that the optimal *quantity* of short-term abatement depends on long-term objectives — an extensive literature based on integrated assessment models has reached the same conclusion (e.g. Luderer et al., 2013a; Bertram et al., 2015; Riahi et al., 2015). Using a theoretical MAC curve, Vogt-Schilb et Hallegatte (2014) show that the *quality* of abatement is also important. The authors argue short-term abatement targets should be reached with some of the high-potential but long to implement measures that will make deeper decarbonization possible in the long term, even if these are not the less expensive measures available in the short term. As a consequence, focusing on short-term targets (e.g., for 2030) without considering longer-term objectives (e.g., for 2050 and beyond) would lead to carbon-intensive lock-ins, making it much more expensive (and potentially impossible) to achieve the long-term objectives.[3]

[2]In this paper we assume implementation barriers make the implementation of measures slower, without affecting their cost. In economic theory, an alternative approach is to consider adjustment costs that capture a trade-off between implementing options quickly and implementing them at low cost (Vogt-Schilb et al., 2014b; Lecuyer et Vogt-Schilb, 2014).

[3]A related line of argumentation is on learning by doing and directed technical



Wedge curve   Flipped MAC curve

Figure 5.2: A "flipped" achievable-potential MAC curves next to the corresponding emission reduction scenario (wedge curve). By displaying together the cost, the potential, and the time required to implement the options, confusion on how to interpret MAC curves may be avoided.

In this paper, we apply Vogt-Schilb and Hallegatte's method on a MAC curve built at the World Bank for studying low-carbon development in Brazil in the 2010-2030 period (de Gouvello, 2010). Lack of data beyond 2030 does not allow us to investigate how using only the 2010-2030 MAC curve to design a mitigation strategy would lead to suboptimal choices in view of longer-term objectives (2050 and beyond). We can however investigate this problem by assuming that we want to achieve an objective for 2030, and that we use the MAC curve to design a mitigation strategy for the 2010-2020 period only.

We find that a strategy for 2010-2020 that disregards the 2030 target under-invests in clean transportation infrastructure such as metro and train; and over-invests in marginal, cheap but low-potential options, such as heat integration and other improvements in existing refineries. In other words, developing clean transportation infrastructure in the short term is appealing only if the long-term abatement target is accounted for. In addition, we find that not developing clean transportation infrastructure in the short term (by 2020) closes the door to deeper emission reductions in the middle (2030) and longer term. Loosely speaking, the 2020 strategy provides a sensible *quan-*

change (Gerlagh et al., 2009; Acemoglu et al., 2012; Kalkuhl et al., 2012). Many of the technologies used to reduce emissions — for instance more efficient cars or renewable energy — are still in the early stage of their development, such that their cost will decrease as their deployment continues. Many authors have found in a variety of settings that this is a sound rationale to use expensive options in the short term (e.g., Rosendahl, 2004b; del Rio Gonzalez, 2008; Azar et Sandén, 2011). In the present work, we account for technical progress only to the (limited) extent that it can be captured by the slow technological diffusion encompassed in our diffusion speed constraint.

tity of abatement by 2020, but abatement is of insufficient *quality* to reach the 2030 target. These results stress the need for policymakers to take into account long term targets and the limited speed at which emission-reductions may be implemented when deciding on short-term action.

We derive two conclusions from this work.

First, MAC curves do not report a very important piece of information, namely the implementation pace of each measure and option. We suggest that when MAC curves are produced, they should be presented together with the corresponding emission reduction scenario — using the graphical representation that Pacala et Socolow (2004), Williams et al. (2012) and Davis et al. (2013) call *wedge curves* — making the dynamic aspect of the mitigation scenarios more explicit (Fig. 5.2). Note that this proposal concerns only the graphical communication of abatement measures, their impact on greenhouse gas emissions over time, and their cost; without any prescription on the method used to assess those numbers.

For instance, emission reduction potentials and costs are frequently assessed from expert surveys (e.g. ESMAP, 2012). MAC curves built this way would be greatly improved by an explicit discussion of implementation barriers and factors limiting the pace at which emission reductions may be achieved with each particular measure (see B for suggested guidance for the experts in charge of collecting the information to build a MAC curve). This information would be particularly useful for decision makers if it permits identifying distinct bottlenecks (e.g. availability of skilled workers) that can be translated into specific policies (e.g. training).

Emission reduction scenarios, costs and potentials can also be derived from energy system models (Kesicki, 2012b).[4] These models account for the limited ability to implement emission-reduction measures by building in particular on maximum investment speeds (Wilson et al., 2013; Iyer et al., 2015), making them suitable for studying path dependency in emission reduction strategies (Kesicki, 2012a). MAC curves built this way can also be presented next to the corresponding wedge curve, as in Fig. 5.2. In this case also, the policy debate is improved by an explicit discussion of how the growth constraints are calibrated

[4] While existing MAC curves in the gray literature are mainly derived from expert surveys, the academic literature frequently studies emission reduction pathways with energy system models or integrated assessment models.

in the models (Wilson et al., 2013; Iyer et al., 2015).

Second, climate change mitigation policies are designed for a relatively short term horizon (e.g., 2020 or 2030), while mitigation objectives go beyond this horizon (e.g., the EU has a 2050 objective). Most importantly, stabilizing climate change and tackling other environmental threats will require a reduction in emissions to near-zero levels by the end of the century (Collins et al., 2013; Steinacher et al., 2013); following the wording by Sachs et al. (2014), *any* climate stabilization target requires *deep decarbonization*.

An ideal policy would be to announce well in advance a perfectly credible long-term target to a forward-looking market. In practice, however, governments have limited ability to commit, and markets cannot perfectly anticipate future regulations (Golombek et al., 2010; Brunner et al., 2012). Following the World Bank (2012, p. 153), we thus suggest to combine a "synergy approach" focusing on mitigation options that provide co-benefits in terms of development, economic growth, job creation, local environmental quality, or poverty alleviation, with an "urgency approach", based on defining long-term objectives and working backward to identify which measures are needed early to achieved stated objective.

Accordingly, sector-specific mitigation policies have two roles: (i) to remove implementation barriers on negative- and low-cost options, and (ii) to ensure short-term targets are met without under-investing in the ambitious and long-to-implement abatement measures required to achieve otherwise-difficult-to-enforce long-term targets. In other words, these policies should ensure that the mitigation strategy reaches not only the desired quantity of abatement at a given date, but also a sufficient quality to make further emission reduction possible.

This second argument for sector-specific policies, in line with Waisman et al. (2012), remains a novelty in the academic literature: to date, such policies have been discussed as a way to tackle several market failures or policy objectives, including learning by doing (Sandén et Azar, 2005; Fischer et Preonas, 2010); to correct for the effects of misperceived energy savings (Tsvetanov et Segerson, 2013; Parry et al., 2014); to complement an imperfect carbon-pricing mechanism (Lecuyer et Quirion, 2013); or as a political economy constraint (Hallegatte et al., 2013; Jenkins, 2014; Rozenberg et al., 2014).

The rest of the paper is structured as follows. In section 1, we review different types of MAC curves. While the construction of MAC curves sometimes requires to investigate the diffusion speed of emission-reduction options, MAC curves do not report separately the long-term abatement potential and the diffusion speed. In section 2, we reanalyze the data from the Brazilian MAC curve. We extract the cost, long-term potential and diffusion speed of each emission-reduction measure, and use them in a simple optimization model to investigate the least-cost emission-reduction schedule, depending on whether the objective is to reach a 2030 target or the corresponding 2020 target. We conclude in section 3.

1 Existing MAC curves

We call *measure-explicit MAC curves* (MAC curves for short) these which represent abatement costs and potentials of a set of mitigation measures.[5] Measure-explicit MAC curves have been developed since the early 1990s (Rubin et al., 1992), and have reached a wide public after McKinsey and Company published assessments of the cost of abatement potentials in the United States (McKinsey, 2007) and at the global scale (Enkvist et al., 2007). This type of curve is increasingly used to inform policy makers. For instance, McKinsey currently lists MAC curves for 15 different countries or regions on its website. The World Bank also uses MAC curves routinely (ESMAP, 2012), and has recently developed the MACTool to build them (see below). Similar depictions have been used by other institutions (e.g., Climate Works Australia, 2010; NERA, 2011a; CE Delft, 2012; O'Brien et al., 2014) and to analyze other climate-change related topics, such as waste reduction, energy savings and water savings (see Kesicki et Ekins, 2012, who also offer a richer historical perspective).

Depending on their implicit definition of the abatement potential of a measure, two types of measure-explicit MAC curves can be distinguished.

[5] While the literature consistently calls these curves *marginal* abatement cost curves, in most occasions the cost of each option is computed as an *average* cost, as the net present cost of using that option instead of the baseline option, divided by discounted avoided emissions. Marginal and average costs are equal only if the unit cost of abatement is constant. Note that potentials spreading over large range of abatement costs may be split into smaller potentials of nearly constant abatement cost (Kesicki, 2012b), for instance reporting gas for base load and gas for peak power separately.

1.1 Full potential MAC curves

The full-potential approach gives information on how much GHG could be saved if the measure was used at its technical maximum. It is calculated against a reference or baseline technology, as for instance those used in the present (Wächter, 2013), taking into account the carbon intensity and imperfect substitutability of different technologies. For instance, this approach assesses what fraction of passenger vehicles can be replaced by electric vehicles (EV), accounting for limited driving range and exiting mobility practices. Given emissions from baseline vehicles (e.g. 140g/km today in Europe) and emissions from EVs (say 30g/km), one can compute an amount of emissions avoidable using electric vehicles. Rubin et al. (1992) use this approach. For instance, they assess the potential of nuclear power (in the US) as the quantity of GHG that would be saved if nuclear replaced all the fossil fuel capacity used for base load and intermediate load operation in 1989.

The main value of full potential MAC curves is descriptive: they highlight to which extent some key measures could reduce emissions in the long-run. One weakness is that full-potential MAC curves cannot easily represent the competition between two measures.[6] Finally, full-potential MAC curves do not require investigation of possible diffusion constraints, but these may be assessed separately to build resulting emission reduction scenarios (e.g. World Bank, 2013).

1.2 Achievable potential MAC curves

Achievable-potential MAC curves have a prospective dimension, as they are built for a date in the future. This approach fully acknowledges that large-scale diffusion of new technologies can take decades (Grübler et Messner, 1998; Grübler et al., 1999; Wilson et al., 2013). In this context, the abating potential of a technology is an assessment of the abatement that could be achieved with such a technology if it was implemented at a given speed, starting at a given date. For instance, this approach takes into account that even ambitious fiscal incentives in favor of electric vehicles would induce a limited increase of EV sales,

[6] For instance, if fuel-cell vehicles are much more expensive than EVs, but do not suffer from limited autonomy, the optimal strategy would be to use EVs when possible (say for 25% of the fleet), and fuel cell vehicles otherwise. In this case, the full-potential MAC curve could depict an abatement potential of 25% of private-mobility related emissions for EVs, and 75% for fuel cell. In the absence of EVs, fuel cell vehicles could abate 100% of private mobility emissions, but this information would not appear in the curve.

resulting in a limited share of EVs in the fleet, hence limited emission reductions from EVs by 2020 or 2030. The potential achievable by a given date is therefore lower or equal than the full potential reported on full potential MAC curves.

A key advantage of the achievable-potential approach is that it requires investigation of reasonable assumptions regarding the possible implementation speed of a measure (e.g. 1% of the dwellings can be retrofitted each year). This information is key for a policy maker scheduling emission-reduction investments. Unfortunately, assessed diffusion speeds are not displayed in the resulting MAC curve, and are not always discussed in the accompanying reports.

Most expert-based MAC curves published in the gray literature are constructed this way — see for instance McKinsey (2009, p. 46), or Pellerin et al. (2013, p. 22). The few curves built using integrated assessment models are also achievable-potential MAC curves (Kesicki, 2012b).
Achievable-potential MAC curves are built from emission-reduction pathways (Fig. 5.2), that are investigated taking into account at least some inter-temporal dynamics and sector-specific constraints. It is thus logically inconsistent to conclude from an achievable-potential MAC curve that emission-reduction should be implemented sequentially in the "merit order", cheapest first. The original emission-reduction pathways already provides an answer to when and where to reduce GHG emissions. Unfortunately, achievable-potential MAC curves have been frequently used overlooking their caveats, in particular in the media and policy debate (Haab, 2007; Kesicki et Ekins, 2012).

One weakness of the achievable potential is that it makes the slow diffusion process indistinguishable from the full potential. The reader of a MAC curve does not know, for instance, if a small potential for abatement from residential building retrofit means that residential buildings are already almost entirely retrofitted in the region (the full potential is low), or it if means that only a small fraction of buildings may be retrofitted during the period (the diffusion is slow).

The MAC curve we reanalyze in this paper is an achievable-potential MAC curve. In each economic sector, emission reduction scenarios have been assessed taking into account constraints on implementation and maximum diffusion speeds (de Gouvello, 2010).

1.3 MAC curves at the World Bank: MACTool

The World Bank develops and promotes a piece of software called MACTool, which can produce achievable-potential MAC curves. One aim of the MACtool is to provide policy makers with a common framework to analyze available mitigation measures. MACTool takes as inputs the key socio-technical parameters of a set of large mitigation measures, and macroeconomic variables. For instance, technology options to produce electricity are characterized by required capital and operation expenditures, as well as their lifetime, energy efficiency and type of fuel used. Physical constants as the carbon intensity of each fuel are factored in. The user must also specify at least one scenario on the future macroeconomic variables of interest, such as the price of fossil fuels and the future demand for electricity. Finally, the user must provide scenarios of future penetration of (low-carbon) technologies and measures, in both a baseline and at least one emission-reduction pathway (ESMAP, 2014).

As outputs, MACTool computes the amount of GHG saved by each measure in the long run (in $MtCO_2$), and the cost of doing so (in $\$/tCO_2$). This information is illustrated with two figures: an achievable potential MAC curve, and an abatement wedge curve.

The tool itself does not provide information on what is achievable, this information comes directly from the input scenarios. Input scenarios therefore need to be built taking into account the constraints on technology diffusion and implementation speed. For instance, these scenarios may come from integrated assessment models that factor such constraints in, or be built by sector experts who guesstimate possible penetration scenarios (Kesicki et Ekins, 2012).

In addition to the classical abatement cost and abatement potential, MACTool reports the investment needed in different emission reduction scenarios. MACTool can also compute the carbon price signal that would be required to trigger investments from the private sector, taking into account any private discount rate. These can be different from the social discount rate to reflect different opportunity costs of capital in sectors where funding is restricted, different risk premiums in different sectors, and particular fiscal regimes.

2 Proof of concept: Re-analyzing the case of Brazil by 2030

In a theoretical framework, Vogt-Schilb et Hallegatte (2014) find that using a MAC curve as a supply curve — that is disregarding constraints on implementation speed and focusing on short-term targets — would lead to suboptimal strategies, making the longer-term target more expensive to reach. In some cases, doing so would even lead to a carbon-intensive lock-in, making the longer-term target impossible to reach. They show how a simple optimization model that factors implementation speed in the analysis can be used to avoid this problem.

Here, we perform a proof of concept for these ideas, reanalyzing the data used at the World Bank to create a MAC curve for Brazil with MACTool (de Gouvello, 2010).

We first extract the long-term potential and emission-reduction speed from the emission-reduction pathway that was provided to MACTool, and use them to calibrate the model.

We then take the point of view of a social planner who chooses in 2010 an emission-reduction schedule to comply with an emission target, in two different simulations. In the first one, an emission-reduction target is set for year 2030 and the optimal emission strategy is derived. Then, the *quantity* of abatement obtained in 2020 in this optimal strategy is used as a target for 2020, and the MAC curve is used to design a mitigation strategy between 2010 and 2020, disregarding the longer-term objective. Finally, we investigate differences of the optimal emission reductions up to 2020 in the two simulations.

We find that because of technical inertia, using a MAC curve without taking into account long-term objectives would lead to insufficient short-term investments in metro, rail, waterways, and bullet train, all options with high potential, large costs and slow implementation speed. Instead, the abatement target is met by implementing marginal energy-efficiency improvement in refineries, which provide "lower-quality" abatement. Indeed, while these options are lower cost than clean transportation infrastructure, they have a much lower abatement potential in the long term, meaning that using them in the short term not opening the door to deeper reductions in the long-term.

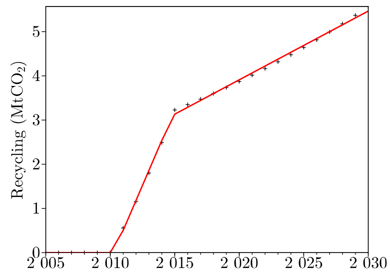


Figure 5.3: Emission reductions achieved over time thanks to recycling. This particular emission-reduction measure illustrates that many emission reduction pathways (the plus signs +) may be approximated by a piecewise-linear curve (in red). The slope of the first piece provides the diffusion speed for that measure. The second part is interpreted as the maximum potential, that grows over time.

2.1 Methods and data

We use a spreadsheet program based on the model proposed by Vogt-Schilb et Hallegatte (2014). The program provides the least-cost emission-reduction schedule that complies with the abatement target. As inputs, it requires a list of measures, characterized by a marginal abatement cost, a maximum diffusion speed, and a maximum abatement potential (A).

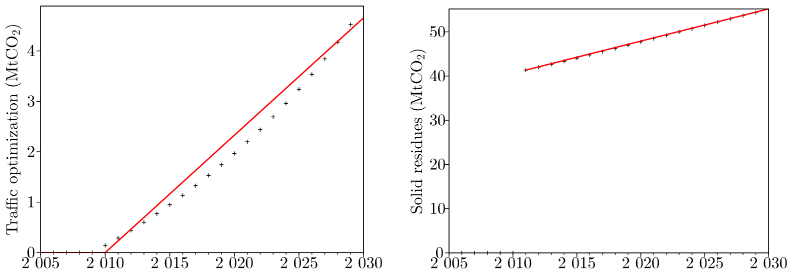
Note that the abatement potential may evolve through time. For instance, if available technology limits intermittent wind power to 20% of the electricity production and electricity production is expected to grow over time, then the abating potential of wind power grows over time. On the other hand, if natural resources provide only few opportunities to build dams, the abating potential of hydro power is fixed, regardless of total electricity demand growth. We thus extend the model by Vogt-Schilb et Hallegatte (2014) to allow for growing abatement potentials (see below and A).

We use data collected at the World Bank to build a MAC curve (using MACTool) for Brazil (de Gouvello, 2010). The MAC curve provides a list of emission-reduction measures, their marginal abatement cost, and the potential achievable by 2030.

While the list of measures and their cost can be used directly in our spreadsheet program (see the first two columns of Tab. 5.1), our program requires the full-abatement potential and diffusion speed. Since the diffusion speed and the full-abatement potential were not reported

Measure	MAC $\$/tCO_2$	Diffusion speed $ktCO_2$	Potential in 2010 $MtCO_2$	Potential growth $ktCO_2$
Combustion optimization	-28.4	955	3.3	218
Heat recovery	-59.6	168	0.6	37
Steam recovery	-62.4	339	1.1	77
Furnace heat recovery	-12.8	1685	9.3	701
New processes	25.8	1200	4.5	265
Other Energy Efficiency	-7.5	162	0.6	35
Thermal Solar	-34.8	233	0.8	53
Recycling	-23.6	679	2.3	155
Natural gas	0	397	1.3	90
Biomass	4.3	716	·	·
Reforestation	·	·	26.9	1002
Wind	64	138	1.2	0
Comb. Heat Power	-43.2	1516	5.7	241
Solar heat	83.9	18	·	·
Air conditioning	419.1	·	0	0
Residential Lightning	-91.9	·	0.1	0
Cooler	5.2	79	·	·
Motor	-5.8	13	·	·
Industrial Lightning	-36.2	3	·	·
Commercial lightning	-27.3	9	·	·
GTL	0.6	1021	·	·
New Refineries	16.4	352	·	·
Refineries Heat Integration	10.9	510	3.1	37
Refineries Fouling Mitigation	45.8	59	0.5	0
Refineries Advanced Control	79.1	59	0.5	0
Ethanol	1.8	1444	·	·
Rail and Waterways	23.3	494	·	·
Bullet train	376.3	45	0.9	0
Rapid transit bus	42	·	0	0
Metro	95.7	1007	·	·
Traffic optimization	0.2	232	·	·
Bike Lanes	2.6	120	·	·
Solid residues	2.1	·	40.5	728
Resid. wastewater	7.8	513	·	·
Indust. Wastewater	80.4	147	8	333
Restauration	·	5899	·	·
Livestock and Forest	0.7	228898	229.4	6580
Tilage	-0.2	2578	17.6	185

Table 5.1: Calibrated speed, cost and potential of the measures in the Brazilian study. A dot (·) denotes lack of reliable data.



(a) No potential

(b) No speed

Figure 5.4: Emission reductions achieved over time thanks to traffic optimization and management of solid residues. For some abatement measures, the data needed to calibrate our model cannot be derived from the emission-reduction pathways. Traffic optimization (a) is an example of measure for which the long term potential is not binding because it cannot be reached before 2030. Solid residues (b) exemplifies that for some other measures, the diffusion speed cannot be assessed — either it was not investigated, or the measure can reach its full potential in less than one year.

separately, we have to reconstruct them with indirect methods, using the emission-reduction pathways that were provided to MACTool. For each measure, the shape of the emission-reduction pathways can be classified in one out of three cases.

In the first case, emission-reduction pathways may be approximated by a two-phases piecewise-linear function as in Fig. 5.3. In this case, the diffusion speed is given by the slope of the first piece, and the second phase is interpreted as the growing full potential. About half the measures fall in this category.

Other emission-reduction pathways may be approximated by a single linear diffusion (Fig. 5.4a). In this case, the full potential is not binding before 2030. We calibrate the diffusion speed from the slope of the penetration pathway, and denote the lack of data on the full potential with a dot $(\cdot)$ in the two last columns of Tab. 5.1.

In some other cases the emission-reduction pathway lacks the first phase; abatement immediately "jumps" to a growing full-potential (Fig. 5.4b). We denote them with a dot in the diffusion speed column in Tab. 5.1. There is usually a handful of such cases in MAC curves exercises. One example from the Brazilian study is solid residues management. In the emission-reduction pathway, solid residues management is able to reduce emissions by more than 40 $MtCO_2$ in one year, and then grow at less than 1 $MtCO_2$/yr. From the perspective of the user of a MAC curve, it is unclear whether this should be considered as a shortcoming in the data (if the investigation could not identify the constraints that limit the diffusion of solid residues management), or a realistic emission-reduction pathway (if solid residues management can actually save lots of GHG in a short time lapse).[7] To avoid this situation in the future, we recommend that the terms of reference for the experts in charge of collecting data on emission reductions options should explicitly ask to report possible diffusion speeds (B).

Finally, some emission-reduction measures (reforestation, air conditioning and rapid bus transit) were included in the list while lacking either a marginal abatement cost or an emission scenario. These measures, as well as those for which the diffusion speed could not be estimated, are discarded for the rest of the analysis. The remaining options allow to reduce Brazilian emissions in 2030 by 223 $MtCO_2$ (compared with 812 $MtCO_2$ in the original MAC curve).

2.2 Results

In a first simulation, we run our spreadsheet model to design the socially optimal strategy to achieve 223 $MtCO_2$ of emission reductions by 2030. The optimal emission-reduction strategy has the following characteristics.

First, all negative-cost measures are introduced at full speed from year 2010, independently of the emission-reduction target. Indeed, these measures are desirable *per se*, as they bring more benefits than costs even in the absence of any carbon pricing or climate change impacts.[8]

Second, the least-cost strategy is to implement the positive-cost

[7] Livestock and forest management is a particular example. In the emission-reduction pathways, this measures allows to save 229 $MtCO_2$, that is almost one third of the total abatement potential by 2030, as soon as 2010. Since Brazil has already managed to reduce drastically its emissions from deforestation (-80% between 2004 and 2009), the study considered that this mitigation option is already enforced. Sustaining such effort over a long period will require that productivity gains in the livestock sector free-up pasture land fast enough to accommodate the growth of the livestock-agriculture sector without deforesting, as recommended in the Brazil Low-carbon study (de Gouvello, 2010).

[8] Remember that our framework accounts for implementation barriers that lower the speed at which emission reduction options may be implemented, but do not increase their cost.

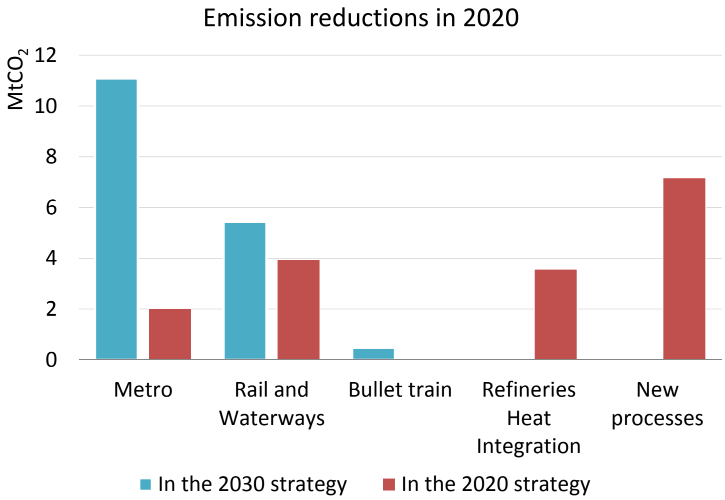
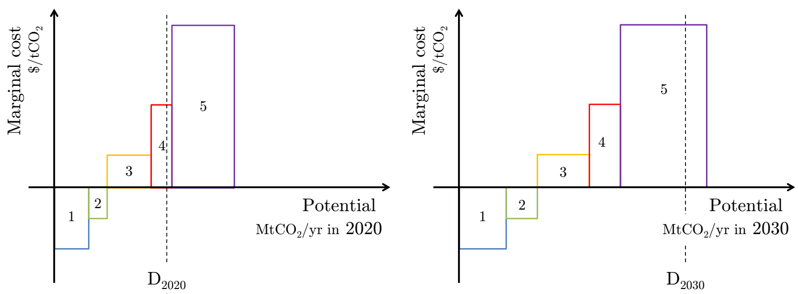


Figure 5.5: Comparison of emission reduction achieved in 2020 with a set of measures when the 2020 target is the final target vs. when it is a milestone toward a more ambitious 2030 target. The picture shows the five emission-reduction for which the difference between the two strategies are the largest.



(a) Achievable by 2020 **(b)** Achievable by 2030

Figure 5.6: Two achievable-potential MAC curves, built for 2020 and 2030. The 2020 MAC curve (a) suggests that the 2020 target (D_{2020}) can be met using only options 1–4, disregarding option 5 before 2020. But then only a fraction of option 5 could be implemented between 2020 and 2030. The 2030 MAC curve (b) however shows that options 1–5 should be implemented by 2030 to meet the D_{2030} target. For option 5 to deliver all the abatement listed by 2030, it should be implemented before 2020.

measures as late as possible, to benefit from the discount rate. This means that under climate targets expressed as an emission reduction in one point in time, such as -30% by 2030, the two-phase penetration pictured in Fig. 5.3 is not optimal for positive-cost measures. A better solution is to delay the implementation such that the maximum potential is reached just in time, when the target needs to be achieved.[9]

Finally, the optimal emission reduction pathway to achieve 223 $MtCO_2$ in 2030 leads to 127 $MtCO_2$ of emission reductions in 2020.

To investigate how focusing on short-term targets may lead to sub-optimal outcomes, we run a second simulation with the only constraint of reducing emissions by 127 $MtCO_2$ in 2020. We then investigate how the "optimal" solution provided by our model in this case compares to the first simulation.

In line with Vogt-Schilb et Hallegatte (2014), the least-cost strategy for 2010-2020 uses different emission-reduction options, depending on whether the strategy aims at a short-term target (127 $MtCO_2$ in 2020) or at a longer-term one (223 $MtCO_2$ in 2030). This is shown in Fig. 5.5, which depicts emission reductions achieved by 2020 in the two strategies, for selected emission reduction options. We chose the five emission-reduction measures with the highest difference between the two scenarios. The simulation that ends in 2020 uses notably less investment in metro and other clean transportation infrastructure, and more heat integration and other marginal improvements in existing refineries than what the 2030 simulation does by 2020.

Indeed, clean transportation infrastructure is characterized by a large abatement potential, and high cost per ton of CO_2 avoided. As illustrated in Fig. 5.6, these options are not implemented when short-term target masks the longer-term target. In addition, clean transportation infrastructure also takes a long time to implement, meaning that in the 2030 scenario, it is implemented as fast as possible — confirming the need for short term investment in clean infrastructure, as recently advocated by Waisman et al. (2012); Framstad et Strand (2013); Kopp et al. (2013); Lecocq et Shalizi (2014) and Avner et al. (2014).

Moreover, because it takes so long to build clean transportation in-

[9]This is a downside of targets expressed in terms of reductions at one point in time. If the climate mitigation target was expressed in terms of a carbon budget (consistently with climate change physics, Zickfeld et al., 2009), then the two-phase penetration target would be optimal (Vogt-Schilb et Hallegatte, 2014, section 4).

frastructure, not starting doing it before 2020 closes the door to deeper emission reductions by 2030. Indeed, reaching the 2030 target requires the implementation of 95 additional $MtCO_2$ of abatement between 2020 and 2030. However, a 2020-2030 strategy would be able to save 84 $MtCO_2$ additionally at best, since not enough time would be left to deploy time intensive solutions. This new low-carbon scenario would therefore be short 11 $MtCO_2$ or 12% in 2030 compared to the first best. In other words, the 2030 target becomes impossible to achieve after 2020, as the limited diffusion speed prevents high-abatement-potential options to achieve their optimal 2030 level in only 10 years. This is an example of how delayed action in key sectors can create carbon lock-ins.

3 Conclusion

In order to put the economy on the track to deep decarbonization, 9 $MtCO_2$ of abatement achieved with metro may be worth more than 11 $MtCO_2$ achieved with energy-efficiency improvements in refineries; for metro avoids locking the transportation system in carbon-intensive patterns, while energy-efficiency improvement in refineries has limited long-term potential.

Regardless of the process used to generate them, MAC curves cannot communicate this type of information to decision makers: they appear as static abatement supply curves, leaving any caveat regarding the dynamic aspect of mitigation strategies to method sections or footnotes. An easy solution to mitigate this issue may be to systematically display flipped MAC curves next to the corresponding emission-reduction pathway, also known as a *wedge curve* (Fig. 5.2).

More generally, the abatement potential and cost are not sufficient information to schedule emission-reduction measures. Both a long-term objective and the speed at which each option may deliver abatement are instrumental in deciding on the quantity and quality of short-term emission reductions.

With this information, decision makers can design policies aiming to achieve two objectives. The first is to remove implementation barriers on negative- and low-cost options. The second is to ensure short-term targets are met with abatement of sufficient quality – that is without under-investing in the ambitious abatement measures required to achieve long-term targets.

Appendices

A Model

We extend the model proposed by Vogt-Schilb et Hallegatte (2014). As inputs, the model takes a set of measures (indexed by i), their respective abatement potential $A_{i,t}$, (marginal) abatement costs c_i,[10] maximum diffusion speeds v_i, an abatement target $a^\star_T$, set for a date in the future T (e.g. 2020 or 2030), and a discount rate r.

The model computes the least-cost schedule $a_{i,t}$ of emission reductions done with each measure i at each time t:

$$\min_{a_{i,t}} \sum_{i,t} e^{-rt} c_i \, a_{i,t} \tag{5.1}$$

The model takes into account the constraint set by maximum abatement potentials:[11]

$$\forall(i,t), \; a_{i,t} \leq A_{i,t} \tag{5.2}$$

The second constraint on emission reduction is that they cannot grow faster than the diffusion speed v_i, such that:

$$a_{i,t+1} \leq a_{i,t} + v_i \tag{5.3}$$

Finally, the abatement target sets the following constraint:

$$\sum_i a_{i,T} \geq a^\star_T \tag{5.4}$$

An Excel implementation of this model is available online.

B Information collection guidance

The following proposes guidance on how data on emission reduction measures could be collected to take into account the findings of this paper. The objective is to collect data that can be used to build emission reduction pathways and MAC curves in order to inform climate mitigation policies. Asking specifically to disclosure assumptions

[10]The model assumes that abatement costs are linear, such that marginal and average cost coincide.

[11]In the model proposed by Vogt-Schilb et Hallegatte (2014), abatement potentials do not evolve over time. This is the only extension we propose.

on the diffusion speed of each option (3c) should help identify bottlenecks preventing some measures to be implemented.

Note that collecting this data does not require more work that what is currently done to build MAC curves from expert surveys; clarifying the difference between implementation speed and full technical potential may actually facilitate the data-gathering process.

Of course, this sketch should be adapted to local conditions; for instance, it should account for existing plans and projections when defining emission baseline and abatement potentials.

1. Inventory of existing GHG emissions

    (a) Provide the list of GHG emissions at a given date in the recent past. Chose the most recent date for which data is available .

    (b) Provide a breakdown of these emissions by sector, e.g. power generation, industry, buildings, transportation, agriculture. Use sub-sectors where possible, for instance as provided by the International Standard Industrial Classification.

    (c) Describe current output of these sectors.

        i. Use physical measures of output when possible, e.g:

            A. In the transportation sector, use passenger-kilometer and ton-kilometer.

            B. In the power sector, use MWh/yr.

            C. In the residential sector, use number of inhabitants at given comfort.

        ii. Express these emissions in CO_2 equivalent using accepted conversion factors.

2. Prospective: provide projections of future GHG emissions reported in 1 using the same breakdown. Report relevant drivers, such as population projections, GDP growth, etc.

3. List available emission-reduction measures

    (a) Full technological potentials

        i. Provide emission intensity of each activity (e.g., gCO_2/km).

        ii. Provide maximum potential with today's technology: e.g. hydro power limited by river availability, electric vehicles limited by range. If relevant provide maximum penetration rate given political and societal constraints (e.g. if nuclear power is unacceptable).

(b) Costs

   i. Report Capex and Opex separately

      A. Report input-efficiency (e.g. fuel-efficiency and fuel type)

      B. Report input prices (report taxes separatedly)

   ii. Report domestic and foreign expenses separately.

   iii. Report costs used to pay domestic salaries separately

   For instance, a photovoltaic power module can be imported but the installation is paid to a local worker; avoided gasoline use from electric vehicles means less oil imports, but also less tax revenue.

(c) Speed at which new technologies may enter the market. This piece of data assesses the speed at which each option can be implemented – taking into account the required accumulation of human and physical capital.

   i. Report typical capital lifetimes for considered technologies and related technologies in the sector — e.g. cars typically live 12 years.

   ii. Report past penetration rates for similar technologies in the sector — e.g. diesel sales took 30 years to go from 0 to 50% in the past.

   iii. Report current bottlenecks (institutional barriers, available resources) — e.g. available workforce can retrofit 100 000 dwellings per year.

6

Transition to clean capital, irreversible investment and stranded assets

For the past centuries, economic growth has involved the accumulation of fossil-fueled capital, such as coal power plants and gasoline-fueled cars, which release greenhouse gases (GHG) to the atmosphere. To stabilize the resulting climate change and subsequent damages, economies now have to reduce emissions to near-zero levels (IPCC, 2014c); and doing so implies a transition from production based on polluting capital to production based on clean, carbon-neutral capital. In principle, the optimal policy to enforce such a transition is to use a carbon price (Pigou, 1932; Nordhaus, 1991; Pearce, 1991). Combined with targeted innovation policies, a carbon price could redirect investment away from polluting and towards clean capital at a relatively low cost (Acemoglu et al., 2012; IPCC, 2014b).

However, implementing substantial carbon prices may be politically challenging. By inducing a sudden change in prices, environmental taxes may result in the creation of *stranded assets* — polluting capital that has to be discarded because its continued use is not compatible with climate policies.[1] For instance, Johnson et al. (2014) estimate that a carbon price consistent with the 2°C target will strand at least 165 billion US dollars worth of coal power plants worldwide. Stranded assets translate into a visible loss of wealth concentrated in a few vested interests, whose owners may oppose the reform — and in some cases may even have the power to veto it (Olson, 1977; Trebilcock, 2014). Furthermore, absent any alternative in the short term, the carbon price may force households and firms to temporarily reduce consumption, resulting in a short-term drop of income for the whole economy. In other words, the carbon price sets immediate costs on the present generation (and present voters) to the benefits of future generations.[2]

This paper uses a simple model to investigate the transition to low-carbon capital and explore how alternative policy instruments may reduce stranded assets and immediate costs in this transition. We focus on the effect of instruments such as corporate average fuel economy (CAFE) standards in the automobile industry, efficiency standards for new power plants, buildings and appliances, *feebate* programs that tax energy-inefficient equipment and subsidize energy-efficient equipment, or subsidized loans and tax breaks for energy efficiency investment. All these instruments are similar in that they redirect private investment away from polluting capital and toward clean capital without affecting the existing stock of polluting capital, for instance without providing incentive to drive less or operate existing gas power plants instead of existing coal power plants. In this paper, we call these policies *investment instruments* for short.[3]

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[1] The words *stranded assets* are used in the literature to describe stranded fossil fuel resources that cannot be burnt into the atmosphere if a given climate target is to be reached (also called *unburnable carbon*), and man-made capital that have to be retired early because of climate policies, such as coal power plants that become unprofitable after a carbon price is implemented. This paper focuses on stranded man-made capital.

[2] A literature on public attitudes towards environmental taxes suggests that aversion to carbon taxes is partly driven by (i) the perception that they are unfair, as their cost is perceived to fall disproportionately in a few actors ; and (ii) the perception that they are inefficient, absent clean alternatives to polluting activities (e.g., Dresner et al., 2006; Winslott-Hiselius et al., 2009; Kallbekken et al., 2011; Harrison et Peet, 2012). Stranded assets are closely related to these two issues, as they are a symptom of limited availability of clean alternatives in the short-term, and they translate into costs concentrated on a few actors.

[3] A motivation for comparing these two types of instruments is that while some governments have enacted carbon prices (World Bank, 2014), most existing climate policies consist of clean investment instruments (IEA, 2015).

We analyze how using either carbon prices or investment instruments leads to different costs and dynamics of the transition from polluting to clean capital, with a particular focus on stranded assets and the value of existing capital. We use a Ramsey model with two types of capital: *polluting* capital, which creates GHG emissions, and *clean* capital, which does not (as in Acemoglu et al., 2012). We disregard knowledge spillovers and we model the climate change constraint as a GHG concentration ceiling.

Investment is assumed irreversible (Arrow et Kurz, 1970): existing polluting capital cannot be converted back into consumption or transformed into clean capital. We however allow for under-utilization of existing polluting capital, a feature that is generally omitted in multi-sector growth models. Under-utilization means that emission-reduction effort can be divided out between two qualitatively different channels: (i) long-term abatement through accumulation of clean capital instead of polluting capital (e.g. agents buy electric cars instead of gasoline-fueled cars); and (ii) immediate abatement through the underutilization or early decommissioning of polluting capital (e.g. agents drive less or scrap their gasoline cars).

We find that, irrespective of which type of instrument is used, the cost of the climate change policy decomposes as a *technical cost* — the cost of using clean instead of polluting capital — and a temporary *legacy cost* due to the irreversibility of capital.[4] The legacy cost quantifies society's regret for excessive past investment in polluting capital, which becomes a liability when emission-reduction policies are implemented.

Carbon prices and investment instruments lead to the same long-term growth path, in which most installed capital is clean and GHG concentration is maintained at its ceiling. Investment-based instruments and the carbon price however induce different short-term pathways in terms of emissions and costs, and in particular different levels and distribution of legacy costs.

Unsurprisingly, the carbon price minimizes the total discounted cost of the climate change policy. Under a carbon price, investment is redirected towards clean capital until polluting capital has depreciated to a level compatible with the concentration ceiling. In addition, part of the existing polluting capital is stranded if climate policies are stringent —

[4]This result is a novelty *per se*, related to the explicit representation of the irreversibility constraint. It resembles but differs from the "transition costs" due to path-dependence in the innovation process (Acemoglu et al., 2012, 2014).

that is, if the carbon price is high with regard to the marginal productivity of polluting capital over its carbon intensity. Such outcomes are part of the least-cost strategy, because stranded assets reduce legacy costs from excessive past investment in polluting assets. But this strategy sets a disproportionate cost on the owners of polluting capital (and the workers who depend on it). Even in the absence of stranded assets, the carbon price ties a new cost to the utilization of existing capital and thus decreases its market value.

In contrast, investment incentives do not prompt producers to underutilize existing polluting capital, and thus do not create stranded assets. Quite the contrary: by inducing a scarcity of polluting capital, investment instruments increase the market price of existing polluting capital. However, investment instruments create a higher legacy cost, compared to the carbon price: society keeps using obsolete polluting capacities until the end of their lifetime instead of scrapping them — as if refusing to recognize that past accumulation of polluting capital was a mistake. This strategy imposes further abatement efforts on the next generations and increases intertemporal welfare losses. But instead of being paid immediately by the owners of polluting capital in the form of stranded assets, legacy costs are now distributed over the whole society and over time.

These results suggest a trade-off between efficiency and political feasibility of climate change policies. While they are blunt instruments from a welfare perspective, investment instruments may reduce the number of opponents to mitigation policies, making them easier to implement than a carbon price in the short term. And as they transform progressively the production system, investment instruments may prepare the economy and the public to easier implementation of carbon prices in the medium term.

Finally, another important difference between the two types of instruments is their mere *efficacy*. As they do not lead to decommissioning any polluting capital, investment instruments reduce emissions slower than a carbon price, and cannot achieve too stringent GHG concentration targets — while carbon prices could reduce emissions arbitrarily quickly. Empirical evidence suggests that it is still technically possible to reach the 2°C target with investment instruments alone. For instance, Davis et al. (2010) estimate that emissions embedded in existing long-lived capital and infrastructure commits us to a warming of less than 1.4°C. However, findings by Rogelj et al. (2013)

and Johnson et al. (2014) suggest that the least-cost pathway toward a 2°C-compliant economy does involve stranding assets. These results suggest that governments willing to limit global warming below 2°C still have a choice between carbon prices and investment incentives, and that this choice implies a trade-off between minimizing discounted costs and avoiding stranded assets.

Our paper relates to several branches of the literature. First, the literature on instrument choice for environmental policy has long established that the carbon price is the most efficient instrument (Pigou, 1932; Goulder et Parry, 2008; Fischer et Newell, 2008).[5] The distributional impacts of climate change policies have also received attention, but most studies focus on the distribution in terms of different income categories (e.g., Rausch et al., 2010; Fullerton et al., 2012). Few papers explore how different policies set costs on different sectors of the economy. One is Fullerton et Heutel (2010), who find in a two-sector static model that the additional welfare cost of performance standards, compared to that generated by a carbon price, is not supported by the dirty sector, but spread over the clean one.[6] We expand this literature by introducing the dynamics and comparing carbon taxes and investment instruments in the context of a transition to clean capital, with a focus on temporary legacy costs and stranded assets. With our dynamic model, we find that carbon prices and investment instruments lead not only to different distribution of costs between sectors but also over time. Carbon prices indeed lead to a temporary drop in income in the short-run while investment instruments smooth costs over time.

Second, papers have studied how carbon pricing schemes can be designed to avoid stranded assets or compensate firms for stranded assets. Richels et al. (2009) and Williams (2011) note that a policy phase-in, for instance announcing a carbon tax in advance, would give economic actors the time to adjust. Goulder et al. (2010) find that under a cap-and-trade system, the owners of stranded assets may be fully compensated if a fraction of emissions allowances are grandfathered for free; and Goulder et Schein (2013) note that the same result could be

[5]For instance, the extensive literature on CAFE standards stresses that they may create a rebound effect, worsening the effect of unaddressed externalities such as congestion or emission of local pollutants; and slow down capital turnover, reducing the speed at which the new, energy-efficient cars enter the fleet (Anderson et al., 2011). All these important effects are left out of our model.

[6]Giraudet et Quirion (2008) reach a similar conclusion in the case of policies that promote energy efficiency.

obtained with carefully-designed exemptions under a carbon tax.[7] We expand this literature by looking at the impact of investment instruments on stranded assets. We find that investment instruments avoid stranded assets and thereby avoid the temporary economy-wide drop in income which happens with carbon pricing schemes despite compensations.

Last but not least, our paper relates to the literature that studies the transition to a clean economy through the lens of the directed technical change theory (e.g. Gerlagh et al., 2009; Grimaud et al., 2011; André et Smulders, 2014). This literature focuses on the optimal policy mix to tackle both the climate change externality and sector-specific knowledge accumulation and spillovers, but disregards sector-specific accumulation of physical capital. One finding highlighted by Kverndokk et Rosendahl (2007) and Acemoglu et al. (2012, 2014) is that, in the short term, the least-cost policy relies relatively more on research subsidies in the clean sector than on carbon prices. The reason is that the most powerful lever to reduce GHG emissions is to encourage a structural transformation of the economy over the long term, not to distort production decisions in the short term.[8] We expand this literature by considering other policy instruments and analyzing the effect of irreversible accumulation of physical capital on structural change. Our findings suggest that investment instruments help trigger structural change, like research subsidies, and that they avoid stranded assets and associated political costs — at the expense of a higher inter-temporal welfare cost.

The remainder of the paper is structured as follows. Section 1 presents the model and section 2 solves for the *laissez-faire* equilibrium. In section 3 we analyze the least-cost growth path, that can be obtained with a carbon price, which we compare with second-best investment instruments in section 4. In section 5, we study the timing issues of investment instruments and risks of lock-in. Section 6

[7] It is well established that a potential advantage of carbon pricing schemes over regulations — not captured in our model — is that the remaining revenues from carbon pricing can be used to generate a double dividend by reducing other distortive fiscal policies (Bovenberg et Goulder, 1996; Parry et Bento, 2000; Metcalf, 2014; Rausch et Reilly, 2015). Investment instruments do not have this feature, except for taxes on polluting investment (if the revenues are not used to finance a rebate as in feebate schemes). Gas-guzzler taxes provide an example of revenue-raising clean investment instruments.

[8] Grimaud et Lafforgue (2008) also note that, in that framework, R&D subsidies impose a lower cost on the present generation than a carbon tax does.

concludes.

1 Model

We consider a Ramsey framework with a representative infinitely-lived household, who saves by accumulating assets[9], receives income on assets at interest r_t and purchases goods for consumption $c(x_t)$. Their wealth thus evolves as:

$$\dot{a}_t = r_t \cdot a_t - c(x_t) \tag{6.1}$$

At time t, consuming $c(x_t)$ provides consumers with a utility $u\left(c(x_t)\right)$. The utility function is increasing with consumption, and strictly concave ($u' > 0$ and $u'' < 0$).
The household maximizes intertemporal discounted utility W, given by:

$$W = \int_0^\infty e^{-\rho t} \cdot u(c(x_t))\, dt \tag{6.2}$$

where ρ is the rate of time preference.

Firms produce one final good y_t, using two types of available capital: polluting capital k_p (e.g., coal power plants, thermal engine vehicles) and clean capital k_c (renewable or nuclear power, electric vehicles).

Production is used for consumption ($c(x_t)$) and investment ($i_{p,t}$ and $i_{c,t}$).

$$y_t = c(x_t) + i_{p,t} + i_{c,t} \tag{6.3}$$

Investment $i_{p,t}$ and $i_{c,t}$ increase the stock of installed capital, which otherwise depreciates exponentially at rate δ:[10]

$$\dot{k}_{p,t} = i_{p,t} - \delta\, k_{p,t} \tag{6.4}$$

$$\dot{k}_{c,t} = i_{c,t} - \delta\, k_{c,t} \tag{6.5}$$

The doted variables represent temporal derivatives.

[9] Assets are capital and loans to other households.

[10] We assume the same depreciation rate for polluting and clean capital to keep notations simple, but this assumption plays no particular role in the analysis.

Investment is irreversible (Arrow et Kurz, 1970):[11]

$$i_{p,t} \geq 0 \tag{6.6}$$
$$i_{c,t} \geq 0 \tag{6.7}$$

This means that for instance, a coal plant cannot be turned into a wind turbine, and only disappears through depreciation.[12] However, firms may use only a portion q_t of installed capital k_t to produce the flow of output y_t given by:

$$y_t = F(A_t, q_{p,t}, q_{c,t}) \tag{6.8}$$
$$q_{p,t} \leq k_{p,t} \tag{6.9}$$
$$q_{c,t} \leq k_{c,t} \tag{6.10}$$

F is a classical production function, with decreasing marginal productivities, to which we add the assumption that capital can be underutilized. A_t is exogenous technical progress, and increases at an exponential rate over time.

In the remaining of this paper, q_t will be called *utilized capital* and k_t *installed capital*. Although it is never optimal in the *laissez-faire* equilibrium, the underutilization of installed polluting capital can be optimal when a carbon price is implemented.[13] For instance, coal plants can be operated part-time and low-efficiency cars can be driven less if their utilization is conflicting with the climate objective.

Polluting capital used a time t emits greenhouse gases ($G \times q_{p,t}$) which accumulate in the atmosphere in a stock m_t. GHG atmospheric concentration increases with emissions, and decreases at a dissipation rate ε:[14]

$$\dot{m}_t = G \cdot q_{p,t} - \varepsilon m_t \tag{6.11}$$

Note that since emissions are a function of polluting capital and capital has a decreasing marginal productivity, the carbon intensity of output increases with the polluting capital stock.

[11]Following the wording by Arltesou (1999) and Wei (2003) capital is putty-clay.

[12]We leave capital retrofit to further research.

[13]In this paper, underutilization of clean capital is never optimal: $\forall t,\ q_{c,t} = k_{c,t}$.

[14]The dissipation rate allows maintaining a small stock of polluting capital in the steady state. The linear relation between polluting capital and pollution emission is not a necessary assumption but simplifies the notations.

2 *Laissez-faire* equilibrium

In the *laissez-faire* equilibrium, intertemporal utility maximization leads to a classical arbitrage equation which gives the basic condition for choosing consumption over time (A):

$$\frac{\dot{c}}{c} = \frac{-u'(c)}{c \cdot u''(c)} \cdot (r_t - \rho) \tag{6.12}$$

As the elasticity of substitution is positive ($\frac{-u'(c)}{cu''(c)} > 0$), consumption grows if the rate of return to saving r_t is higher than the rate of time preference ρ.

Firms rent the services of polluting and clean capital from households at respective rental rates $R_{p,t}$ and $R_{c,t}$. The flow of profit is given by:

$$\Pi_t = F(A_t, q_{p,t}, q_{c,t}) - R_{c,t} \cdot k_{c,t} - R_{p,t} \cdot k_{p,t} \tag{6.13}$$

A competitive firm takes $R_{c,t}$ and $R_{p,t}$ as given and maximizes its profit by using all installed capital, equalizing at each time t the marginal productivity of polluting and clean capital to their respective rental rates:

$$\partial_{q_b} F(q_{p,t}, q_{c,t}) = R_{p,t}$$
$$\partial_{q_g} F(q_{p,t}, q_{c,t}) = R_{c,t}$$

The classical equilibrium in capital markets in a Ramsey model applies:

Proposition 4. *In the laissez-faire equilibrium, households are indifferent between investing in polluting or clean capital or lending to other households, so that the marginal productivities of clean and polluting capital net of depreciation are both equal to the interest rate :*

$$R_{p,t} = R_{c,t} = r_t + \delta \tag{6.14}$$

In the next section, we find that the carbon price forces the marginal productivity of polluting capital to be higher than that of clean capital. Also, because investment is irreversible, the relative price of polluting capital decreases during the transition. We then discuss implications for the political economy of climate mitigation policies.

3 Discounted welfare maximization: carbon price

In this section, we adopt a cost-effectiveness approach (Ambrosi et al., 2003) and analyze policies that allow maintaining atmospheric concentration m_t below a given ceiling $\bar{m}$:

$$m_t \leq \bar{m} \tag{6.15}$$

This threshold can be interpreted as a tipping point beyond which the environment (and output) can be highly damaged, or as an exogenous policy objective such as the UNFCCC 2°C target (Allen et al., 2009; Matthews et al., 2009b). We solve for the welfare maximization program, in which institutions internalize the GHG ceiling constraint. A social planner maximizes intertemporal utility given the constraints set by the economy budget, the capital motion law, investment irreversibility and the GHG ceiling. The same strategy can be decentralized by imposing the shadow price of emissions on producers and consumers through an optimal carbon tax or a comprehensive cap-and-trade system (appendix C).

The social planner program is:

$$\max_{c,i,k} \int_0^\infty e^{-\rho t} \cdot u(c(x_t))\, dt \tag{6.16}$$

$$\begin{aligned}
\text{subject to } & F(q_p, k_c) - c(x_t) - i_{p,t} - i_{c,t} = 0 && (\lambda_t)\\
& \dot{k}_{p,t} = i_{p,t} - \delta k_{p,t} && (\nu_t)\\
& \dot{k}_{c,t} = i_{c,t} - \delta k_{c,t} && (\chi_t)\\
& \dot{m}_t = G\, q_{p,t} - \varepsilon m_t && (\mu_t)\\
& m_t \leq \bar{m} && (d(m_t))\\
& i_{p,t} \geq 0 && (\psi_t)\\
& q_{p,t} \leq k_{p,t} && (\beta_t)
\end{aligned}$$

We indicated in parentheses the co-state variables and Lagrangian multipliers (chosen such that they are positive): λ_t is the value of income, ν_t and χ_t are the prices of polluting and clean capital, and μ_t is the price of carbon, expressed in terms of utility at time t. The Hamiltonian associated to the maximization of social welfare can be found in appendix B.

The main first-order conditions of our problem are (B):

$$u'(c_t) = \lambda_t = \nu_t + \psi_t = \chi_t \tag{6.17}$$

$$\partial_{k_c} F = \frac{1}{\lambda}\left((\delta+\rho)\chi_t - \dot{\chi}_t\right) \tag{6.18}$$

$$\beta_t = \frac{1}{\lambda}\left((\delta+\rho)\nu_t - \dot{\nu}_t\right) \tag{6.19}$$

$$\partial_{q_p} F = \beta_t + \tau_t \cdot G \tag{6.20}$$

Where τ is the price of carbon expressed in dollars per ton:

$$\tau_t = \frac{\mu_t}{\lambda_t} \tag{6.21}$$

Before the ceiling on atmospheric GHG is reached, a classical result (see for instance footnote 11 in Goulder et Mathai, 2000) is that the carbon price exponentially grows at the endogenous interest rate r_t plus the dissipation rate of GHG (B):

$$\forall t,\ m_t < \bar{m} \implies \dot{\tau}_t = \tau_t \left(r_t + \varepsilon\right) \tag{6.22}$$

The steady state is reached when $m_t = \bar{m}$. In the steady state, atmospheric emissions are stable, implying that polluting capital is constant at $k_{p,t} = \bar{m}\,\varepsilon/G$ ($\dot{m}_t = 0$, eq. 6.11) and the rest of the economy keeps growing on a balanced growth path, thanks to exogenous technical change A_t.

In equations 6.18 and 6.19 we recognize the rental rates of clean and polluting capital $R_{c,t}$ and $R_{p,t}$, as defined by Jorgenson (1967):

$$R_{c,t} := \frac{1}{\lambda}[(\delta+\rho)\chi_t - \dot{\chi}_t] \tag{6.23}$$

$$R_{p,t} := \frac{1}{\lambda}[(\delta+\rho)\nu_t - \dot{\nu}_t] \tag{6.24}$$

where χ_t and ν_t are respectively the clean and polluting capital shadow prices (for buying one unit of capital and keep it forever). As explained by Jorgenson (1967), the relationship between the rental costs $(R_{c,t}, R_{p,t})$ and the prices of capital (χ_t, ν_t) ensures private agents would be indifferent between buying and renting capital, given the depreciation rate δ, the pure preference for present ρ, and the future price of capital (implied by $\dot{\chi}_t$ and $\dot{\nu}_t$).

The following proposition can be deduced from the first-order conditions:

Proposition 5. *Along the optimal path, the marginal productivity of clean capital equals the rental rate of clean capital:*

$$\partial_{k_c} F = R_{c,t} \tag{6.25}$$

The marginal productivity of polluting capital is equal to the rental rate of polluting capital plus the marginal cost of carbon emissions:

$$\partial_{q_p} F = R_{p,t} + \tau_t \, G \tag{6.26}$$

Proof. Equation 6.25 derives from eq. 6.18 and 6.23. Equation 6.26 is obtained by substituting β_t in eq. 6.20, using eq. 6.24. $\square$ $\square$

In the *laissez-faire* equilibrium, the marginal productivity of polluting capital was also equal to its rental rate. This is no longer the case when the pollution externality is internalized, as firms have to pay the carbon tax when they use polluting capital. Also, the rental rate of polluting capital $R_{p,t}$ is no longer equal to that of clean capital, as it is now affected by a *legacy cost*:

Proposition 6. *Along the optimal path, the interest rate r_t that arbitrates between consumption and investment is given by:*

$$r_t = R_{c,t} - \delta \tag{6.27}$$

The rental rate of polluting capital can be lower than that of clean capital:

$$R_{p,t} = R_{c,t} - \ell_t \tag{6.28}$$

Where the legacy cost *ℓ_t is the monetary impact of the irreversibility constraint on the rental rate of polluting capital:*

$$\ell_t = \frac{1}{\lambda_t} \left((\rho + \delta)\psi_t - \dot{\psi}_t \right) \in [0, \; R_{c,t}] \tag{6.29}$$

Note that ψ_t is the Lagrange multiplier associated with the irreversibility constraint in (6.16)*.*

Proof. See B for eq. 6.27. Equation eq. 6.28 is obtained by replacing ν_t by $\chi_t - \psi_t$ (eq. 6.17) in eq. 6.24. Since $R_{p,t} = \beta_t \geq 0$ (eq. 6.19), $\ell_t = R_{c,t} - R_{p,t} \leq R_{c,t}$. $\square$ $\square$

Because investment is irreversible, when the carbon price is implemented the stock of polluting capital cannot be instantaneously adjusted to its long-term level. Polluting capital therefore becomes relatively more abundant and its rental rate decreases.

The legacy cost ℓ_t quantifies the regret that society has because of excessive past investment in polluting capital (e.g. having built a coal power plant before the climate mitigation policy has been announced). It allows decomposing the shadow price of emissions τ_t as a technical abatement cost (e.g. renewable power plants are more expensive than coal power plants) plus the legacy cost:

$$\underbrace{\tau_t}_{\text{Economic cost}} = \underbrace{\frac{\partial_{q_p} F - \partial_{k_c} F}{G}}_{\text{technical cost}} + \underbrace{\frac{\ell_t}{G}}_{\text{legacy cost}} \tag{6.30}$$
$$\text{with } \ell_t \in [0,\ \partial_{k_c} F]$$

The next proposition states that the legacy cost is necessarily strictly positive at the moment when the carbon tax is implemented,[15] but then decreases and reaches zero once polluting capital has adjusted through natural depreciation.

Proposition 7. *Two phases can be distinguished during the least-cost transition to clean capital:*

1. *A phase with strictly positive legacy costs, during which the rental price of polluting capital is lower than the rental rate of clean capital and no investment is made in polluting capital:*

$$\begin{aligned} &0 < \ell_t \leq R_{c,t} \\ &R_{p,t} < R_{c,t} \\ &i_{p,t} = 0 \end{aligned}$$

2. *A phase with zero legacy costs, during which the rental rate of polluting capital is equal to the rental rate of clean capital and*

[15] In the analysis by Arrow et Kurz (1970), the irreversibility constraint is binding only if the initial capital stock is higher than the steady-state level; here, the irreversibility constraint is binding for any level of initial polluting capital because of the new constraint on emissions.

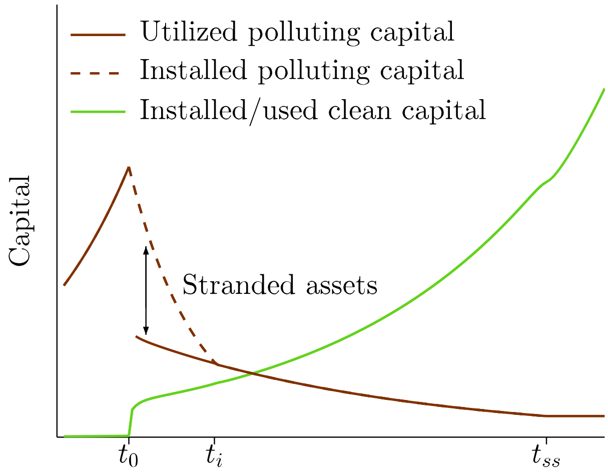

Figure 6.1: Installed polluting and clean capital, and utilized polluting capital in the least-cost transition to clean capital

Note: Before t_0, the economy is on the *laissez-faire* equilibrium, during which the stock of clean capital is small but not null. At t_0 the carbon price is implemented, investment in polluting capital stops, and polluting capital depreciates until t_i ($\forall t \in (t_0, t_i)$, $i_b = 0$). During this period, a portion of polluting capital may be underutilized ($q_{p,t} < k_{p,t}$), becoming stranded assets ($k_{p,t} - q_{p,t}$). The steady state is reached at t_{ss}.

polluting investment is strictly positive:[16]

$$\ell_t = 0$$
$$R_{p,t} = R_{c,t}$$
$$i_{p,t} > 0$$

Proof. Appendix B. □ □

When the transition to clean capital is enforced with a carbon price, the maximum possible value for the legacy cost ℓ_t is the marginal productivity of clean capital $\partial_{k_c} F (= R_{c,t})$: at worst, the social planner regrets not to have invested in clean instead of polluting capital before t_0. In that case, the rental rate of polluting capital falls down to zero, reflecting that polluting capital is overabundant and should be underused:[17]

[16]Investment in polluting capacity net of depreciation is however negative during both phases.

[17]When clean capital is under-utilized, the strictly positive marginal productivity of utilized polluting capital is transferred to households through the tax revenue

Proposition 8. *If the carbon price is higher than the marginal productivity of installed polluting capital, polluting capital is underutilized:*

$$\tau_t\, G > \partial_{k_p} F(k_{p,t}, k_{c,t}) \implies \begin{cases} \ell_t = R_{c,t} \\ R_{p,t} = 0 \\ q_{p,t} < k_{p,t} \\ \partial_{q_p} F(q_p, k_c) = \tau_t\, G \end{cases} \tag{6.31}$$

Proof. Eq. 6.26 implies that the rental rate of polluting capital $R_{p,t}$ is the difference between the marginal productivity of polluting capital and the carbon price. As the rental rate of polluting capital $R_{p,t}$ is equal to the positive multiplier associated to the capacity constraint β_t (eq. 6.19 and 6.24), when the carbon price is higher than the marginal productivity of installed polluting capital the rental rate of polluting capital is nill and capital is underutilized. □ □

Proposition 8 means that stopping to use some of the polluting capital that was constructed before the climate policy is enacted can be part of the optimal strategy to reduce the cost of the transition to clean capital.[18] In other words, stranding polluting assets allows containing legacy costs.

Underutilization of polluting capital depends on the GHG concentration ceiling $\bar{m}$, on the initial stock of polluting capital k_{b,t_0} and on other parameters of the model such as the functional forms of F and u, on the depreciation rate δ and the preference for the present ρ. As illustrated in Fig. 6.2, for a given set of functions and parameters the underutilization of polluting capital happens if initial polluting capital is high (right end of the x-axis) and/or if the ceiling is stringent (lower part of the y-axis).

In this section, we have found that under irreversible investment, society has to live with past mistakes for a while, once it realizes it has been on a non-optimal growth path. A way to limit the associated legacy cost is to give up part of installed polluting capital in order to

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$\tau_t\, G$.

[18] Since in our framework all polluting capital is substitutable, this proposition can be interpreted as an underutilization of the whole stock of polluting capital, with the rental rate of the whole stock falling to zero. Another interpretation is that the most polluting units of capital are decommissioned while the rest of the stock is used at full capacity.

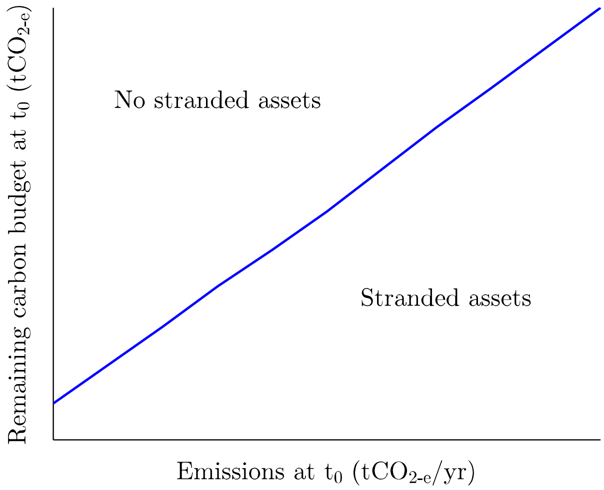

Figure 6.2: Under-utilization of polluting capital as a function of initial emissions and the ceiling.

Note: Depending on initial emissions (i.e. initial brown capital $k_{b,0}$) and on the concentration ceiling ($\bar{m}$), brown capital is underutilized or not in the first-best optimum.

reduce emissions faster (thereby creating stranded assets). In the next section, we find that investment instruments reduce emissions without affecting existing polluting capital (in particular they cannot create stranded assets), and thus increase legacy costs in the transition to clean capital.

4 Investment instruments

Current climate mitigation policies are not limited to carbon prices; many governments rely instead on instruments such as energy efficiency standards, fiscal incentives for green investment (as feebates, which impose additional fees on polluting capital and rebates for clean capital) or direct public investment in "green" sectors (e.g. in public transport). These instruments redirect investment towards clean capital but have no effect on the use of existing capital — we thus call them *investment instruments*.

We investigate the optimal transition to a clean-capital economy using investment incentives and find that (i) investment instruments are less efficient than the first-best carbon price in terms of inter-temporal welfare maximization (they impose higher legacy costs than the carbon price); (ii) investment instruments may reach the same steady state than carbon prices; and (iii) investment instruments induce a full utilization of polluting capital in the short run (they avoid stranded assets), thereby reducing short-term income losses.

One way to trigger the transition to a clean economy is to differentiate investment costs with feebate programs, i.e. fiscal incentives that include subsidies on clean investment ($\theta_{c,t} > 0$) and taxes on polluting investment ($\theta_{p,t} > 0$). With such a feebate program, π_t, the flow of firms' net receipt at time t is equal to:

$$\pi_t = F(q_{p,t}, q_{c,t}) - (\lambda_t - \theta_{c,t})\, i_{c,t} - (\lambda_t + \theta_{p,t})\, i_{p,t} \tag{6.32}$$

where λ_t is the cost of investment (it is the opportunity cost of saving a dollar rather than consuming it). The optimal values of $\theta_{c,t}$ and $\theta_{p,t}$ can be obtained with a constrained maximization of social welfare given the ceiling constraint.

The same steady state as in the social optimum is reached (at a date $t_{ss,2}$ which is different than $t_{ss,1}$ in general). However, investment instruments induce a different short-term transition than a carbon tax. Over the short-run, investment in polluting capital stops, but since firms do not pay carbon emissions directly, it is never optimal to underutilize polluting capital (appendix D). As a consequence, short-term output may be higher than in the first-best strategy:[19]

Proposition 9. *With the second-best feebate program, short-term output is equal or higher than with the first-best carbon price.*

Proof. The first-best carbon price may induce underutilization of polluting capital in the short-run ($q_{p,1,t_0} < k_{p,t_0}$). In the second-best solution, capital is not underused ($q_{p,2,t_0} = k_{p,t_0}$). At t_0, production is thus higher with feebates than with a carbon price $F(q_{p,2,t_0}, k_{c,t_0}) \geq F(q_{p,1,t_0}, k_{c,t_0})$. $\square$ $\square$

Similarly to the carbon price, investment instruments differentiate the marginal productivities of capital (appendix D):[20]

[19] Analytically, the effect on consumption is ambiguous because it involves the offsetting impacts from an income effect (short-term output is higher) and two substitution effect (investment in clean capital is cheaper and investment in polluting capital is more expensive).

[20] Note that the same investment pathways can be reached using taxes on polluting investment alone or subsidies to clean investment alone, since what matters is the sum of the tax plus the subsidy. A tax and a subsidy however lead to different

$$\partial_{q_p} F = \partial_{k_c} F - \underbrace{\frac{1}{\lambda_t}\Big((\rho+\delta)\psi_t - \dot{\psi_t}\Big)}_{\ell_t} + \underbrace{\frac{1}{\lambda_t}\Big((\delta+\rho)(\theta_{c,t}+\theta_{p,t}) - (\dot{\theta_{c,t}} + \dot{\theta_{p,t}})\Big)}_{\tau_{t,2}\ G}$$

where ℓ_t is the legacy cost. In this second-best setting the shadow price of carbon $\tau_{t,2}$ is still equal to a technical abatement cost plus a legacy cost:

$$\underbrace{\tau_{t,2}}_{\text{Marginal economic cost}} = \underbrace{\frac{\partial_{q_p} F - \partial_{k_c} F}{G}}_{\text{technical cost}} + \underbrace{\frac{\ell_t}{G}}_{\text{legacy cost}} \tag{6.33}$$

The legacy cost ℓ_t, however, is no longer bounded by the marginal productivity of clean capital: it is bounded by the shadow price of carbon $\tau_{t,2}$ (D). With the carbon price, indeed, the maximum regret linked to excess past installation of polluting capital was the opportunity cost of not having invested in clean capital (and this cost was borne by the owners of polluting capital who had to underutilize their capital). Here, preventing underutilization is like refusing to recognize that past accumulation of polluting capital was a mistake. When society keeps using obsolete polluting capital instead of early-scrapping it, the legacy cost can be as high as the cost of the carbon emissions generated by the polluting capital. In this case, however, the legacy cost is not borne by the owners of polluting capital, but by future households who will have to increase future mitigation effort.[21]

Figure 6.3 compares the shadow cost of carbon with the first and second-best policies. Investment instruments generate a higher emissions shadow cost than the first-best carbon price, however the dynamics of capital accumulation mean that the social cost of carbon at each point in time does not translate into consumption losses at the same point in time (Vogt-Schilb et al., 2014b). In this case, while investment instruments set a higher shadow cost of carbon at each time t (Fig.

transfers in the society, which can play a key role on the acceptability of a particular environmental policy (e.g Sterner et Höglund Isaksson, 2006; Fischer, 2008). As mentioned in the introduction, subsidies and taxes also differ in that taxes alone can be used to reduce other more distorting fiscal instruments, enhancing the overall efficiency of the scheme.

[21] Or, thinking outside our cost-effectiveness framework, suffer from higher climate change damage.

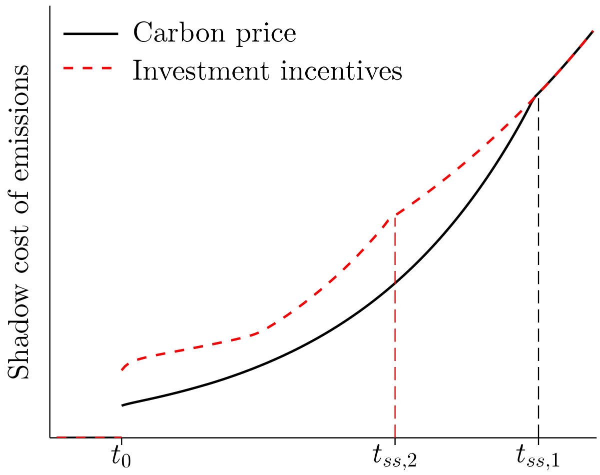

Figure 6.3: Shadow carbon price in the two simulations.

Note: The shadow price of emissions is higher with investment instruments than with a carbon price.

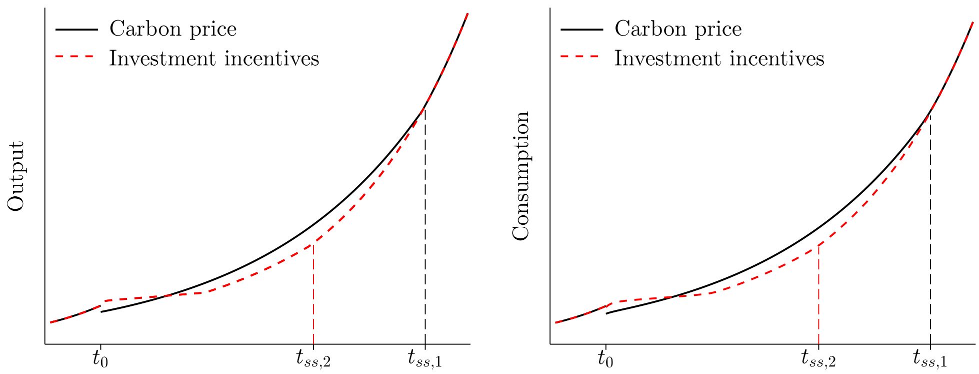

Figure 6.4: Output and consumption in the two simulations.

Note: On the left, output y in the two cases. In the short-run output is lower in the first-best case because of the adjustment of polluting capital utilization. On the right, consumption c is higher in the second-best case because of a higher output y. t_{ss} is the date at which the steady state is reached, it is reached sooner in the second-best case ($t_{ss,2} < t_{ss,1}$).

6.3), they lead to higher output over the short-run (Prop. 9, Fig. 6.4).

Investment instruments yield an emission-reduction pathway that differs only temporarily from the first-best pathway, and smooth the transition costs: they decrease effort in the short-run (Prop. 9), leave them unchanged in the long-run (as the same steady-state is reached at the end, Appendix D), and thus increase effort in the medium-run (Fig. 6.4).

Moreover, feebate programs induce a different intra-generational distribution of abatement effort from the carbon tax, since they avoid stranded assets. By preventing new investment in polluting capital, they even increase the value of existing polluting assets:

Proposition 10. *When a feebate program is implemented, the market price of polluting capital becomes higher than the price of clean capital.*

Proof. First-order conditions for firms' receipt maximization give:

$$\forall t > t_0, \quad \nu_t = \chi_t + \theta_{c,t} + \theta_{p,t} - \psi_t \tag{6.34}$$

where ν_t is the price of polluting capital and χ_t is the price of clean capital. The policy creates a scarcity effect on polluting capital, that increases its price while the irreversibility constraint reduces its price in the short-run. Appendix D shows that the first effect is greater than the second ($\theta_{c,t} + \theta_{p,t} - \psi_t \geq 0$). □ □

To provide a simple example, a gas-guzzler tax on new SUV sales may increase the value of existing SUVs in the aftermarket, as buying a used SUV is a way of evading the fee.

Investment instruments are not limited to feebates. Other examples include performance standards for new vehicles, buildings, and appliances.[22]

Proposition 11. *In our model the optimal feebate program is equivalent to the optimal performance standards on new capital: (1) the two instruments induce the same investment and output pathways and (2) they have the same impact on the price of polluting capital.*

Proof. Appendix E. □ □

[22] Investment instruments can also be provided through financial instruments in favor of clean capital, as the *carbon certificates* proposed by Rozenberg et al. (2013).

Similarly to feebates, performance standards induce a full utilization of existing polluting capital in the short-run and redirect investment towards clean capital. They also create scarcity on existing polluting capital and increase the price of polluting capital.

With this increase in the price of polluting capital, investment instruments over-compensate the owners of polluting capital. A similar over-compensation can occur through windfall profits when 100% of carbon permits are allocated for free in a carbon trading scheme; to avoid over-compensation, the government should allocate only a limited portion of permits for free (Goulder et al., 2010). Note that free allowances do not avoid the other effect of stranded assets, that is a drop in national production and income when the policy is implemented.

One solution to avoid both the income drop and over-compensation for the owners of polluting capital would be to implement a carbon price while subsidizing production from existing polluting capital. Such a set-up would lead to the same investment and production pathway as investment instruments (in particular, it avoids stranded assets) and would maintain, not increase, the price of polluting capital in the short run (Appendix F). Those results corroborate findings by Fischer et Newell (2008); Holland et al. (2009); Fullerton et Heutel (2010), who show, using static models, that performance standards and feebate schemes act as the combination of a carbon tax and a production (or emission) subsidy.[23] With our dynamic model, we find that this shadow subsidy applies only to production with pre-existing polluting capital; it does not provide incentive to invest in new polluting capital. The effect of the subsidy is thus only temporary since once the level of polluting capital has decreased to a sustainable level, investment instruments are equivalent to a carbon tax alone.

5 Timing of action and carbon-intensive lock-in

Since they maintain a full utilization of polluting capital in the short term, investment instruments result in higher short-term emissions than the carbon tax (Prop. 9 and Fig. 6.5). Investment instruments may thus not be sufficient to reach stringent climate objectives if past accumulation of polluting capital is substantive.

[23]In our model, production from dirty capital and GHG emissions are proportional, so that a subsidy on emissions and a subsidy on production have the exact same effects.

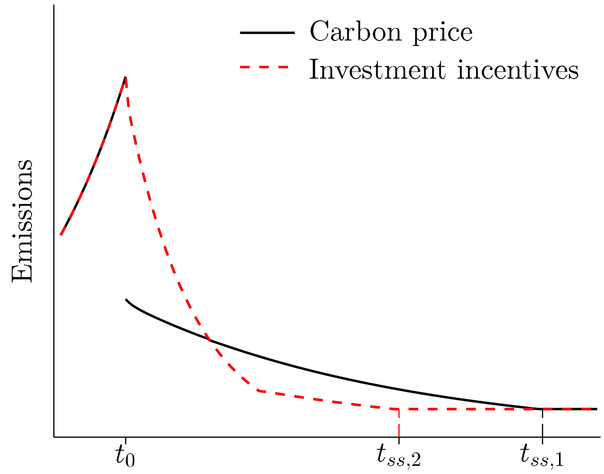

Figure 6.5: GHG emissions in the two cases.

Note: GHG emissions in the two cases. The carbon price induces decommission of polluting capital and thus reduces carbon emissions faster than investment instruments.

Figure 6.6 proposes a visualization of this issue. At low polluting capital stocks (thus low emissions), a carbon tax does not lead to underutilization of polluting capital. In this case, the first-best carbon price leads to the exact same pathway as "second-best" investment instruments. This is a situation of flexibility in which a government can enforce the optimal transition to clean capital using either a carbon price or investment-based instruments (although the distributional impacts of the two instruments remain different).

But as long as climate policies are absent or too lax, the economy accumulates polluting capital, making GHG emissions grow and reducing the residual carbon budget for a given climate target (the *conventional growth* arrow).

At one point, the threshold when the marginal productivity of polluting capital is lower than the optimal carbon price is crossed (see eq. 6.31), meaning that polluting capital should be underutilized and output reduced along the optimal pathway. From there, a carbon price may become even more difficult to implement because of political-economy constraints. But the alternative option of using investment instruments is still available to reach the same carbon budget without immediate drop in income.

There is thus a window of opportunity, during which alternative

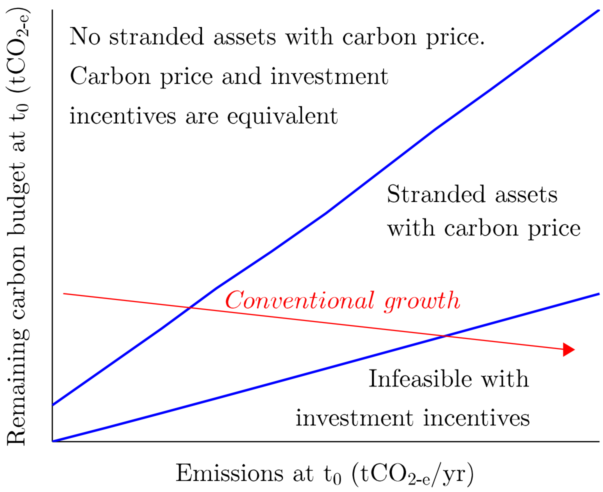

Figure 6.6: Under-utilization of polluting capital and feasibility of the climate target with investment instruments as a function of initial emissions.
Note: Depending on initial emissions (i.e. initial polluting capital k_{b,t_0}) and on the carbon budget ($\bar{m} - m_{t_0}$), the carbon tax and investment instruments can lead to different or similar outcomes (for a given set of parameters, and in particular ρ and δ). If the carbon budget is too stringent, such that waiting for polluting capital depreciation is not sufficient, the investment instruments cannot be used. If the carbon budget is not stringent, there is no underutilization of polluting capital in the first-best optimum with the carbon tax and investment instruments are equivalent. While the economy is on the laissez-faire growth path (red arrow), polluting capital accumulates and the carbon budget is reduced for a given climate objective.

investment instruments may induce a smooth and maybe politically-easier transition to a low-carbon economy. If this occasion is missed (right hand side, Fig. 6.6), it becomes impossible to reach the climate target without underutilization of polluting capital and investment instruments are not an option anymore (if the climate objective is not revised). In this last area, not only the economic cost of reaching the climate target is higher, but the political economy also creates a carbon lock-in: the only option to reach the climate target involves stranded assets and thus has a significant short-term cost, making it more difficult to implement successfully a climate policy consistent with the target.

The zone in which polluting capital must be underutilized to remain below the ceiling depends on the capital depreciation rate δ, the GHG dissipation rate ε, initial GHG concentration m_0 and initial polluting capital k_0. The lower blue line in Fig. 6.6 is expressed analytically in G and can be approximated by:

$$\bar{m} < m_0 + \frac{G\,k_0}{\delta}$$

According to Davis et al. (2010), the level of existing polluting infrastructure in 2010 was still low enough to achieve the 2°C target without underutilizing polluting capital. They find that if existing energy infrastructure was used for its normal life span and no new polluting devices were built, future warming would be less than 0.7°C. Reaching the 2°C target might however imply to stop investing in polluting capital soon,[24] which depends on our ability to overcome infrastructural inertia and develop clean energy and transport services (Guivarch et Hallegatte, 2011). Also, while Davis et al. (2010) do not discuss whether the least-cost policy would lead to underutilization — i.e. whether we are in the top or the middle triangle in Fig. 6.6 — several studies based on integrated assessment models find that in most 2°C scenarios polluting capital (coal power plants in particular) are decommissioned before the end of their lifetime (Rogelj et al., 2013; Johnson et al., 2014) — suggesting that the global economy is in the middle zone. In other words, empirical evidence suggests the optimal pathway to a stabilization of the climate at 2°C involves decommissioning existing capital, but that we can still get there by only reducing the carbon content of

[24] Investment in polluting capacity has accelerated since 2010 (Davis et Socolow, 2014)

new capital.

6 Conclusion

The present analysis should be interpreted cautiously, as we only explored a few aspects of the transition to clean capital. In particular, our model ignores uncertainty, limited foresight from investors, limited ability to commit from governments and knowledge accumulation effects, all known to play a key role in the transition to a low-carbon economy. One possibility for further research is to integrate and quantify these effects in a unifying framework.

Keeping in mind these limitations, our results suggest that governments willing to limit global warming to 2°C still have a choice between carbon prices and investment incentives. They can arbitrate between the cost-efficiency of the transition to clean capital and its immediate impact in terms of stranded assets and associated political costs.

The analysis carried here may also be relevant for studying other public economy issues. In essence, we propose a parsimonious model able to analyze structural change triggered by policy changes, its impact on vested interests, and policies to manage the transition.

Appendices

A Maximization of the household's utility

The household maximizes their inter temporal utility (eq. 6.2) given the motion law of wealth (eq. 6.1). The present value Hamiltonian is:

$$H_h(c_t, a_t) = e^{-\rho t} \cdot \{u(c_t) + \lambda_t[r_t \cdot a_t + y_t - c_t]\} \tag{6.35}$$

where λ_t is the shadow cost of investment in assets at time t. The first order conditions for a maximum of W are:

$$\forall t,\ \partial_c H_h = 0 \Rightarrow \lambda_t = u'(c_t) \tag{6.36}$$

$$\forall t,\ \partial_a H_h + \frac{d(e^{-\rho t}\lambda_t)}{dt} = 0 \Rightarrow \dot{\lambda}_t = (\rho - r_t)\lambda_t \tag{6.37}$$

The doted variables represent temporal derivatives. Differentiating eq. 6.36 with respect to time and substitute for λ from eq. 6.37, yields the Euler equation:

$$\frac{\dot{c}_t}{c_t} = \frac{-u'(c_t)}{c_t \cdot u''(c_t)} \cdot (r_t - \rho) \tag{6.38}$$

B Social optimum (section 3)

The present value Hamiltonian associated to the maximization of social welfare (6.16) is:

$$\begin{aligned} H_t = e^{-\rho t} \cdot \Big\{ & u(c(x_t)) + \lambda_t[F(q_p, k_c) - c(x_t) - i_{p,t} - i_{c,t}] + \nu_t[i_{p,t} - \delta k_{p,t}] \\ & + \chi_t[i_{c,t} - \delta k_{c,t}] - \mu_t \cdot [G\, q_{p,t} - \varepsilon m_t] + d(m_t) \cdot [\bar{m} - m_t] \\ & + \psi_t \cdot i_{p,t} + \beta_t[k_{p,t} - q_{p,t}] \Big\} \end{aligned} \tag{6.39}$$

All multipliers are positive.
The complementary slackness conditions are:

$$\forall t,\ \psi_t \geq 0 \text{ and } \psi_t \cdot i_{p,t} = 0 \tag{6.40}$$
$$\forall t,\ \beta_t \geq 0 \text{ and } \beta_t \cdot (k_{p,t} - q_{p,t}) = 0 \tag{6.41}$$
$$\forall t,\ d(m_t) \geq 0 \text{ and } d(m_t) \cdot (\bar{m} - m_t) = 0 \tag{6.42}$$

First order conditions

First order conditions give:

$$\begin{aligned} \frac{\partial H_t}{\partial c_t} = 0 \Rightarrow & \quad u'(c_t) = \lambda_t \\ \frac{\partial H_t}{\partial i_{p,t}} = 0 \Rightarrow & \quad \lambda_t = \nu_t + \psi_t \\ \frac{\partial H_t}{\partial i_{c,t}} = 0 \Rightarrow & \quad \lambda_t = \chi_t \\ \frac{\partial H_t}{\partial k_{p,t}} = -\frac{d(e^{-\rho t}\nu_t)}{dt} \Rightarrow & \quad -\nu_t \delta + \beta_t = -\dot{\nu}_t + \rho \nu_t \\ \frac{\partial H_t}{\partial k_{c,t}} = -\frac{d(e^{-\rho t}\chi_t)}{dt} \Rightarrow & \quad \lambda_t \partial_{k_c} F(k_{p,t}, k_{c,t}) - \chi_t \delta = -\dot{\chi}_t + \rho \chi_t \end{aligned} \tag{6.43}$$

$$
\begin{aligned}
\frac{\partial H_t}{\partial q_{p,t}} = 0 \Rightarrow \qquad & \lambda_t \partial_{q_p} F(q_{p,t}, k_{c,t}) - \mu_t \cdot G = \beta_t \\
\frac{\partial H_t}{\partial m_t} = \frac{d(e^{-\rho t}\mu_t)}{dt} \Rightarrow \qquad & -d(m_t) + \varepsilon\mu_t = \dot{\mu}_t - \rho\mu_t
\end{aligned}
\tag{6.44}
$$

Equilibrium on the capital market and interest rate: proof of proposition 6

If we differentiate eq. 6.43 with respect to time and substitute λ_t and $\dot{\lambda}_t$, we can write:

$$
\frac{c_t \cdot u''(c_t)}{u'(c_t)} \cdot \frac{\dot{c}_t}{c_t} = (\rho + \delta - R_{c,t}) \tag{6.45}
$$

As in the laissez-faire equilibrium (eq. 6.38), the interest rate r_t that ensures households are indifferent between consumption and investment is thus given by:

$$
r_t := R_{c,t} - \delta \tag{6.46}
$$

Carbon price

Eq. 6.44 gives the evolution of μ_t. Using $\dot{\mu}_t = (\dot{\lambda}_t \tau_t + \lambda_t \dot{\tau}_t)$ (from eq. 6.21), eq. 6.43, eq. 6.45 and eq. 6.46 yields:

$$
\dot{\tau}_t = \tau_t[\varepsilon + r_t] - \frac{d(m_t)}{\lambda_t}
$$

We call t_{ss} the date at which GHG concentration reaches the ceiling:

$$
\forall t \geq t_{ss}, \; m_t = \bar{m}
$$

During the steady state, $\dot{m}_t = 0 \implies G\, q_{p,t} = \varepsilon\, \bar{m}$ (eq. 6.11). On the long run, installed capital is not underused, polluting installed capital is thus constant at $k_{p,t} = \bar{m}\,\varepsilon/G$ during the steady state.

Before t_{ss}, $d(m_t) = 0$ (6.42). The carbon price thus exponentially grows at the endogenous interest rate plus the dissipation rate of GHG until the ceiling is reached:

$$
\dot{\tau}_t = \tau_t[\varepsilon + r_t] \tag{6.47}
$$

These dynamics may be interpreted as a generalized Hotelling rule applied to clean air: along the optimal pathway, and before the ceiling is reached, the discounted abatement costs are constant over time. The appropriate discount rate is $r_t + \varepsilon$, to take into account the natural decay of GHG in the atmosphere.

The irreversibility constraint is binding in the short run : proof of proposition 7

A binding GHG ceiling is imposed at t_0. Before that, the economy was in the competitive equilibrium, such that clean and polluting capital have the same marginal productivity and installed capital is fully used (Proposition 4):

$$\lim_{t \to t_0^-} q_{p,t} = k_{p,t} \tag{6.48}$$

$$\lim_{t \to t_0^-} \partial_{q_p} F(q_{p,t}, q_{c,t}) = \partial_{k_c} F(q_{p,t}, q_{c,t}) \tag{6.49}$$

We use a proof by contradiction to show that at t_0^+ (when the constraint is internalized) the irreversibility condition is necessarily binding. Suppose that the transition starts with a phase when the irreversibility constraint is not binding, i.e. $\psi_t = 0$. This would lead to (Propositions 5 and 6):

$$\lim_{t \to t_0^+} \partial_{q_p} F(q_{p,t}, q_{c,t}) = \partial_{k_c} F(q_{p,t}, q_{c,t}) + \tau_{t_0} \cdot G \tag{6.50}$$

Besides, investment means that capital is a continuous function of time:

$$\lim_{t \to t_0^+} q_{p,t} = k_{p,t} \tag{6.51}$$

If the GHG ceiling is binding then $\tau_{t_0} > 0$ (eq. 6.47). So from eq. 6.49 and eq. 6.50:

$$\lim_{t \to t_0^+} \partial_{q_p} F(q_{p,t}, q_{c,t}) \neq \lim_{t \to t_0^+} \partial_{q_p} F(q_{p,t}, q_{c,t}) \tag{6.52}$$

$\partial_{q_p} F$ is a continuous function of $q_{p,t}$ so eq. 6.52 implies that $\lim_{t \to t_0^+} q_{p,t} \neq \lim_{t \to t_0^+} q_{p,t}$, which is incompatible with eq. 6.48 and eq. 6.51. $\square$

C Decentralized equilibrium with a tax on emissions

In a decentralized economy, it is possible to trigger the same outcome as in the social optimum with a lump-sum tax applied to carbon emissions. In this case, the firm's flow of profit at time t is given by:

$$\Pi_t = F(q_{p,t}, k_{c,t}) - R_{c,t} \cdot k_{c,t} - R_{p,t} \cdot k_{p,t} - \tau_t \, G \, q_{p,t} \tag{6.53}$$

With $R_{p,t}$ and $R_{c,t}$ the rental prices of polluting and clean capacities respectively, and τ_t the carbon tax. The tax is redistributed through the assets equation:

$$\dot{a}_t = r_t \cdot a_t + y_t - c(x_t) + \tau_t \, G \, q_{p,t} \tag{6.54}$$

The Lagrangian corresponding to the firm's maximization program is:

$$L(t) = \Pi_t + \beta_t(k_{p,t} - q_{p,t}) + \gamma_t(k_{c,t} - q_{c,t}) \tag{6.55}$$

First order conditions are:

$$\partial_{q_g} L = 0 \Rightarrow \qquad \partial_{q_c} F(q_{p,t}, q_{c,t}) = \gamma_t \tag{6.56}$$
$$\partial_{q_b} L = 0 \Rightarrow \qquad \partial_{q_p} F(q_{p,t}, q_{c,t}) = \beta_t + \tau_t \cdot G \tag{6.57}$$
$$\partial_{k_g} L = 0 \Rightarrow \qquad \gamma_t = R_{c,t} \tag{6.58}$$
$$\partial_{k_b} L = 0 \Rightarrow \qquad \beta_t = R_{p,t} \tag{6.59}$$

For all t,

$$\gamma_t \geq 0 \text{ and } \gamma_t \cdot (k_{c,t} - q_{c,t}) = 0$$
$$\beta_t \geq 0 \text{ and } \beta_t \cdot (k_{p,t} - q_{p,t}) = 0$$

(complementary slackness conditions).
With eq. 6.56 we have $\gamma_t = \partial_{q_c} F(q_{p,t}, q_{c,t}) > 0$, so $q_{c,t} = k_{c,t}$ for all t.
The combination of eq. 6.56 and eq. 6.58 gives

$$\partial_{k_c} F(q_{p,t}, k_{c,t}) = R_{c,t}$$

Combining eq. 6.57 and eq. 6.59, we find

$$\partial_{q_p} F(q_{p,t}, k_{c,t}) = R_{p,t} + \tau_t \cdot G \tag{6.60}$$

In the equilibrium, the rental price of clean capacities is equal to the interest rate (plus delta): $R_{c,t} = r_t + \delta$, because clean capacities and loans are perfect substitutes as assets for households. When the irreversibility constraint is not binding (see eq. 6.6), and in particular on the balanced growth path, the rental rate of polluting capacities is equal to the interest rate as well and $R_{p,t} = R_{c,t} = r_t + \delta$.

However, when the carbon price is implemented at t_0, the irreversibility constraint is binding (7). In this case, since the use of polluting capacities suddenly becomes too expensive, the rental rate of polluting capacities is endogenously reduced. As a consequence of a lower rate of return for owners of polluting capital, households stop investing in polluting capacities. If the carbon tax is very high, the rental rate of polluting capacities can even become nil and polluting capacities may be under-utilized.

D Firms' maximization problem with differentiation of investment costs (feebates)

The present value Hamiltonian associated to the firm's maximization program is:

$$\begin{aligned}H_t = e^{-\rho t} \cdot \{&F(q_{p,t}, q_{c,t}) - (\lambda_t - \theta_{c,t})\, i_{c,t} - (\lambda_t + \theta_{p,t})\, i_{p,t} \\ &+\nu_t[i_{p,t} - \delta k_{p,t}] + \chi_t[i_{c,t} - \delta k_{c,t}] \\ &+ \psi_t \cdot i_{p,t} + \beta_t[k_{p,t} - q_{p,t}]\}\end{aligned}$$

First order conditions give:

$$\begin{aligned}
\frac{\partial H_t}{\partial i_{p,t}} = 0 \Rightarrow &\qquad \lambda_t + \theta_{p,t} = \nu_t + \psi_t \\
\frac{\partial H_t}{\partial i_{c,t}} = 0 \Rightarrow &\qquad \lambda_t - \theta_{c,t} = \chi_t \\
\frac{\partial H_t}{\partial k_{p,t}} = -\frac{d(e^{-\rho t}\nu_t)}{dt} \Rightarrow &\qquad -\nu_t\delta + \beta_t = -\dot{\nu}_t + \rho\nu_t \\
\frac{\partial H_t}{\partial k_{c,t}} = -\frac{d(e^{-\rho t}\chi_t)}{dt} \Rightarrow &\qquad \rho\chi_t - \dot{\chi}_t = \lambda_t \partial_{k_c} F(k_{p,t}, k_{c,t}) - \chi_t\delta \\
\frac{\partial H_t}{\partial q_{p,t}} = 0 \Rightarrow &\qquad \lambda_t \partial_{q_p} F(q_{p,t}, k_{c,t}) = \beta_t \qquad (6.61)
\end{aligned}$$

The complementary slackness condition $\forall t,\ \beta_t[k_{p,t} - q_{p,t}] = 0$ combined with equation 6.61 gives that — if F satisfies the Inada conditions — capital is never underused with investment-based instruments $\forall t, k_{p,t} = q_{p,t}$.

FOCs can be reduced to:

$$\nu_t + \psi_t = \chi_t + \theta_{c,t} + \theta_{p,t} \tag{6.62}$$

$$\partial_{k_c} F = \frac{1}{\lambda}((\delta + \rho)\chi_t - \dot{\chi}_t) \tag{6.63}$$

$$\partial_{q_p} F = \frac{1}{\lambda}((\delta + \rho)\nu_t - \dot{\nu}_t) \tag{6.64}$$

We thus obtain

$$\partial_{q_p} F = \partial_{k_c} F + \underbrace{\frac{1}{\lambda_t}\Big((\delta + \rho)(\theta_{c,t} + \theta_{p,t}) - (\dot{\theta_{c,t} + \theta_{p,t}})\Big)}_{\theta_t} - \underbrace{\frac{1}{\lambda_t}\Big((\rho + \delta)\psi_t - \dot{\psi}_t\Big)}_{\ell_t} \tag{6.65}$$

With ℓ_t the legacy cost and θ_t a positive term that depends on $(\theta_{c,t} + \theta_{p,t})$.

Equation 6.65 is similar to eq. 6.78 with $\theta_t = \tau_{t,2}\, G$, where $\tau_{t,2}$ is the shadow price of carbon. In the optimal pathway with a full-utilization of capital, θ_t is therefore equal to the shadow price of carbon (multiplied by G).

In this setting under-utilizing polluting capital is never optimal because firms do not pay carbon emissions directly. Instead, investment in polluting capital is more expensive that investment in clean capital and over the short-run, as in the social optimum the economy does not invest in new polluting capital. Once polluting capital has depreciated to a level compatible with the GHG ceiling, polluting investments become profitable and start again.

The policy creates a scarcity effect on polluting capital, that increases its price ($\theta_{c,t} + \theta_{p,t}$, eq. 6.62) while the irreversibility constraint reduces its price in the short-run (ψ_t, eq. 6.62).

Along the optimal transition to the new long-term steady state,

$$\begin{aligned} & \partial_{k_c} F \leq \partial_{q_p} F \\ \iff & \ell_t \leq \theta_t (= \tau_{t,2}) \\ \iff & \psi_t \leq \theta_{c,t} + \theta_{p,t} \end{aligned} \tag{6.66}$$

so that the price of pre-existing polluting capital is higher than that of clean capital is the short-run.

In the steady state, the legacy cost is nill ($\ell_t = 0$) and the marginal productivity of polluting capital is equal to that of clean capital plus θ_t. The same steady state as in the social optimum is reached and the optimal value of θ_t is equal to the first-best carbon tax multiplied by the marginal emissions of polluting capital:

$$\forall t \geq t_{ss},\ \theta_t = \tau_t \cdot G$$

with t_{ss} the date at which the steady state is reached.

With investment-based instruments, the shadow price of emissions $\tau_{t,2}$ is still equal to a technical abatement cost plus the legacy cost:

$$\underbrace{\tau_{t,2}}_{\text{economic cost}} = \underbrace{\frac{\partial_{q_p} F - \partial_{k_c} F}{G}}_{\text{technical cost}} + \underbrace{\frac{\ell_t}{G}}_{\text{legacy cost}} \tag{6.67}$$

$$\text{with } \ell_t \in [0,\ \tau_{t,2}]$$

The legacy cost ℓ_t is now bounded by the shadow carbon price $\tau_{t,2}$ (eq. 6.66). One interpretation is that preventing under-utilization is like refusing to recognize that past accumulation of polluting capital may have been a mistake. By doing so, the legacy cost can be has high as the cost of the GHG emissions that installed brown capital produces.

E Investment regulation (performance standards)

Another equivalent possibility is to regulate polluting investment through efficiency standards. In particular, the most polluting investments can be forbidden. Here, we crudely impose polluting investments to be nil until polluting capital has depreciated to a level allowing to reach the carbon ceiling without under-utilizing polluting capital.

We come back to the social planner's program (beginning of section 3) and remove the concentration and ceiling constraints (eq. 6.11 and eq. 6.15). To simplify the exposition, we can also remove the irreversibility constraint (eq. 6.6) which will not be binding in this case. Instead, we add a polluting investment constraint that forces $i_{p,t}$ to be equal to a standard at each point in time, and we call σ_t its Lagrangian multiplier:

$$\forall t,\ i_{p,t} = sd_t \qquad (\sigma_t) \tag{6.68}$$

The standard sd_t can be optimally set to equal polluting investments found in the previous section and the next section. Basically, $sd_t = 0$ until polluting capacities have depreciated to a level compatible with the ceiling. The present value Hamiltonian associated to the maximization of social welfare is:

$$\begin{aligned} H_t = e^{-\rho t} \cdot \{ & u(c(x_t)) + \lambda_t[F(q_p, k_c) - c(x_t) - i_{p,t} - i_{c,t}] + \nu_t[i_{p,t} - \delta k_{p,t}] \\ & + \chi_t[i_{c,t} - \delta k_{c,t}] + \sigma_t \cdot (sd_t - i_{p,t}) + \beta_t[k_{p,t} - q_{p,t}]\} \end{aligned} \tag{6.69}$$

λ_t is the current value shadow price of income. ν_t and χ_t are the current shadow values of investments in polluting and clean capital.
First order conditions can be reduced to the following equations:

$$u'(c_t) = \lambda_t = \nu_t - \sigma_t = \chi_t \tag{6.70}$$
$$\lambda_t \partial_{k_c} F = (\delta + \rho)\chi_t - \dot{\chi}_t \tag{6.71}$$
$$\lambda_t \partial_{q_p} F = \beta_t \tag{6.72}$$
$$\beta_t = (\delta + \rho)\nu_t - \dot{\nu}_t \tag{6.73}$$

Here, σ_t is equivalent to $(\theta_{c,t} + \theta_{p,t} - \psi_t)$ in the previous section.

The maximization of intertemporal welfare results in the same equations as in the previous sections:

$$\begin{aligned} & R_{p,t} = R_{c,t} + n_t \\ & \text{with } n_t = \frac{1}{\lambda_t}\left((\rho + \delta)\sigma_t - \dot{\sigma}_t\right) \end{aligned} \tag{6.74}$$

This equation is equivalent to Eq. 6.65, with $n_t = \theta_t - \ell_t$. The variable n_t is positive, which means that the rental price of polluting capacities is higher than the interest rate. Indeed, as with the differentiation of investment costs the polluting investment standard creates a scarcity effect on polluting capital, which becomes more expensive than clean capital.

This instrument must be thought of as temporary, since once polluting capital has depreciated to a sustainable level, a carbon price can be implemented without inducing under-utilization of polluting capital, and thus becomes politically acceptable. Investment regulation can be compared with existing efficiency standards on cars or electric plants, that forbid the construction of the most polluting kinds of polluting capital.

F Maximization of social welfare with full utilization constraint: temporary subsidy on existing polluting capital

The same outcome as with feebates or standards can be reached with the same social planner program as in B and a full-utilization constraint:

$$\max_{c,i,k} \int_0^\infty e^{-\rho t} \cdot u(c(x_t))\, dt \tag{6.75}$$

$$\begin{aligned}
\text{subject to } & F(q_p, k_c) - c(x_t) - i_{p,t} - i_{c,t} = 0 && (\lambda_t) \\
& \dot{k}_{p,t} = i_{p,t} - \delta k_{p,t} && (\nu_t) \\
& \dot{k}_{c,t} = i_{c,t} - \delta k_{c,t} && (\chi_t) \\
& \dot{m}_t = G\, q_{p,t} - \varepsilon m_t && (\mu_t) \\
& m_t \leq \bar{m} && (d(m_t)) \\
& i_{p,t} \geq 0 && (\psi_t) \\
& q_{p,t} \leq k_{p,t} && (\beta_t) \\
& q_{p,t} = k_{p,t} && (\alpha_t)
\end{aligned}$$

The present value Hamiltonian associated to the maximization of social welfare is:

$$\begin{aligned}
H_t = e^{-\rho t} \cdot \{ & u(c(x_t)) + \lambda_t [F(q_p, k_c) - c(x_t) - i_{p,t} - i_{c,t}] + \nu_t [i_{p,t} - \delta k_{p,t}] \\
& + \chi_t [i_{c,t} - \delta k_{c,t}] - \mu_t \cdot [G\, q_{p,t} - \varepsilon m_t] + d(m_t) \cdot [\bar{m} - m_t] \\
& + \psi_t \cdot i_{p,t} + \beta_t [k_{p,t} - q_{p,t}] + \alpha_t [q_{p,t} - k_{p,t}] \}
\end{aligned}$$

All multipliers are positive.

Equations 6.19 and 6.20 become:

$$\beta_t - \alpha_t = \frac{1}{\lambda}((\delta + \rho)\nu_t - \dot{\nu}_t)$$
$$\partial_{q_p} F = \beta_t - \alpha_t + \tau_t \cdot G$$

The rental price of polluting capital is therefore equal to $\beta_t - \alpha_t$. The condition on the marginal productivity of polluting capital becomes:

$$\partial_{q_p} F = \beta_t - \alpha_t + \tau_t \cdot G \tag{6.76}$$

Note that due to complementary slackness conditions, if $\beta_t > 0$ then $\alpha_t = 0$ and if $\alpha_t > 0$ then $\beta_t = 0$. In the first phase when polluting investment is nil, if the carbon tax is higher than the marginal productivity of polluting capital, the value of polluting capital is nil, $\beta_t = 0$ and the equation becomes:

$$\partial_{q_p} F = -\alpha_t + \tau_t \cdot G \tag{6.77}$$

α_t interprets as a subsidy to the utilization of polluting capital.
Similarly to the first-best pathway, the marginal productivities are differentiated as follows:

$$\begin{aligned} &\partial_{q_p} F = \partial_{k_c} F - \ell_t + \tau_t \, G \\ &0 < \ell_t < \tau_t \, G \end{aligned} \tag{6.78}$$

With the legacy cost $\ell_t > 0$ during the first phase and $\ell_t = 0$ when polluting capital reaches a sustainable level.

In the long run when $i_b > 0$ the equilibrium is equivalent to the social optimum. In the short run when $i_b = 0$, $\psi_t > 0$ and $R_{p,t} < R_{c,t}$, except that in this case $R_{p,t}$ becomes negative if the carbon price is higher than the marginal productivity of the last unit of polluting capital (expressed in output per emissions). Thus polluting capital is always fully-utilized.

This instrument leads to the same investments and output as the differentiation of investment costs or standards, however it is not perfectly equivalent. Indeed, the carbon tax also affects polluting capital on the aftermarket, thus the price of polluting capital does not increase the short-run. Conversely, with taxes on investments or standards on investments, polluting capital becomes scarce and so its price increase on the aftermarket.

G Second-best infeasibility zone

This zone defines the cases when the ceiling is reached before polluting capacities have depreciated to a sustainable level. If no investment is made in polluting capacities, we have:

$$k_{p,t} = k_0\, e^{-\delta t}$$

Therefore, the stock of pollution follows this dynamic:

$$\dot{m} = k_0\, e^{-\delta t} - \varepsilon\, m$$

The solution to this differential equation is:

$$m_t = -\frac{G\, k_0}{\delta - \varepsilon}\, e^{-\delta t} + \left(m_0 + \frac{G\, k_0}{\delta - \varepsilon}\right)\, e^{-\varepsilon t}$$

This function first increases to a maximum $m_{max} = \frac{G\, k_0}{\delta}\, e^{-\delta t}$ and then decreases. The maximum date is

$$t_{max} = -\frac{1}{\delta}\, \ln(\frac{m_{max}\, \varepsilon}{G\, k_0})$$

The expression of m at the maximum date gives the limit of the infeasibility zone if $m_{max} = \bar{m}$:

$$\bar{m} = -\frac{G\, k_0}{\delta - \varepsilon}\, e^{\ln(\frac{\bar{m}\, \varepsilon}{G\, k_0})} + \left(m_0 + \frac{G\, k_0}{\delta - \varepsilon}\right)\, e^{\frac{\varepsilon}{\delta}\ln(\frac{\bar{m}\, \varepsilon}{G\, k_0})}$$

This can be rewritten:

$$\bar{m} = \left[\left(m_0 + \frac{G\, k_0}{\delta - \varepsilon}\right)\left(\frac{\varepsilon}{G\, k_0}\right)^{\frac{\varepsilon}{\delta}}\left(\frac{\delta - \varepsilon}{\delta}\right)\right]^{\frac{\delta}{\delta - \epsilon}}$$

The “clean incentives infeasibility zone” depends on the capital depreciation rate, the GHG dissipation rate, initial GHG concentration and initial polluting capacities.

Conclusion

D'UN strict point de vue théorique, les résultats de cette thèse ne permettent pas d'affirmer que des objectifs sectoriels (comme les 20% de renouvelable en 2020 au niveau européen) sont nécessaires, ni que les instruments de politiques agissant uniquement sur le capital (comme les normes d'efficacité énergétique pour les bâtiments et les véhicules routiers) sont plus efficaces ou plus justes qu'un prix du carbone.

En théorie, la meilleure approche pour les pouvoirs publics reste de mettre en place un prix du carbone parfaitement crédible. Un taxe carbone (ou des quotas vendus aux enchères) aurait l'avantage de fournir un revenu au gouvernement, utilisable pour réduire d'autres taxes plus distorsives, par exemple pesant sur la masse salariale, et récolter ainsi un double dividende (Parry et Bento, 2000; Bovenberg et Goulder, 1996). Une autre partie des revenus, ainsi que le fruit d'une croissance plus soutenue grâce à ce double dividende, pourrait alors servir à compenser les perdants d'une fiscalité carbone, par exemple ceux qui ont investi dans du capital inerte et polluant avant sa mise en place.[25]

La question de la crédibilité de cette taxe à long terme reste en pratique incontournable. Pour déclencher les bonnes décisions d'investissement dans le secteur de la production d'électricité, où la durée de vie du capital varie entre 30 et 60 ans, une taxe carbone doit être crédible sur 30 à 60 ans. Les décisions touchant à la forme des villes et aux infrastructures de transport, elles, doivent considérer que le prix du carbone est donné pour les cinq à vingt prochaines décennies. Ce besoin de crédibilité des signaux prix sur le long terme contraste avec les exemples

[25] Le Chapitre 5 de cette thèse suggère qu'une cartographie des perdants face à un prix du carbone devrait étudier l'impact sur la distribution « horizontale » des revenus de l'économie, et en particulier identifier les secteurs de l'économie les plus vulnérables. Une autre considération, ignorée ici mais de même importance, est l'impact d'une taxe carbone sur la distribution « verticale » des revenus dans l'économie, par exemple en termes de déciles de la population (Combet, 2013; Rausch et al., 2011)

Australien et Canadien, qui montrent que les gouvernements peuvent à tout moment défaire ce qu'ont fait leurs prédécesseurs.

La question de l'acceptabilité politique d'une taxation du carbone reste également un problème pratique. En Australie encore, ou aux Etats-Unis, le pouvoir législatif fédéral est clair dans son refus catégorique de la mise en place d'un prix du carbone. Les transferts de rente que provoquerait un prix du carbone expliquent sans doute en partie ce refus.

Ces difficultés politiques appellent plusieurs types de réponse de la part des économistes. La première est de répéter, expliquer, et vulgariser le consensus sur le bien-fondé du prix du carbone, ses multiples cobénéfices économiques, environnementaux, sociétaux, sa capacité à répondre aux enjeux sociétaux contemporains, y compris en insistant sur les solutions aux problèmes distributifs soulevés par la taxe (Combet 2013). Elle peut également s'efforcer de démontrer, au cas par cas, la supériorité théorique des prix du carbone sur les instruments de politiques proposés par les agences gouvernementales et les décideurs publics (Goulder et Parry, 2008). L'unanimité des économistes va peut-être finalement convaincre la classe politique et l'opinion publique en général du bien-fondé d'une taxe carbone qui croitrait continument dans le temps, résolvant ainsi le problème de sa crédibilité.

Une deuxième réponse peut-être de s'intéresser en parallèle au rôle que les politiques sectorielles peuvent jouer pour préparer l'économie et la société en général à la transition vers une fiscalité verte (Hallegatte et al., 2013). Cette thèse contribue à cet effort, en suggérant que les politiques sectorielles qui redirigent l'investissement sans immédiatement mettre en place un prix du carbone peuvent préparer le système productif à une taxe carbone à moyen terme, en évitant à la racine les problèmes distributifs, et en contournant l'absence de crédibilité de long terme des signaux prix.

Parce qu'elle étudie l'investissement optimal dans du capital bas carbone, cette thèse est riche en enseignements pertinents pour la calibration de ce type d'instruments. Elle montre qu'exprimé en euros par tonne de carbone évitée (calculés grâce au cout annualisé des investissement bas carbone), l'investissement optimal peut être plus élevé que le prix du carbone ; et qu'il doit être plus important dans les secteurs qui sont plus difficiles à décarbonner, c'est-à-dire les secteurs ou le capital bas carbone est plus cher et les secteurs ou les émissions de gaz à effet de serre sont plus importantes.

Cette thèse montre aussi que le prix (ou une valeur tutélaire) du carbone seul ne donne pas assez d'information pour évaluer des politiques visant à favoriser l'investissement optimal dans chaque secteur de l'économie. La détermination des efforts optimaux à court terme requiert d'anticiper une stratégie entière de décarbonisation de l'économie. Par exemple, évaluer la pertinence du développement d'une filière de véhicules électriques requiert de prendre en compte que la stabilisation du climat passe de toute façon par la décarbonisation de la production d'électricité. Arbitrer entre la construction d'une centrale à gaz et d'un parc d'éoliennes demande de prendre en compte que la durée de vie effective des centrales à gaz va dépendre des autres décisions d'investissement : à moyen terme, les centrales à gaz peuvent être chassées par des centrales plus propres.

Ces résultats proviennent de modèles analytiques simples, qui font abstraction de plusieurs éléments importants. Au moins quatre pistes me semblent prometteuses pour enrichir l'analyse à l'avenir.

D'abord, la prise en compte dans un même modèle analytique des effets d'apprentissage et de l'accumulation de capital propre devrait permettre de clarifier l'effet de chacun de ces facteurs. D'une part, les modèles de changement technique dirigé utilisés actuellement donnent parfois l'impression de décrire un monde dans lequel les chercheurs fabriquent le capital bas carbone (les éoliennes, voitures électriques, bâtiments isolés) dans la foulé de leur invention, et que les producteurs n'ont plus qu'à s'en saisir à loisir pour les incorporer immédiatement au capital productif (Acemoglu et al. 2012 ; Gerlagh, Kverndokk, et Rosendahl 2009).[26] En réalité, la recherche et développement d'un côté, le remplacement du capital polluant par du capital propre de l'autre côté, sont deux processus distincts, mus par des dynamiques différentes. D'autre part, les modèles analytiques mobilisés le long de cette thèse lient investissement optimal à court terme et valeur de marché du capital à long terme. L'effet de l'apprentissage sur le cout de remplacement, et donc sur la valeur du capital propre à long terme, devrait donc jouer un rôle dans le timing optimal de l'investissement bas carbone.

Ensuite, les analyses exposées ici négligent toute incertitude. Il est bien établi que sous incertitude, les stratégies optimales évitent les décisions irréversibles. La littérature économique standard a mis en avant

[26]L'absence de représentation explicite du capital physique et de l'inertie associée est d'ailleurs l'une des critiques que formulent Pottier et al. (2014) à l'encontre du modèle utilisé par Acemoglu *et al.* (2012).

que l'investissement dans du capital physique est une source importante d'irréversibilité, suggérant que le décisions d'investissement, en particulier dans du capital propre, doivent être reportées le plus possible (Pindyck, 1991). Mais dans le domaine du changement climatique, une autre irréversibilité d'importance est l'accumulation de gaz à effet de serre dans l'atmosphère. Ha-Duong *et al. (1997)* et Ambrosi et al. (2003) montrent que réduire les émissions de gaz à effet de serre dès maintenant permet d'éviter les effets de cette irréversibilité. Des travaux futurs pourraient étudier dans un cadre analytique dans quels secteurs devraient avoir lieu ces abattement précautionneux[27]. Le rôle de l'inertie semble ici ambigu : elle peut augmenter le regret d'avoir investi si l'urgence de l'action climatique s'avère moins sévère que prévue, mais également de ne pas avoir investi si elle s'avère plus urgente.

Une troisième piste concerne l'étude de la distribution optimale des efforts de réduction de gaz à effet de serre entre pays. Des pays différents partent de stocks de capital polluant différents, et vont croitre à des vitesses différentes. De plus, le cout du capital propre dans les pays « suiveurs » peut dépendre fortement des efforts antérieurs dans les pays « à la pointe ». Dans ce cadre, où doit-on investir en priorité les fonds d'une épargne internationale ? Par ailleurs, des accords internationaux portant uniquement sur les nouveaux investissements peuvent-ils aider à lisser les couts de l'atténuation climatique et rendre la transition moins rude pour les pays les plus intensifs en carbone ? Les modèles développés ici peuvent servir de point de départ pour explorer ces questions.

Finalement, les analyses exposées dans cette thèse montrent que le cout de la transition vers du capital bas carbone s'exprime avant tout comme un besoin de financement. Cette thèse montre donc l'importance, pour informer au mieux la prise de décision publique comme privée, de s'intéresser aux contraintes pesant sur ce financement. En corolaire, elle suggère que (i) des politiques réduisant le risque pour les investisseurs, (ii) la mobilisation de nouveaux instruments financiers verts, voire même (iii) une réforme plus radicale du système financier sont autant de pistes à explorer pour faciliter la transition vers une économie décarbonée.

[27]Lecocq *et al.* (1998) proposent une première étude cette question grâce à un modèle numérique.

References

Acemoglu, D., Aghion, P., Bursztyn, L., et Hemous, D. (2012). The environment and directed technical change. *American Economic Review*, 102(1):131–166.

Acemoglu, D., Akcigit, U., Hanley, D., et Kerr, W. (2014). Transition to clean technology. Working Paper 20743, National Bureau of Economic Research.

Agarwal, R. et Bayus, B. L. (2002). The market evolution and sales takeoff of product innovations. *Management Science*, 48(8):1024–1041.

Allcott, H. et Greenstone, M. (2012). Is there an energy efficiency gap? *Journal of Economic Perspectives*, 26(1):3–28.

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., et Meinshausen, N. (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, 458(7242):1163–1166.

Alvarez, R. A., Pacala, S. W., Winebrake, J. J., Chameides, W. L., et Hamburg, S. P. (2012). Greater focus needed on methane leakage from natural gas infrastructure. *Proceedings of the National Academy of Sciences*, 109(17):6435–6440.

Ambec, S. et Crampes, C. (2012). Electricity provision with intermittent sources of energy. *Resource and Energy Economics*, 34(3):319–336.

Ambrosi, P., Hourcade, J., Hallegatte, S., Lecocq, F., Dumas, P., et Ha Duong, M. (2003). Optimal control models and elicitation of attitudes towards climate damages. *Environmental Modeling and Assessment*, 8(3):133–147.

Amigues, J.-P., Ayong Le Kama, A., Chakravorty, U., et Moreaux, M. (2013). Equilibrium transitions from non renewable energy to renewable energy under capacity constraints. LERNA Working Papers 11.07.341.

Amigues, J.-P., Favard, P., Gaudet, G., et Moreaux, M. (1998). On the optimal order of natural resource use when the capacity of the inexhaustible substitute is limited. *Journal of Economic Theory*, 80(1):153 – 170.

Anderson, S. T., Parry, I. W. H., Sallee, J. M., et Fischer, C. (2011). Automobile fuel economy standards: Impacts, efficiency, and alternatives. *Review of Environmental Economics and Policy*, 5(1):89–108.

André, F. J. et Smulders, S. (2014). Fueling growth when oil peaks: Directed technological change and the limits to efficiency. *European Economic Review*, 69:18–39.

Arltesou, A. (1999). Models of energy use: Putty-putty versus putty-clay. *The American Economic Review*, 89(4):1028–1043.

Arrow, K. J. et Kurz, M. (1970). Optimal growth with irreversible investment in a Ramsey model. *Econometrica*, 38(2):331–344.

Audoly, R., Vogt-Schilb, A., et Guivarch, C. (2014). Pathways toward zero-carbon electricity required for climate stabilization. *World Bank Policy Research Working Paper*, 7075.

Avner, P., Rentschler, J. E., et Hallegatte, S. (2014). Carbon price efficiency: Lock-in and path dependence in urban forms and transport infrastructure. World Bank Policy Research Working Paper 6941.

Azar, C. et Sandén, B. A. (2011). The elusive quest for technology-neutral policies. *Environmental Innovation and Societal Transitions*, 1(1):135–139.

BBC (2012). Electric cars 'pose environmental threat'.

Beaumont, N. J. et Tinch, R. (2004). Abatement cost curves: a viable management tool for enabling the achievement of win–win waste reduction strategies? *Journal of Environmental Management*, 71(3):207–215.

Bertram, C., Johnson, N., Luderer, G., Riahi, K., Isaac, M., et Eom, J. (2015). Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technological Forecasting and Social Change*, 90, Part A:62–72.

Böhringer, C. et Rosendahl, K. E. (2010). Green promotes the dirtiest: on the interaction between black and green quotas in energy markets. *Journal of Regulatory Economics*, 37(3):316–325.

Bibas, R. et Méjean, A. (2014). Potential and limitations of bioenergy for low carbon transitions. *Climatic Change*, 123(3-4):731–761.

Biggar, D. et Hesamzadeh, M. (2014). *The economics of electricity markets*. Wiley, United Kingdom.

Bloomberg (2010). A fresh look at the cost of reducing U.S. carbon emissions. *Carbon Markets-North America- Research Note*.

Boiteux, M. (1960). Peak-load pricing. *The Journal of Business*, 33(2):pp. 157–179.

Bosello, F., Carraro, C., et De Cian, E. (2010). Climate policy and the optimal balance between mitigation, adaptation and unavoided damage. *Climate Change Economics*, 01(02):71–92.

Bovenberg, A. L. et Goulder, L. H. (1996). Optimal environmental taxation in the presence of other taxes: General- equilibrium analyses. *The American Economic Review*, 86(4):985–1000.

Braathen, N. A. (2007). Instrument mixes for environmental policy: How many stones should be used to kill a bird? *International Review of Environmental and Resource Economics*, 1(2):185–235.

Bramoullé, Y. et Olson, L. J. (2005). Allocation of pollution abatement under learning by doing. *Journal of Public Economics*, 89(9–10):1935–1960.

Brock, W. A. et Taylor, M. S. (2010). The green solow model. *Journal of Economic Growth*, 15(2):127–153.

Brook, A., Kendrick, D., et Meeraus, A. (1988). GAMS, a user's guide. *SIGNUM Newsl.*, 23(3-4):10–11.

Bruin, K. C. d., Dellink, R. B., et Tol, R. S. J. (2009). AD-DICE: an implementation of adaptation in the DICE model. *Climatic Change*, 95(1-2):63–81.

Brunner, S., Flachsland, C., et Marschinski, R. (2012). Credible commitment in carbon policy. *Climate Policy*, 12(2):255–271.

Cairns, R. D. (1998). The microeconomics of mineral extraction under capacity constraints. *Nonrenewable Resources*, 7(3):233–244.

Campbell, H. F. (1980). The effect of capital intensity on the optimal rate of extraction of a mineral deposit. *The Canadian Journal of Economics*, 13(2):349–356.

CE Delft (2012). Marginal abatement cost curves for heavy duty vehicles. Background report, Arno Schroten, Geert Warringa and Mart Bles, Delft.

Chakravorty, U., Moreaux, M., et Tidball, M. (2008). Ordering the extraction of polluting nonrenewable resources. *The American Economic Review*, 98(3):1128–1144.

Chichilnisky, G. et Heal, G. (1994). Who should abate carbon emissions?: An international viewpoint. *Economics Letters*, 44(4):443–449.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., et Tavoni, M. (2009). International climate policy architectures: Overview of the EMF 22 international scenarios. *Energy Economics*, 31:S64–S81.

Climate Works Australia (2010). *Low carbon growth plan for Australia*. ClimateWorks Australia Clayton.

Coase, R. H. (1960). The Problem of Social Cost. *Journal of Law and Economics*, 3:1–44.

Collins, M., Knutti, R., Arblaster, J. M., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., et Krinner, G. (2013). Long-term climate change: projections, commitments and irreversibility. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Combet, E. (2013). *Fiscalité carbone et progrès social. Application au cas français*. Ph.D. thesis, École des Hautes Études en Sciences Sociales (EHESS).

Dasgupta, P. et Heal, G. (1974). The optimal depletion of exhaustible resources. *The Review of Economic Studies*, 41:3–28.

Davis, L. W. et Metcalf, G. E. (2014). Does Better Information Lead to Better Choices? Evidence from Energy-Efficiency Labels. Working Paper 20720, National Bureau of Economic Research.

Davis, S. J., Caldeira, K., et Matthews, H. D. (2010). Future CO2 emissions and climate change from existing energy infrastructure. *Science*, 329(5997):1330 –1333.

Davis, S. J., Cao, L., Caldeira, K., et Hoffert, M. I. (2013). Rethinking wedges. *Environmental Research Letters*, 8(1):011001.

Davis, S. J. et Socolow, R. H. (2014). Commitment accounting of CO2 emissions. *Environmental Research Letters*, 9(8):084018.

de Gouvello, C. (2010). *Brazil Low-carbon Country Case Study*. The World Bank, Washington DC, USA.

DECC (2011). Impact assessment of fourth carbon budget level. Impact Assessment DECC0054, Department of Energy and Climate Change, UK.

del Rio Gonzalez, P. (2008). Policy implications of potential conflicts between short-term and long-term efficiency in CO2 emissions abatement. *Ecological Economics*, 65(2):292–303.

Dietz, S. et Stern, N. (2014). Endogenous growth, convexity of damages and climate risk: How Nordhaus' framework supports deep cuts in carbon emissions. *Economic Journal*.

Dixit, A. et Lambertini, L. (2003). Interactions of commitment and discretion in monetary and fiscal policies. *The American Economic Review*, 93(5):pp. 1522–1542.

Dresner, S., Dunne, L., Clinch, P., et Beuermann, C. (2006). Social and political responses to ecological tax reform in europe: an introduction to the special issue. *Energy Policy*, 34(8):895–904.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., et al. (2010). The economics of low stabilization: model comparison of mitigation strategies and costs. *The Energy Journal*, 31(1):11–48.

ENERDATA (2012). Global energy & CO_2 database.

Enkvist, P., Nauclér, T., et Rosander, J. (2007). A cost curve for greenhouse gas reduction. *McKinsey Quarterly*, 1:34.

ESMAP (2012). Planning for a low carbon future: Lessons learned from seven country studies. Knowledge series 011/12, Energy Sector Management Assistance Program - The World Bank, Washington DC, USA.

ESMAP (2014). Modeling tools and e-learning: MACTool.

Espagne, E., Perrissin-Fabert, B., Pottier, A., Nadaud, F., et Dumas, P. (2012). Disentangling the Stern/Nordhaus Controversy: Beyond the Discounting Clash. Working Paper 2012.61, Fondazione Eni Enrico Mattei.

EU (2011). Impact assessment accompanying the communication from the commission: Energy roadmap 2050. Staff Working Document Sec(2011) 1569 final, European Commission.

Eurostat (2014). Statistiques de l'union européenne.

EWEA (2014). Wind in power: 2013 european statistics. Technical report, The European Wind Association.

Fay, M., Hallegatte, S., Vogt-Schilb, A., Rozenberg, J., Narloch, U., et Kerr, T. (2015). *Decarbonizing Development: Three Steps to a Zero-Carbon Future*. World Bank Publications.

Fischer, C. (2008). Comparing flexibility mechanisms for fuel economy standards. *Energy Policy*, 36(8):3116–3124.

Fischer, C., Newell, R., et Preonas, L. (2012). Environmental and technology policy options in the electricity sector: Interactions and outcomes. Technical report, RFF.

Fischer, C. et Newell, R. G. (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management*, 55(2):142–162.

Fischer, C. et Preonas, L. (2010). Combining policies for renewable energy: Is the whole less than the sum of its parts? *International Review of Environmental and Resource Economics*, 4:51–92.

Fischer, C., Withagen, C., et Toman, M. (2004). Optimal investment in clean production capacity. *Environmental and Resource Economics*, 28(3):325–345.

Framstad, N. C. et Strand, J. (2013). Energy intensive infrastructure investments with retrofits in continuous time: Effects of uncertainty on energy use and carbon emissions. World bank policy research working paper, 6430.

Fullerton, D. et Heutel, G. (2010). The general equilibrium incidence of environmental mandates. *American Economic Journal: Economic Policy*, 2(3):64–89.

Fullerton, D., Heutel, G., et Metcalf, G. E. (2012). Does the indexing of government transfers make carbon pricing progressive? *American Journal of Agricultural Economics*, 94(2):347–353.

G7 (2015). Leaders' Declaration after the G7 Summit held in Germany.

Gaudet, G. (1983). Optimal investment and adjustment costs in the economic theory of the mine. *The Canadian Journal of Economics / Revue canadienne d'Economique*, 16(1):39–51.

Gaudet, G. et Lasserre, P. (2011). The efficient use of multiple sources of a nonrenewable resource under supply cost uncertainty. *International Economic Review*, 52(1):245–258.

Gaudet, G. et Salant, S. W. (2014). The hotelling model with multiple demands. In Halvorsen, R. et Layton, D., editors, *Handbook on the Economics of Natural Resources*. Edward Elgar Publishing, Cheltenham, U.K.

Gerlagh, R., Kverndokk, S., et Rosendahl, K. (2009). Optimal timing of climate change policy: Interaction between carbon taxes and innovation externalities. *Environmental and Resource Economics*, 43(3):369–390.

Gerlagh, R., Kverndokk, S., et Rosendahl, K. E. (2014). The optimal time path of clean energy R&D policy when patents have finite lifetime. *Journal of Environmental Economics and Management*, 67(1):2–19.

Gillingham, K., Harding, M., et Rapson, D. (2012). Split Incentives in Residential Energy Consumption. *The Energy Journal*, 33(2).

Gillingham, K. et Palmer, K. (2014). Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence. *Review of Environmental Economics and Policy*, 8(1):18–38.

Gilotte, L. et Fortin, E. (2004). Optimal policy and inertia of carbon intensity trends. In *6th IAEE European Conference*, pages 1–3. Zurich, Suisse.

Giraudet, L.-G. et Houde, S. (2014). Double Moral Hazard and the Energy Efficiency Gap. *E2e Working Paper 009*.

Giraudet, L.-G. et Quirion, P. (2008). Efficiency and distributional impacts of tradable white certificates compared to taxes, subsidies and regulations. *Revue d'économie politique*, 118(6):885–914.

Golombek, R., Greaker, M., et Hoel, M. (2010). Carbon taxes and innovation without commitment. *The B.E. Journal of Economic Analysis & Policy*, 10(1).

Gould, J. P. (1968). Adjustment costs in the theory of investment of the firm. *The Review of Economic Studies*, 35(1):47.

Goulder, L. H., Hafstead, M. A. C., et Dworsky, M. (2010). Impacts of alternative emissions allowance allocation methods under a federal cap-and-trade program. *Journal of Environmental Economics and Management*, 60(3):161–181.

Goulder, L. H. et Mathai, K. (2000). Optimal CO2 abatement in the presence of induced technological change. *Journal of Environmental Economics and Management*, 39(1):1–38.

Goulder, L. H. et Parry, I. W. H. (2008). Instrument choice in environmental policy. *Review of Environmental Economics and Policy*, 2(2):152–174.

Goulder, L. H. et Schein, A. R. (2013). Carbon taxes versus cap and trade: a critical review. *Climate Change Economics*, 04(03):1350010.

Graff Zivin, J. S., Kotchen, M. J., et Mansur, E. T. (2014). Spatial and temporal heterogeneity of marginal emissions: Implications for electric cars and other electricity-shifting policies. *Journal of Economic Behavior & Organization*, 107, Part A:248–268.

Grübler, A. et Messner, S. (1998). Technological change and the timing of mitigation measures. *Energy Economics*, 20(5-6):495–512.

Grübler, A., Nakićenović, N., et Victor, D. G. (1999). Dynamics of energy technologies and global change. *Energy policy*, 27(5):247–280.

Grimaud, A. et Lafforgue, G. (2008). Climate change mitigation policies: Are R&D subsidies preferable to a carbon tax? *Revue d'économie politique*, Vol. 118(6):915–940.

Grimaud, A., Lafforgue, G., et Magné, B. (2011). Climate change mitigation options and directed technical change: A decentralized equilibrium analysis. *Resource and Energy Economics*, 33(4):938–962.

Gritsevskyi, A. et Nakicenovi, N. (2000). Modeling uncertainty of induced technological change. *Energy Policy*, 28(13):907–921.

Grubb, M., Chapuis, T., et Ha-Duong, M. (1995). The economics of changing course: Implications of adaptability and inertia for optimal climate policy. *Energy Policy*, 23(4-5):pp. 417–431.

Guivarch, C. et Hallegatte, S. (2011). Existing infrastructure and the 2°C target. *Climatic Change*, 109(3-4):801–805.

Guivarch, C. et Hallegatte, S. (2013). 2C or not 2C? *Global Environmental Change*, 23(1):179–192.

Guivarch, C., Hallegatte, S., et Crassous, R. (2009). The resilience of the indian economy to rising oil prices as a validation test for a global energy–environment–economy CGE model. *Energy Policy*, 37(11):4259–4266.

Guivarch, C., Monjon, S., Rozenberg, J., et Vogt-Schilb, A. (2015). Would climate policy improve the european energy security? *Climate Change Economics*, 06(02):1550008.

Gustavsson, L. et Joelsson, A. (2010). Life cycle primary energy analysis of residential buildings. *Energy and Buildings*, 42(2):210–220.

Ha-Duong, M., Grubb, M., et Hourcade, J. (1997). Influence of socioeconomic inertia and uncertainty on optimal CO2-emission abatement. *Nature*, 390(6657):270–273.

Haab, T. (2007). Environmental economics: Look! it's a carbon supply curve.

Hallegatte, S., Fay, M., et Vogt-Schilb, A. (2013). Green industrial policies: When and how. *World Bank Policy Research Working Paper*, (6677).

Harrison, K. et Peet, C. (2012). Historical legacies and policy reform: Diverse regional reactions to british columbia's carbon tax. *BC Studies: The British Columbian Quarterly*, 0(173):97–122.

Hawkins, T. R., Gausen, O. M., et Strømman, A. H. (2012a). Environmental impacts of hybrid and electric vehicles—a review. *The International Journal of Life Cycle Assessment*, 17(8):997–1014.

Hawkins, T. R., Singh, B., Majeau-Bettez, G., et Strømman, A. H. (2012b). Comparative environmental life cycle assessment of conventional and electric vehicles. *Journal of Industrial Ecology*.

Heal, G. M. et Millner, A. (2014). Agreeing to disagree on climate policy. *Proceedings of the National Academy of Sciences*, 111(10):3695–3698.

Herfindahl, O. C. (1967). Depletion and economic theory. In Gaffney, M., editor, *Extractive resources and taxation*, pages 63–90. University of Wisconsin Press, Madison, Wisconsin.

Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., Heath, G. A., Bergesen, J. D., Ramirez, A., Vega, M. I., et Shi, L. (2014). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences*, page 201312753.

Hoel, M. (1996). Should a carbon tax be differentiated across sectors? *Journal of Public Economics*, 59(1):17–32.

Holland, S. P. (2003). Extraction capacity and the optimal order of extraction. *Journal of Environmental Economics and Management*, 45(3):569–588.

Holland, S. P., Hughes, J. E., et Knittel, C. R. (2009). Greenhouse gas reductions under low carbon fuel standards? *American Economic Journal: Economic Policy*, 1(1):106–146.

Hotelling, H. (1931). The economics of exhaustible resources. *The Journal of Political Economy*, 39(2):175–137.

Hwang, I. C., Reynès, F., et Tol, R. S. J. (2013). Climate policy under fat-tailed risk: An application of DICE. *Environmental and Resource Economics*, 56(3):415–436.

ICCT (2012). How vehicle standards and fuel fees can cut CO2 emissions and boost the economy. Policies That Work 2, International Council on Clean Transportation, Washington DC.

ICCT (2014). Global passenger vehicle standards. International Council on Clean Transportation. theicct.org/info-tools/global-passenger-vehicle-standards.

IEA (2009). *Transport Energy and CO2 : Moving towards Sustainability.* Organisation for Economic Co-operation and Development,, Paris, France.

IEA (2010). Projected cost of generating electricity, 2010 edition. Technical report, International Energy Agency.

IEA (2012). CO_2 emissions from fuel combustion. IEA statistics, International Energy Agency.

IEA (2014a). *Energy technology perspectives 2014: Harnessing electricity's potential.* International Energy Agency and Organisation for Economic Co-operation and Development, Paris, France.

IEA (2014b). *Harnessing Electricity's Potential.* Energy Technology Perspectives. International Energy Agency.

IEA (2015). Policies and measures database. International Energy Agency. `http://iea.org/policiesandmeasures`.

IIASA (2014). AMPERE public database. International Institute for Applied Systems Analysis. secure.iiasa.ac.at/web-apps/ene/AMPEREDB.

IPCC (2007). Summary for policymakers. In *Climate change 2007: Mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change.* Cambridge University Press, Cambridge, UK and New York, USA.

IPCC (2013). Summary for policymakers. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge, United Kingdom and New York, USA., cambridge university press edition.

IPCC (2014a). Annex II: Metrics and methodology. In *Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge, United Kingdom and New York, NY, USA., cambridge university press edition.

IPCC (2014b). Summary for policymakers. In *Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge, United Kingdom and New York, NY, USA., cambridge university press edition.

IPCC (2014c). Summary for policymakers. In *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.* Cambridge, United Kingdom and New York, NY, USA., cambridge university press edition.

Iyer, G., Hultman, N., Eom, J., McJeon, H., Patel, P., et Clarke, L. (2015). Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technological Forecasting and Social Change*, 90, Part A:103–118.

Jaccard, M. et Rivers, N. (2007). Heterogeneous capital stocks and the optimal timing for CO2 abatement. *Resource and Energy Economics*, 29(1):1–16.

Jackson, T. (1991). Least-cost greenhouse planning supply curves for global warming abatement. *Energy Policy*, 19(1):35–46.

Jacoby, H. D. et Wing, I. S. (1999). Adjustment Time, Capital Malleability and Policy Cost. *The Energy Journal*, 20:73–92.

Jaffe, A. B., Newell, R. G., et Stavins, R. N. (2005). A tale of two market failures: Technology and environmental policy. *Ecological Economics*, 54(2-3):164–174.

Jenkins, J. D. (2014). Political economy constraints on carbon pricing policies: What are the implications for economic efficiency, environmental efficacy, and climate policy design? *Energy Policy*.

Johnson, N., Krey, V., McCollum, D. L., Rao, S., Riahi, K., et Rogelj, J. (2014). Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change*.

Jorgenson, D. (1967). The theory of investment behavior. In *Determinants of investment behavior*. NBER.

Kalkuhl, M., Edenhofer, O., et Lessmann, K. (2012). Learning or lock-in: Optimal technology policies to support mitigation. *Resource and Energy Economics*, 34:1–23.

Kallbekken, S., Kroll, S., et Cherry, T. L. (2011). Do you not like pigou, or do you not understand him? tax aversion and revenue recycling in the lab. *Journal of Environmental Economics and Management*, 62(1):53–64.

Keller, K., Bolker, B. M., et Bradford, D. F. (2004). Uncertain climate thresholds and optimal economic growth. *Journal of Environmental Economics and Management*, 48(1):723–741.

Kemp, M. C. et Long, N. V. (1980). On two folk theorems concerning the extraction of exhaustible resources. *Econometrica*, 48(3):663–673.

Kesicki, F. (2012a). Intertemporal issues and marginal abatement costs in the UK transport sector. *Transportation Research Part D: Transport and Environment*, 17(5):418–426.

Kesicki, F. (2012b). Marginal abatement cost curves: Combining energy system modelling and decomposition analysis. *Environmental Modeling & Assessment*.

Kesicki, F. et Ekins, P. (2012). Marginal abatement cost curves: a call for caution. *Climate Policy*, 12(2):219–236.

Klepper, G. et Peterson, S. (2006). Marginal abatement cost curves in general equilibrium: The influence of world energy prices. *Resource and Energy Economics*, 28(1):1–23.

Kolstad, C., Urama, K., Broome, J., Bruvoll, A., Olvera, M. C., Fullerton, D., Gollier, C., Hanemann, W., Hassan, R., Jotzo, F., Khan, M., Meyer, L., et Mundaca, L. (2014). Social, economic and ethical concepts and methods. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Kolstad, C. D. (1996). Learning and stock effects in environmental regulation: The case of greenhouse gas emissions. *Journal of Environmental Economics and Management*, 31(1):1–18.

Kopp, A., Block, R. I., et Iimi, A. (2013). *Turning the Right Corner: Ensuring Development through a Low-Carbon Transport Sector*. The World Bank.

Krey, V., Luderer, G., Clarke, L., et Kriegler, E. (2014). Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. *Climatic Change*, 123(3-4):369–382.

Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V. J., Petermann, N., Bosetti, V., Marcucci, A., Otto, S., Paroussos, L., Rao, S., Arroyo Currás, T., Ashina, S., Bollen, J., Eom, J., Hamdi-Cherif, M., Longden, T., Kitous, A., Méjean, A., Sano, F., Schaeffer, M., Wada, K., Capros, P., P. van Vuuren, D., et Edenhofer, O. (2015). Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change*, 90, Part A:24–44.

Kriegler, E., Weyant, J. P., Blanford, G. J., Krey, V., Clarke, L., Edmonds, J., Fawcett, A., Luderer, G., Riahi, K., Richels, R., Rose, S. K., Tavoni, M., et Vuuren, D. P. v. (2014). The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, 123(3-4):353–367.

Kuik, O., Brander, L., et Tol, R. S. (2009). Marginal abatement costs of greenhouse gas emissions: A meta-analysis. *Energy Policy*, 37(4):1395–1403.

Kverndokk, S. et Rosendahl, K. E. (2007). Climate policies and learning by doing: Impacts and timing of technology subsidies. *Resource and Energy Economics*, 29(1):58–82.

Kydland, F. E. et Prescott, E. C. (1977). Rules rather than discretion: The inconsistency of optimal plans. *Journal of Political Economy*, 85(3):pp. 473–492.

Labandeira, X., Labeaga, J. M., et López-Otero, X. (2012). Estimation of elasticity price of electricity with incomplete information. *Energy Economics*, 34(3):627 – 633.

Laffont, J.-J. (1999). Political economy, information, and incentives. *European Economic Review*, 43:649–669.

Lasserre, P. (1985). Exhaustible-resource extraction with capital. In *Progress in natural resource economic*, pages 178–202. Anthony Scott, oxford: clarendon press, edition.

Lecocq, F., Hourcade, J., et Ha Duong, M. (1998). Decision making under uncertainty and inertia constraints: sectoral implications of the when flexibility. *Energy Economics*, 20(5-6):539–555.

Lecocq, F. et Shalizi, Z. (2014). The economics of targeted mitigation in infrastructure. *Climate Policy*, 14(2):187–208.

Lecuyer, O. et Quirion, P. (2013). Can uncertainty justify overlapping policy instruments to mitigate emissions? *Ecological Economics*, 93:177–191.

Lecuyer, O. et Vogt-Schilb, A. (2014). Optimal transition from coal to gas and renewable power under capacity constraints and adjustment costs. *World Bank Policy Research Working Paper 6985*.

Lemoine, D. et Traeger, C. (2014). Watch your step: Optimal policy in a tipping climate. *American Economic Journal: Economic Policy*, 6(1):137–166.

Loulou, R. (2008). ETSAP-TIAM: the TIMES integrated assessment model. *Computational Management Science*, 5(1-2):41–66.

Lucas, R. E., Jr. (1967). Adjustment costs and the theory of supply. *Journal of Political Economy*, 75(4):321–334.

Luderer, G., Bertram, C., Calvin, K., Cian, E. D., et Kriegler, E. (2013a). Implications of weak near-term climate policies on long-term mitigation pathways. *Climatic Change*, pages 1–14.

Luderer, G., Bosetti, V., Jakob, M., Leimbach, M., Steckel, J. C., Waisman, H., et Edenhofer, O. (2012). The economics of decarbonizing the energy system—results and insights from the RECIPE model intercomparison. *Climatic Change*, 114(1):9–37.

Luderer, G., Pietzcker, R. C., Bertram, C., Kriegler, E., Meinshausen, M., et Edenhofer, O. (2013b). Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters*, 8(3):034033.

Manne, A. et Richels, R. (2004). The impact of learning-by-doing on the timing and costs of CO2 abatement. *Energy Economics*, 26(4):603–619.

Manne, A. S. et Richels, R. G. (1992). *Buying greenhouse insurance: the economic costs of carbon dioxide emission limits.* MIT Press, Cambridge, Mass.

Mansfield, E. (1998). Academic research and industrial innovation: An update of empirical findings. *Research policy*, 26(7):773–776.

Matthews, H. D. et Caldeira, K. (2008). Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, 35(4).

Matthews, H. D., Gillett, N., Stott, P., et Zickfeld, K. (2009a). The proportionality of global warming to cumulative carbon emissions. *Nature*, 459(7248):829–832.

Matthews, H. D., Gillett, N. P., Stott, P. A., et Zickfeld, K. (2009b). The proportionality of global warming to cumulative carbon emissions. *Nature*, 459(7248):829–832.

McCollum, D., Krey, V., Kolp, P., Nagai, Y., et Riahi, K. (2014). Transport electrification: A key element for energy system transformation and climate stabilization. *Climatic Change*, 123(3-4):651–664.

McKinsey (2007). Reducing US greenhouse gas emissions: How much at what cost? Technical report, McKinsey & Company.

McKinsey (2009). Charting our water future: Economic frameworks to inform decision-making. Technical report, McKinsey & Company.

McKinsey (2009). Pathways to a low-carbon economy: Version 2 of the global greenhouse gas abatement cost curve. Technical report, McKinsey & Company.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J., et Allen, M. R. (2009a). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, 458(7242):1158–1162.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J., et Allen, M. R. (2009b). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, 458(7242):1158–1162.

Metcalf, G. E. (2014). Using the tax system to address competition issues with a carbon tax. *National Tax Journal*, 67(4):779.

Meunier, G. et Finon, D. (2013). Option value in low-carbon technology policies. *Climate Policy*, 13(1):1–19.

Ministry of Finance (2015). Carbon tax. Province of british columbia. www.fin.gov.bc.ca/tbs/tp/climate/carbon_tax.htm.

Morris, J., Paltsev, S., et Reilly, J. (2011). Marginal abatement costs and marginal welfare costs for greenhouse gas emissions reductions: Results from the EPPA model. *Environmental Modeling & Assessment*, 17(4):325–336.

Mussa, M. (1977). External and internal adjustment costs and the theory of aggregate and firm investment. *Economica*, 44(174):163–178.

Narain, U. et Veld, K. (2008). The clean development mechanism's low-hanging fruit problem: When might it arise, and how might it be solved? *Environmental and Resource Economics*, 40(3):445–465.

NCE (2014). *Better growth better climate: the new climate economy report*. Washington DC, USA, New Climate Economy edition.

NERA (2011a). The demand for greenhouse gas emissions reduction investments: An investors' marginal abatement cost curve for Kazakhstan. Prepared for the European Bank for Reconstruction and Development, NERA Economic Consulting and Bloomberg New Energy Finance.

NERA (2011b). The demand for greenhouse gas emissions reductions: An investors' marginal abatement cost curve for Turkey. Prepared for the European Bank for Reconstruction and Development, NERA Economic Consulting and Bloomberg New Energy Finance.

NERA (2012). The demand for greenhouse gas emissions reduction investments: An investors' marginal abatement cost curve for Ukraine. Prepared for the European Bank for Reconstruction and Development, NERA Economic Consulting and Bloomberg New Energy Finance.

Nordhaus, W. D. (1991). To slow or not to slow: The economics of the greenhouse effect. *The Economic Journal*, 101(407):920–937.

Nordhaus, W. D. (1992). An optimal transition path for controlling greenhouse gases. *Science*, 258(5086):1315–1319.

Nordhaus, W. D. et Sztorc, P. (2013). *DICE 2013R: Introduction and user's manual*. http://dicemodel.net.

O'Brien, D., Shalloo, L., Crosson, P., Donnellan, T., Farrelly, N., Finnan, J., Hanrahan, K., Lalor, S., Lanigan, G., Thorne, F., et Schulte, R. (2014). An evaluation of the effect of greenhouse gas accounting methods on a marginal abatement cost curve for irish agricultural greenhouse gas emissions. *Environmental Science & Policy*, 39:107–118.

Olson, M. (1977). *The logic of collective action: public goods and the theory of groups*. Harvard University Press.

Pacala, S. et Socolow, R. (2004). Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science*, 305(5686):968–972.

Parry, I. W. H. et Bento, A. M. (2000). Tax deductions, environmental policy, and the "double dividend" hypothesis. *Journal of Environmental Economics and Management*, 39(1):67–96.

Parry, I. W. H., Evans, D., et Oates, W. E. (2014). Are energy efficiency standards justified? *Journal of Environmental Economics and Management*, 67(2):104–125.

Pearce, D. (1991). The Role of Carbon Taxes in Adjusting to Global Warming. *The Economic Journal*, 101(407):938–948.

Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoît, M., Butault, J., Chenu, C., Colnenne-David, C., De Care, S., Delame, N., Doreau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Hénault, C., Jeuffroy, M., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E., Savini, I., et Pardon, L. (2013). Quelle contribution de l'agriculture française à la réduction des émissions de gaz à effet de serre? Potentiel d'atténuation et coût de dix actions techniques. Synthèse du rapport d'étude, INRA, France.

Philibert, C. (2007). Technology penetration and capital stock turnover: Lessons from IEA scenario analysis. *OECD Working Paper*.

Pigou, A. (1932). *The economics of welfare*. Macmillan and Co., London.

Pindyck, R. S. (1991). Irreversibility, uncertainty, and investment. *Journal of Economic Literature*, 29(3):1110–1148.

Pindyck, R. S. (2013). Climate change policy: What do the models tell us? *Journal of Economic Literature*, 51(3):860–872.

Popp, D. (2004). ENTICE: endogenous technological change in the DICE model of global warming. *Journal of Environmental Economics and Management*, 48(1):742–768.

Pottier, A., Hourcade, J.-C., et Espagne, E. (2014). Modelling the redirection of technical change: The pitfalls of incorporeal visions of the economy. *Energy Economics*, 42:213–218.

Ramesh, T., Prakash, R., et Shukla, K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, 42(10):1592–1600.

Rausch, S., Metcalf, G. E., et Reilly, J. M. (2011). Distributional impacts of carbon pricing: A general equilibrium approach with micro-data for households. *Energy Economics*, 33, Supplement 1:S20–S33.

Rausch, S., Metcalf, G. E., Reilly, J. M., et Paltsev, S. (2010). Distributional implications of alternative u.s. greenhouse gas control measures. *The B.E. Journal of Economic Analysis & Policy*, 10(2).

Rausch, S. et Reilly, J. (2015). Carbon taxes, deficits, and energy policy interactions. *National Tax Journal*, in press.

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., McCollum, D. L., Mima, S., Turton, H., van Vuuren, D. P., Wada, K., Bosetti, V., Capros, P., Criqui, P., Hamdi-Cherif, M., Kainuma, M., et Edenhofer, O. (2015). Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, 90, Part A:8–23.

Richardson, D. B. (2013). Electric vehicles and the electric grid: A review of modeling approaches, impacts, and renewable energy integration. *Renewable and Sustainable Energy Reviews*, 19:247–254.

Richels, R. G., Blanford, G. J., et Rutherford, T. F. (2009). International climate policy: a 'second best' solution for a 'second best' world? *Climatic Change*, 97(1-2):289–296.

Rodrik, D. (2008). Normalizing industrial policy. Commission for Growth and Development. Working Paper 3, World Bank.

Rogelj, J., McCollum, D. L., O'Neill, B. C., et Riahi, K. (2013). 2020 emissions levels required to limit warming to below 2c. *Nature Climate Change*, 3(4):405–412.

Rose, A., Bulte, E., et Folmer, H. (1999). Long-run implications for developing countries of joint implementation of greenhouse gas mitigation. *Environmental and Resource Economics*, 14(1):19–31.

Rose, S. K., Kriegler, E., Bibas, R., Calvin, K., Popp, A., Vuuren, D. P. v., et Weyant, J. (2014). Bioenergy in energy transformation and climate management. *Climatic Change*, 123(3-4):477–493.

Rosendahl, K. E. (2004a). Cost-effective environmental policy: implications of induced technological change. *Journal of Environmental Economics and Management*, 48(3):1099–1121.

Rosendahl, K. E. (2004b). Cost-effective environmental policy: implications of induced technological change. *Journal of Environmental Economics and Management*, 48(3):1099–1121.

Rozenberg, J., Hallegatte, S., Perrissin-Fabert, B., et Hourcade, J.-C. (2013). Funding low-carbon investments in the absence of a carbon tax. *Climate Policy*, 13(1):134–141.

Rozenberg, J., Vogt-Schilb, A., et Hallegatte, S. (2014). Transition to clean capital, irreversible investment and stranded assets. *World Bank Policy Research Working Paper*, (6859).

Rubin, E. S., Cooper, R. N., Frosch, R. A., Lee, T. H., Marland, G., Rosenfeld, A. H., et Stine, D. D. (1992). Realistic mitigation options for global warming. *Science*, 257(5067):148–149.

Sachs, J., Tubiana, L., Guerin, E., Waisman, H., Mas, C., Colombier, M., et Schmidt-Traub, G. (2014). Pathways to deep decarbonization. Interim 2014 report, Deep Decarbonization Pathways Project.

Sandén, B. A. et Azar, C. (2005). Near-term technology policies for long-term climate targets—economy wide versus technology specific approaches. *Energy Policy*, 33(12):1557–1576.

Schwoon, M. et Tol, R. S. (2006). Optimal CO2-abatement with socioeconomic inertia and induced technological change. *The Energy Journal*, 27(4).

Scilab Consortium (2011). *Scilab: The free software for numerical computation*. Scilab Consortium, Paris, France.

Seebregts, A., Goldstein, G., et Smekens, K. (2002). Energy/environmental modeling with the MARKAL family of models. In Chamoni, P., Leisten, R., Martin, A., Minnemann, J., et Stadtler, H., editors, *Operations Research Proceedings 2001*, volume 2001 of *Operations Research Proceedings 2001*, pages 75–82. Springer Berlin Heidelberg.

Shindell, D. T. (2015). The social cost of atmospheric release. *Climatic Change*, pages 1–14.

Sims, R. E., Rogner, H.-H., et Gregory, K. (2003). Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. *Energy Policy*, 31(13):1315–1326.

Sioshansi, R. et Denholm, P. (2009). Emissions impacts and benefits of plug-in hybrid electric vehicles and vehicle-to-grid services. *Environmental Science & Technology*, 43(4):1199–1204.

Slechten, A. (2013). Intertemporal links in cap-and-trade schemes. *Journal of Environmental Economics and Management*, 66(2):319–336.

Smith, H. J., Fahrenkamp-Uppenbrink, J., et Coontz, R. (2009). Clearing the air - Introduction to the special issue on Carbon Capture and Sequestration. *Science*, 325(5948):1641.

Smulders, S. et Van Der Werf, E. (2008). Climate policy and the optimal extraction of high- and low-carbon fossil fuels. *Canadian Journal of Economics/Revue canadienne d'économique*, 41(4):1421–1444.

Solow, R. M. (1974). Intergenerational equity and exhaustible resources. *The Review of Economic Studies*, 41:29–45.

Steinacher, M., Joos, F., et Stocker, T. F. (2013). Allowable carbon emissions lowered by multiple climate targets. *Nature*, 499(7457):197–201.

Stern, N. (2013). The structure of economic modeling of the potential impacts of climate change: Grafting gross underestimation of risk onto already narrow science models. *Journal of Economic Literature*, 51(3):838–859.

Stern, N. H. (2006). *Stern Review: The economics of climate change*. HM treasury London.

Sterner, T. et Höglund Isaksson, L. (2006). Refunded emission payments theory, distribution of costs, and swedish experience of NOx abatement. *Ecological Economics*, 57(1):93–106.

Stiglitz, J. (1974). Growth with exhaustible natural resources: Efficient and optimal growth paths. *The Review of Economic Studies*, 41:123–137.

Stocker, T. F. (2013). The closing door of climate targets. *Science*, 339(6117):280–282.

Stoft, S. E. (1995). The economics of Conserved-Energy ”Supply” curves. *The Energy Journal*, 16(4):109–140.

Sugiyama, M. (2012). Climate change mitigation and electrification. *Energy Policy*, 44:464–468.

Sweeney, J. et Weyant, J. (2008). Analysis of measures to meet the requirements of California’s Assembly Bill 32. Technical report, Stanford University.

Tahvonen, O. et Salo, S. (2001). Economic growth and transitions between renewable and nonrenewable energy resources. *European Economic Review*, 45(8):1379–1398.

Tavoni, M. et Socolow, R. (2013). Modeling meets science and technology: an introduction to a special issue on negative emissions. *Climatic Change*, 118(1):1–14.

Tavoni, M. et Tol, R. S. (2010). Counting only the hits? the risk of underestimating the costs of stringent climate policy. *Climatic change*, 100(3-4):769–778.

Taylor, S. (2012). The ranking of negative-cost emissions reduction measures. *Energy Policy*, 48:430–438.

Thomson, M., Evenson, E., Kempe, M., et Goodfellow, H. (2000). Control of greenhouse gas emissions from electric arc furnace steelmaking: evaluation methodology with case studies. *Ironmaking & Steelmaking*, 27(4):273–279.

Tinbergen, J. (1956). *Economic policy: principles and design.* North Holland Pub. Co., Amsterdam.

Trebilcock, M. J. (2014). *Dealing with Losers: The Political Economy of Policy Transitions*. Oxford University Press.

Trotignon, R. et Delbosc, A. (2008). Échanges de quotas en période d’essai du marche européen du CO_2: ce que révèle le CITL. Étude climat 13, Caisse des dépots.

Tsvetanov, T. et Segerson, K. (2013). Re-evaluating the role of energy efficiency standards: A behavioral economics approach. *Journal of Environmental Economics and Management*, 66(2):347–363.

UE (2011). A roadmap for moving to a competitive low carbon economy in 2050. Communication from the Commission COM(2011) 112 final, European Commission.

Ulph, A. et Ulph, D. (2013). Optimal climate change policies when governments cannot commit. *Environmental and Resource Economics*, 56(2):161–176.

UNFCCC (2011). Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010. FCCC/CP/2010/7/Add. 1, 15 March 2011, United Nations Framework Convention on Climate Change.

van der Ploeg, F. et Withagen, C. (1991). Pollution control and the ramsey problem. *Environmental and Resource Economics*, 1(2):215–236.

van der Ploeg, F. et Withagen, C. (2012). Too much coal, too little oil. *Journal of Public Economics*, 96(12):62–77.

van der Ploeg, F. et Withagen, C. (2014). Growth, renewables, and the optimal carbon tax. *International Economic Review*, 55(1):283–311.

van der Zwaan, B. C. C., Gerlagh, R., G., Klaassen, et Schrattenholzer, L. (2002). Endogenous technological change in climate change modelling. *Energy Economics*, 24(1):1–19.

van Vuuren, D. P., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S., Chateau, J., Scrieciu, S., van Vliet, J., Masui, T., Blok, K., Blomen, E., et Kram, T. (2009). Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. *Energy Policy*, 37(12):5125–5139.

Vogt-Schilb, A., Guivarch, C., et Hourcade, J.-C. (2013). Les véhicules électrifiés réduiront-ils les émissions de carbone? *Revue de l'énergie*, (611):5–11.

Vogt-Schilb, A. et Hallegatte, S. (2014). Marginal abatement cost curves and the optimal timing of mitigation measures. *Energy Policy*, 66:645–653.

Vogt-Schilb, A., Hallegatte, S., et de Gouvello, C. (2014a). Marginal abatement cost curves and quality of emission reductions: A case study on Brazil. *Climate Policy (forthcoming) DOI: 10.1080/14693062.2014.953908*.

Vogt-Schilb, A., Meunier, G., et Hallegatte, S. (2014b). Optimal timing, cost and sectoral allocation of abatement investment. *AEA conference in Philadelphia*.

Waisman, H., Guivarch, C., Grazi, F., et Hourcade, J. C. (2012). The Imaclim-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. *Climatic Change*, 114(1):101–120.

Wächter, P. (2013). The usefulness of marginal CO2-e abatement cost curves in Austria. *Energy Policy*, 61:1116–1126.

Wei, C. (2003). Energy, the stock market, and the putty-clay investment model. *The American Economic Review*, 93(1):311–323.

Wigley, T. M. L., Richels, R., et Edmonds, J. A. (1996). Economic and environmental choices in the stabilization of atmospheric CO2 concentrations. *Nature*, 379(6562):240–243.

Williams, J. H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow, W. R., Price, S., et Torn, M. S. (2012). The technology path to deep greenhouse gas emissions cuts by 2050: The pivotal role of electricity. *Science*, 335(6064):53–59.

Williams, R. (2010). Setting the initial time-profile of climate policy: The economics of environmental policy phase-ins. Working Paper 16120, National Bureau of Economic Research.

Williams, R. C. (2011). Setting the initial time-profile of climate policy: The economics of environmental policy phase-ins. *NBER*, pages 245–254.

Wilson, C., Grubler, A., Bauer, N., Krey, V., et Riahi, K. (2013). Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Climatic Change*, 118(2):381–395.

Winkler, R. (2008). Optimal compliance with emission constraints: dynamic characteristics and the choice of technique. *Environmental and Resource Economics*, 39(4):411–432.

Winslott-Hiselius, L., Brundell-Freij, K., Vagland, s., et Byström, C. (2009). The development of public attitudes towards the stockholm congestion trial. *Transportation Research Part A: Policy and Practice*, 43(3):269–282.

World Bank (2012). *Inclusive green growth : the pathway to sustainable development.* World Bank, Washington, D.C.

World Bank (2013). Applying abatement cost curve methodology for low-carbon strategy in Changning district, Shanghai. Technical Report 84068, The World Bank.

World Bank (2014). *State and Trends of Carbon Pricing 2014.* The World Bank, Washington DC, USA.

World Bank et International Finance Corporation (2013). *Doing business 2013: Smarter regulations for small and medium-sized enterprises.* World Bank : International Finance Corporation, Washington, D.C.

WRI (2015). CAIT 2.0: WRI's climate data explorer. *World Resources Institute* *http://cait2.wri.org*.

Wuppertal Institute for Climate, Environment and Energy (2006). Options and potentials for energy end-use efficiency and energy services. Technical report.

Zabalza Bribián, I., Aranda Usón, A., et Scarpellini, S. (2009). Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment*, 44(12):2510–2520.

Zickfeld, K., Eby, M., Matthews, H. D., et Weaver, A. J. (2009). Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proceedings of the National Academy of Sciences*, 106(38):16129–16134.