Les Cahiers de la Chaire

Chaire Modélisation prospective au service du développement durable

The Policy Path to Low-Carbon Societies

Frédéric GHERSI

CIRED

Working Paper N° 2011-01

The Policy Path to Low-Carbon Societies

Frédéric GHERSI*

Abstract

This paper provides a survey of the policies and measures that are asso-ciated to low carbon societies in the recent literature, both peer-reviewed and "grey". A first section focuses on carbon pricing, the policy measure most frequently represented. It starts by analysing the somewhat confusing use made of carbon pricing expertise in policy reports emanating from the French and the British governments, then reviews some modelling results on carbon pricing in a "second best" world, and concludes on the acknowledged limits of this central policy instrument. A second section lists an impressive collection of more focused policy instruments that are advocated in both governmental and non-governmental literature. It insists on the contrast between the high degree of precision of some of these policy proposals, and the absence of scientific assessment of their impacts, either from an environmental or an economic point of view. A third section concludes on the research agenda emerging from this hiatus between the large body of scientific literature devoted to carbon pricing, and the policy relevance of much more focused policy instruments.

* CNRS, CIRED, 45 bis, avenue de la Belle Gabrielle, 94736 Nogent sur Marne CEDEX, France. This paper was written during a visiting year at (with the support of) the Fondazione Eni Enrico Mattei, Isola di San Giorgio Maggiore, 30124 Venice, Italy.

Introduction

The dramatic shifts in lifestyle and development patterns implied by the transition to low carbon societies call for an extremely ambitious policy action, in both its scope and coverage. Crafting the details of such action will require particular care, considering the stakes: the orders of magnitude of long term studies hint that the cost of deviating from the least-cost option—whatever this option—could be in the order of some GDP points in 2050 for the most ambitious targets, a measure that translates into hundreds of billions of euros in Europe. From the available literature on the topic there emerges a set of generic principles that, theoretically guaranteeing cost minimisation, should at least hedge against massive excess costs.

First and foremost, a requisite to efficient action is some degree of coordination in the policy process. In economic terms, the primary aim of such coordination is to guarantee 'where flexibility' to abatement measures: considering that their impact on climate is independent from their geographical origin, emissions should be cut down in those places where it is the cheapest to do so. The rationale is certainly relevant at the European level, where recent governmental reports and studies insist on the need for a strengthened integrated approach (Radanne, 2004; CAS, 2006, 2009 and 2008b; BMU, 2008). It does also hold at the global level, although the recent semi-failure of the Copenhagen summit, and the monitoring difficulties inherent to Clean Development Mechanism (CDM) actions, postpone to some unknown future the equalisation of marginal abatement cost across the globe—the following sections will focus on European policymaking and avoid opening the debate on the contribution of extra-European offsets.

The same series of governmental reports, drawing conclusions from a profuse scientific literature, stresses the importance of the timing issue: even accounting for the slack given by the ongoing global economic crisis, delayed action closes one after another windows of opportunity to reach the lower concentration levels, while it increases the costs of meeting those that can still be met. Policy action is needed, at the very least, to set the European economy on such tracks that its laxer 2050 target of a 60% emission cut from 1990 levels could still be reachable. In a similar line of thought, fears are expressed that the -20% 2020 objective might be too conservative a milestone on the way to this ambitious 2050 target. Considering the political process that led to the adoption of these targets it is hard to rule out that another emission pathway might induce the same environmental benefits at a lower economic cost.

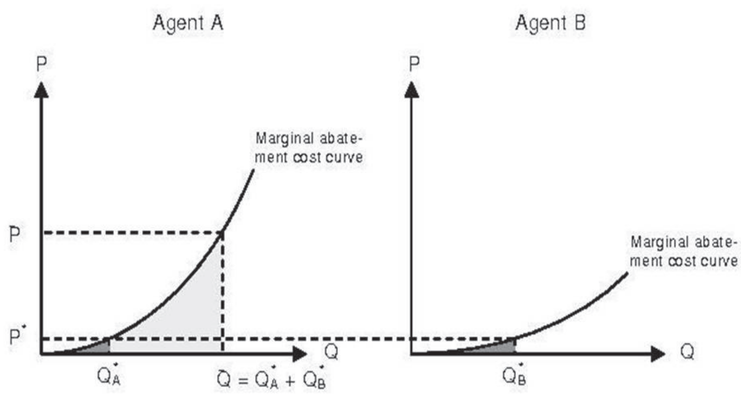
A third generic recommendation of most studies and reports is that the distributive consequences of ambitious climate policies should be duly assessed, and controlled as far as can be: on households, to shield the poorer from strong direct impacts on their living standards; on firms, to prevent unilateral action to overly degrade their competitiveness on international markets; on governments,[1] to guarantee that climate policies neither deteriorate (through subsidies and tax cuts) nor improve (through tax and auction proceeds) public budget balances.[2]

1. National accounting conventionally distinguishes between households, firms and public administrations for the secondary distribution of income. In that sense the impact of any policy action on public budgets is a matter of income distribution, broadly understood.
2. Although the corresponding principle of 'budget neutrality' offers some leeway in its practical implementation.

At last, many studies underline the need for pedagogy: to be accepted by public opinions the policy portfolio will have to be straightforward enough. At the level of constraint envisaged too-complicated schemes would probably fail to meet public acceptance. This, together with its theoretical properties, naturally points to some generalised form of carbon pricing as the core of any policy action—a first subsection will address this central instrument. However some more targeted policy measures will be required without a doubt, to tackle a number of market failures and imperfections that bar the way to some abating potential of moderate technical cost. A second section will detail the wide range of such instruments promoted in the policy-oriented literature. A third section will then conclude on the research agenda that emerges from the state-of-the-art thus outlined.

I. Carbon pricing: lessons and limits

A vast majority if not all low-carbon[3] studies rely, to some extent at least, on uniform carbon pricing to trigger the dramatic abatement levels they envision. The economic rationale sustaining such quasi unanimity is well known: by equating marginal abatement costs across agents and regions of the world, a common carbon price has the theoretical virtue, notwithstanding equity issues, of minimising the costs of reaching any abatement target (Figure 1).



Agents A and B (households, firms, regions, *etc.*), facing the same carbon price P^*, abate $Q_A^* + Q_B^* = \bar{Q}$, incurring total costs that sum up to the dark gray areas under their curves. Obtaining the same total $\bar{Q}$ from A and B by submitting them to differentiated carbon prices will necessarily induce excess costs. Suppose *e.g.* the extreme case that agent A faces P while agent B emissions are not priced: abating $\bar{Q}$ will induce costs summing up to the light and dark gray areas under curve A; excess total costs will be the difference between the light gray area under curve A and the dark gray area under curve B.

Figure 1 : The economic rationale of uniform carbon pricing

This is a theoretical rationale that governs by and large policy making, as will be explored in a first subsection below. However its ultimate practical implications will have to be clarified in a second subsection.

3. We will continually refer to 'carbon' when discussing policy options as carbon pricing, a carbon tax, carbon abatement, etc. Unless otherwise specified all GHG are implied on carbon-equivalent terms.

I.1. A normative value of carbon as a pillar to policy action

The uniform, universal price of carbon necessary to induce given abatement levels has been consistently used in both the academic and political circles as a support to discussion. On top of the theoretical virtues that were just exposed, it is indeed a standardised, concise way of measuring the 'effort' required to achieve the target envisioned,[4] and thus a basis of comparison between e.g. the relative conclusions of different modelling endeavours, or the relative stringency of different regional targets. The simple static framework of Figure 1, which appeared fit for the relatively short-term and modest mitigation objectives of the Kyoto protocol, had however to be expanded to match the longer-term, ambitious goals of low-carbon societies. This prompted to develop what had conveniently been summed up in static point estimates into dynamic pricing trajectories capable of triggering the transition to futures dramatically different from those attained in a laissez-faire world.

The corpus of recent scientific studies that develop such trajectories to reach a variety of global or regional low-carbon targets is large. Following the shift of focus of the climate policy agenda, most of the energy-economy models prominent in the field of climate policy research have indeed recently produced one or several analyses of ambitious long-term abatement targets, some of them completed by sensitivity studies that multiply the published pricing estimates. The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) provides an overview of the existing studies up to 2007 (IPCC, 2007, section 3.3). Since then, the 22nd round of the Energy Modelling Forum of Stanford University (Clarke et al., 2009 and the series of articles in the same journal issue), the European project ADAM (Edenhofer et al., 2010 and again the series of articles in the same journal issue), or the RECIPE project (Edenhofer et al., 2009) have added to the available expertise. Because of discrepancies in the policy objective (precise target and scope), the implementation schemes, the geographical scope and the reporting templates, a comprehensive comparison of these estimates would require some large scale analysis beyond the scope of this synthesis.

Their policy implications, however, should be clarified. While Kyoto price estimates could still readily be interpreted as prices on a quota market, uniform price trajectories to the middle if not the end of the century do not easily translate into policy action, for contrasted reasons: when estimated globally, because 'first best' agreements at that scale are quite doubtful, at least in the short to mid-term—as testified by the current state of international negotiations; when estimated at the level of the European Union, because of an emerging policy framework quite incompatible with them—namely, the disconnected provisions of an EU-wide Emission Trading System (EU-ETS) covering large emitting sites, and of 27 binding national targets for the reminder of emissions up to 2020.[5] Uniform pricing trajectories should thus rather be taken as normative assessments of the theoretical least-cost option.

Such normative assessments are nonetheless of increasing policy sig-nificance. Indeed,

4. A caveat applies here: it is only in the specific theoretical framework of a benevolent planner maximising aggregate utility under perfect foresight, and in a close economy, that the price of carbon strictly matches the marginal social cost of the constraint (Edenhofer et al., 2006; Hour-cade and Ghersi, 2009; Böhringer et al., 2009a). A correct interpretation of any published figure thus requires some minimal insight on the modelling framework that delivered it. In most in-stances the carbon price must just be taken for what it is: the price signal that is to be applied to the carbon content of energy carriers to achieve a certain amount of emission reductions. The mismatch between the private and the social abatement costs also has major policy implications that will be addressed in the next section.

5. Bernard and Vielle (2009) or Kretschmer et al. (2009) confirm the analysis of the European commission itself (Capros et al., 2008) that the limited amount of emission trading provisioned among the 27 quotas does not allow for marginal cost equating. The following section further addresses these issues.

three recent governmental reports in the United Kingdom and France (DEFRA, 2007; CAS, 2009; DECC, 2009) discuss at length normative carbon value trajectories up to 2050 that, notwithstanding the particulars of their policy translation, are intended:

• As a signal to policymakers, to be integrated on the same footing as other costs and benefits to assess the net present value of public policy alternatives. The signal is particularly necessary to shape the decision making on long-lived forms of fixed capital (transport and energy infra-structures, building regulations, decisions impacting urban forms, etc.), on the straightforward ground that decisions in these fields strongly impact emission trajectories. But it should be generalised to any public decision, lest some comparatively cheap carbon reduction actions are not pursued, at the cost of efficiency losses.

• Particularly and quite obviously, as a yardstick to mitigation policies, to guarantee a consistent tapping of mitigation potentials by equating marginal abatement costs (the Figure 1 rationale again)—notwithstanding the particulars of the translation into positive policy terms of the normative guidance. Both the French Conseil d'Analyse Stratégique (CAS, 2009) and the British Department of Energy and Climate Change (DECC, 2009) indeed review the energy policies currently in force in France and in the UK and question discrepancies in the underlying implicit carbon values.

• As a signal to shape the anticipations of private agents and influence their investment decisions. Even in the absence of policies that concretise the price trajectory into a price signal, the existence of a public normative carbon price builds up the uncertainty around such pricing in the future, which should impact the trade-offs of private agents. The extent of this impact is of course open to debate, but could be significant in those fields where car-bon emissions weigh, i.e. building construction and retrofit, end-use equipments, but also R&D activities.

The argument in favour of a normative trajectory is thus in line with a strong tradition of economic calculus and economic planning in France—it is indeed advocated on similar ground in other reports commissioned by the French government (CGP, 2001; Radanne, 2004; CAS, 2008); but it also has a strong ground in economic theory, which accounts for the trajectory being supported in the context of the traditionally more market-oriented British economy. All three reports that focus on it (DEFRA, 2007; CAS, 2009; DECC, 2009) insist on its necessity as a pillar to policy action. In this light it is worth taking the time to detail and comment the trajectories outlined by the two most recent reports, and the methods that were employed to construct them.[6]

DECC and CAS share the same cost-efficiency approach to carbon valuation, i.e. they define trajectories that correspond to the price signals leading to predetermined emission profiles—a pragmatic choice, as the existing European and national abatement targets have resolved, at least up to 2050, the numerous theoretical and practical difficulties impairing cost-benefit analysis of climate change at a regional scale (which both reports touch upon). They also happen to follow a similar pattern to pinpoint trajectories: inspired by a series of cost-efficiency modelling exercises they define carbon values for pivotal years, and then interpolate between these years, or extrapolate beyond, on exogenous assumptions.

6. DECC (2009) is explicitly stated as a revision of DEFRA (2007), which will therefore not be presented at length. DEFRA based its trajectory on the Stern report estimate of the social cost of carbon for 2000, which it updated to ca €37 in 2007, and then assumed a 2% annual increase to reach €48 in 2020, €58 in 2030 and €86 in 2050—all of these 2008 euros to allow comparison with Figure 2 below.

To be more specific, CAS opts for a pivotal value of €100 (2008 euros here and hereafter) in 2030, based on a series of modelling exercises applying 3 external models to 3 exogenous emission scenarios up to 2050. This pivotal value is specifically justified as matching the average (across the 3 models) of the 2030 carbon values computed for a "Europe alone" scenario, which aims at a 60% reduction in European 2050 emissions from their 1990 level (the higher bound of the emission objective set by the European commission), without any international offsets. It is also commented as being above the average 2030 values for a "Worldwide vigorous, immediate action" scenario compatible with a 450 ppm CO2e cap and hence a 2°C cap on temperature increase, but on the basis of unlimited global emission reductions trading (one single global carbon price). The report then develops a case for adapting Hotelling's rule to carbon emissions, to conclude that the 2030 value should be extrapolated both to 2050 and to 2008 using the 4% discount rate officially applying to public policy appraisal in France. However its final recommendation diverges, on both ends of the trajectory: in 2008 the need is underlined to make the link with the carbon value currently prevailing, established by the Commissariat Général du Plan (CGP, 2001); in 2050 the €219 that would result from 20 years of 4% annual growth (the 'implied' path of Figure 2) are approximated to €200, completed by a €150 to €350 range, and the path between 2030 and this revised value left unspecified.

Contrary to CAS, DECC fully acknowledges the European Climate and Energy Package[7] by setting out two distinct carbon value trajectories up to 2020, one applying to emissions covered by the EU ETS and the other one to other emissions. The ETS trajectory is drawn from an average 2008-2020 carbon value computed by a model specific to DECC; this value appears to be applied to 2014, and is recommended to be extrapolated both to 2008 and 2020 using a 3.5% nominal rate on the basis of a cost-of-carry rationale—the published path seems to retain a 1.5% real rate. The central path thus constructed is then completed by a range defined by higher and lower estimates specifically linked to the modelling of lower and higher assumptions on fossil fuel prices (Figure 2). The non-ETS trajectory is based on a 2020 pivotal value derived from a set of 2020 bottom-up marginal abatement cost curves (MACCs). These MACCs are themselves drawn from one central estimate by the British Committee on Climate Change (CCC, 2008), on the basis of contrasted availability of the underlying technical potentials. The 2020 pivotal value is extrapolated to 2008 following again a 1.5% real rate, and completed by a -50% to +50% range loosely defined by some sensitivity analysis on the availability of technical potentials (Figure 2).

Beyond 2020 the two trajectories are assumed to converge to a pivotal 2030 value. This, together with a 2050 value, is drawn from another DECC model, whose estimates were broadly adjusted to take into account results from other modelling exercises. The latter exercises—including indeed those of the CAS—provide also evidence pointing at a -50% to +50% range on the entire horizon. Similar to the more ambitious "Worldwide" CAS scenario, both estimates are based on the assumption of full international trading, i.e. reflect the marginal costs of a global least-cost option—at least, again, in a cost-efficiency perspective: the global emission pathways tested to 2050 are exogenous, taken from the SiMCaP model.[8]

7. Cf. http://ec.europa.eu/environment/climat/climate_action.htm.

8. Cf. http://www.simcap.org. The pivotal values retained are loosely based on the averages of those computed for global emission pathways compatible with 475 ppm CO2e (with overshoot at 500 ppm CO2e) and 500 ppm CO2e (without overshoot).

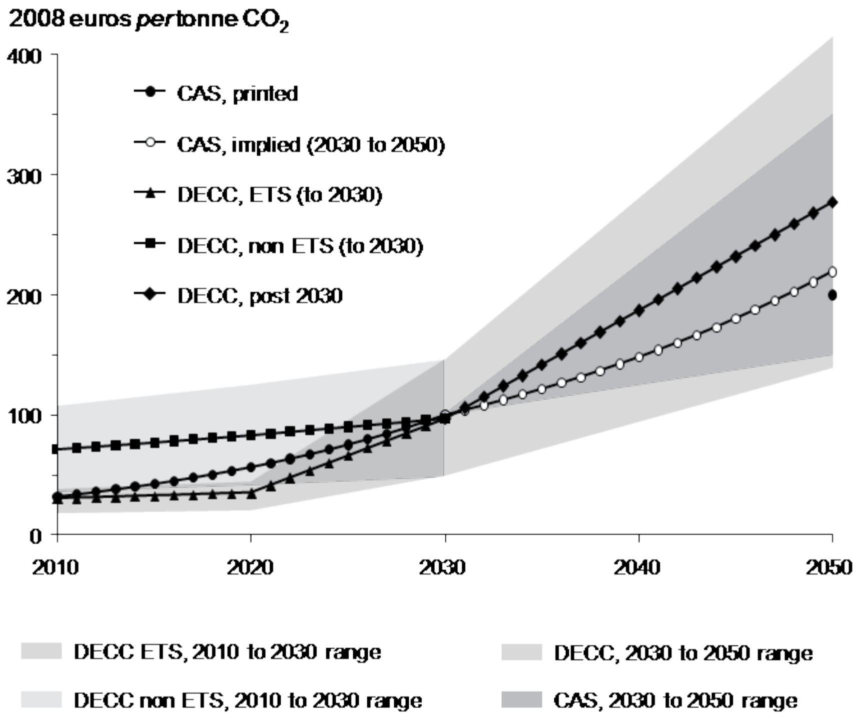


Figure 2 : Normative carbon value trajectories from the CAS and DECC reports [9]

At first glance the resulting trajectories appear broadly comparable (Figure 2). Particularly,

• the CAS trajectory is almost systematically within the different ranges defined by DECC, and the DECC trajectory is indeed within the range defined by CAS from 2030 to 2050,

• the central 2030 estimates of the two reports match remarkably well, at ca €100,

• so does their 'floor-price' 2050 estimate, at ca €150.

This relative convergence of views should however not be over-interpreted. To begin with, the ranges defined by DECC are of a width corresponding to 100% of their central value (with the sole exception of the ETS 2010-2020 estimates), and thus quite inclusive—it is unclear, incidentally, how this affects their usefulness in policy making.

Secondly, the trajectories diverge in their choices of accounting or not for the existing split in European policy between the ETS-covered emissions (which are abated on a least-cost basis at the European level) and the remainder of them (which can be abated on a least-cost basis at the national level only). DECC follows a pragmatic approach, taking stock of the existing policy context, but in doing so departs from the 'first best' notion attached to a normative recommendation: up to 2020 and indeed 2030, its recommended double trajectory, while compatible with current UK commitments, implies efficiency losses. CAS follows a more theoretical approach by defining a single least-cost trajectory for Europe over the whole

9. 2009 £ were converted to 2005 € using the 0.778 ratio retained by DECC (31.1/40). 2005 € were converted to 2008 € using a 0.928 ratio on the basis of inflation data for the euro zone from the Central European Bank.

time horizon. But this trajectory probably implies abatement of ETS-covered emissions at costs higher than the ETS market price, together with a deficit in non-ETS abatement, up to 2020.[10] A clear definition of the costs of not complying would allow performing an economic trade-off between the two stances. But the political factor most probably plays a role that cannot be disregarded.

Thirdly, the 2030 match is partly explained by DECC acknowledging some of CAS's modelling results to adjust the value computed by its own model (by ca +10%). However, the underlying simulations are not comparable: DECC is loosely averaging on 4 global least-cost options formed by combining two exogenous estimates of forestry contribution, and two concentration targets, 475 ppm (with overshoot) and 500 ppm CO2e; CAS quite distinctly centres its estimate on a 'Europe alone' -60% scenario, and its €86 and €29 estimates for the global price of least-cost 450 ppm CO2e and 550 ppm CO2e scenarios suggest that its least-cost global price estimate for the concentration objectives of DECC would have been substantially lower than €100, most likely below €60.[11] The match is thus between carbon values attached to contrasted if not disconnected (regional vs global) objectives.

At last, the coincidence of the lower 2050 bound is simply explained by DECC explicitly accounting for the CAS results to define its own range.

On a more methodological note, both reports exhibit an ambiguous stance regarding modelling. On one hand, modelling results explicitly provide the raw material on which the trajectories are built. On the other hand their conclusions are systematically stripped down to values for some pivotal years, which are equally systematically rounded up to some central estimate,[12] while their spread provides the loose basis to some accompanying range.[13] Then, the dynamics of the signal between the pivotal years and beyond are postulated exogenously, on the basis of Hotelling's rule for CAS, and on an unjustified simple linear basis for DECC. But the consistency of such assumptions with the trajectories outlined by the initial modelling exercises is not discussed—indeed the latter trajectories are not detailed in either of the two reports. In the case of CAS at least it is obvious that the abstract model that supports adopting Hotelling's rule is quite incompatible with the complex dynamics of POLES, IMACLIM-R or GEMINI-E3, as appears only from the 4 point estimates reported for these models (Figure 3). The challenge of reconciling quite contrasted trajectories, not to be underestimated, should probably have been highlighted rather than masked. For one thing both reports should have communicated the crucial piece of information of the precise exogenous emission trajectories imposed to the models.

---

10. Assuming that, similar to DECC's assessment of the UK case, the marginal abatement cost of France's non-ETS commitment is higher than the ETS market price.

11. Making the consensual assumption of convex marginal abatement costs.

12. Both reports round up many of the price estimates averaged on different runs (CAS eventually rounds up its own produced estimate for 2050). DECC argues this avoids giving a misleading sense of precision—a questionable position, as the trajectories will regularly have to be corrected for inflation, and will also be converted to other currencies or deflated, for comparison purposes (cf. e.g. Figure 2).

13. This with the exception of DECC's price estimate for the ETS sector to 2020, whose lower and higher ranges are set by further modelling on the assumption of higher and lower fossil fuel prices.

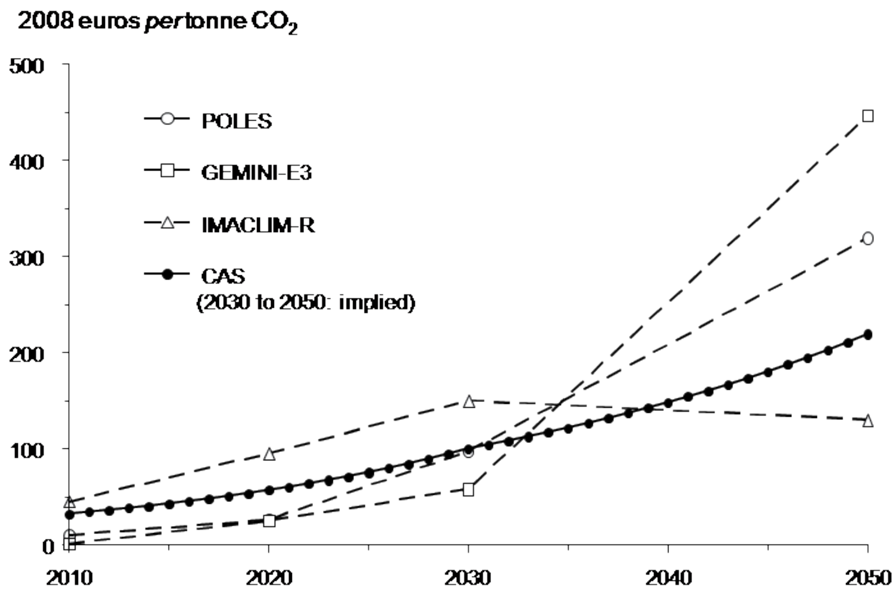


Figure 3 : Normative value of carbon from the CAS report and supporting modelling estimates

This critique should however not be interpreted as an overly negative assessment of the endeavours of DECC and CAS. While having had to make choices, the two public bodies must be credited for having extensively discussed some of the numerous methodological issues hampering the establishment of a normative carbon price trajectory, and having raised yet many others. With this contribution the CAS and DECC reports open the way to further research on the matter, as will be highlighted in a further section. We will now turn to a broad survey of the concrete policy applications that derive from the normative value principle in low-carbon scenarios.

I.2. Implementing carbon prices in a 'second best' world

The policy instruments that jump to mind to embody a normative value of carbon are either a universal carbon tax, or the market price of some com-prehensive emission trading system (ETS). Economic theory indeed stipulates that both instruments are strict substitutes, provided the 'first best' setting of perfect information on abatement costs and perfect ETS markets, and the auctioning of all emission allowances to guarantee some public income matching the tax proceeds. In a 'second best' world however, the chronicle of abatement costs for ambitious objectives up to long-term horizons is anything but certain. The dilemma is then, in well-known terms (Weitzman, 1974), between certainty on the 'price' (the marginal abatement cost) in the case of a tax, and certainty on the 'quantity' (the emission objective) in the case of an ETS. In theory an ETS is thus more apt than a tax to structure the policy path to concentration objectives, as it allows for the explicit programming of a quota trajectory.

Two main arguments contest this superiority. The first is the general point that an ETS implies investment decisions under uncertainty; this cannot but incur efficiency losses that will be all the higher as prices rise. The second is more specific to the higher abatement targets: a strict quota policy on particularly ambitious objectives may lead to prices escalating at a rate that could threaten its sustainability. By contrast a tax trajectory can be the object of a social negotiation that guarantees at least partial support to its rising. Even if it reaches the same heights as prices would on the dual ETS market it will do so in an anticipated, graduated manner that will facilitate its acceptability. A third minor argument in favour of a tax is the speculative risk on ETS markets as volatiles as the one of the first EU-ETS phase—a politically sensitive issue in the current global crisis, which finds its roots in the financial system. Then again the tax trajectory compatible with e.g. the 2020 and 2050 European abatement objectives is quite conjectural, as clearly established by the CAS and DECC endeavours (cf. above).

The choice between the two options is anyway already partially made in the European Union, where the EU-ETS has been extended to 2020. In the same policy decision,[14] the ETS has also been completed by a set of specific national 2020 targets, with restricted trading either between member states or with the rest of the world (through the CDM). But this segmented treatment of emissions comes at the risk of transgressing the uniform pricing rule. The commission's expertise itself evaluates that the 2020 ETS market price could be up to 33% higher than the average 2020 non-ETS marginal cost, while not reporting on the country-specific marginal costs that make up this average (Capros et al., 2008). Kretschmer et al. (2009) estimate a comparable wedge between slightly higher prices, but Bernard and Vielle (2009) and especially Böhringer et al. (2009a)[15] assess a larger and systematically reversed gap: the average marginal cost of non-ETS abatement is up to 7 times higher than the ETS market price in 2020 (Böhringer et al., 2009a, "ets+rps" scenario). The two former papers also assess country-specific non-ETS marginal costs that exhibit even larger discrepancies, particularly between the western and eastern European countries.

A key question is then that of the excess compliance costs induced by such discrepancies. Böhringer et al. (2009a) compute that the existence of two carbon prices only, one for the ETS and one for the non-ETS emissions (assuming unrestricted trading), increases compliance costs by ca 50%. The two other papers estimate up to a 40% supplementary increase (according to Böhringer et al., 2009b) from the country-specific nature of non-ETS commitments—access to trade is indeed severely restricted for non-ETS abatement actions. However, Böhringer et al. (2009a) also develop a set of sensitivity analyses, whose results are of critical importance: in 2 out of 4 cases defined by alternate baseline growth, uniform pricing turns out to induce higher compliance costs than the segmented efforts. The authors identify, as reasons for these seemingly heterodox results, that the private and social marginal abatement costs do not match in their modelling framework, on the simple ground that it accounts for the pre-existing distortions embedded in tax systems and international trade. Deviating from uniform pricing can thus be welfare-improving, if the increase in private abatement costs caused by differential pricing is more than offset by terms-of-trade gains, or the alleviation of initial tax distortions.

14. The 'EU climate and energy package', cf. http://ec.europa.eu/environment/climat/climate_action.htm.

15. Böhringer et al. (2009b) sum up the three papers' findings. The three studies were conducted in the framework of the 22nd round of the Energy Modelling Forum of Stanford University (Clarke et al., 2009).

This conclusion must immediately be qualified with a caveat: it holds under the particular assumption by Böhringer et al. of a lump-sum rebate of the pricing proceeds to the representative agent, in both cases when the pricing is differentiated and when it is not. But there is ultimately no question that minimising the private costs through uniform pricing is the first step to hitting the least-cost option. This first step must however be followed by that of optimising the recycling of the pricing proceeds, be they tax income, auction revenue, or for that matter the rents extracted from emission permits grandfathering. What Böhringer et al. effectively demonstrate is that a lump-sum rebate to consumers is not welfare-maximising in an economy exposed to international competition, and with prior tax distortions.

The consequences for policy making are to some extent daunting: in a second best world, optimal abatement policies cannot anymore be explored by moving the cursor of a uniform carbon price along its monetary axis, under the standard assumption of a lump-sum rebate to households. Uniform pricing could be retained at the cost of a complex recycling scheme carefully weighing the impact of carbon pricing on pre-existing distortions. But the implementation costs of such a scheme would probably be high enough to warrant exploring differentiated pricing as a way to account for these distortions ex-ante rather than ex-post. This does not disqualify the establishment of a normative pricing trajectory: beyond remaining valid as a yardstick to concrete public abatement endeavours, the normative trajectory also constitutes the necessary central value from which deviations would have to be considered, to an extent that depends on the magnitude of the pre-existing distortions.

What this calls for is an extension rather than a radical shift of the policy process: translating the central pricing trajectory into policy action is made under the constraint of some initial distortions. The further policy challenge is to identify these distortions, and adapt the pricing policy to them, if need be, but above all take great care of making the most of the pricing proceeds in second best economic conditions. To conclude on an optimistic note, this gap between the private and social abatement costs echoes the large body of literature devoted to the 'double dividend' issue (for a survey cf. IPCC, 2001, section 8.2.2.1; IPCC, 2007, section 2.4.2.2 sums up the case for a double dividend and provides 3 further references): in extreme cases it may happen that the gains from alleviating pre-existing distortions are such that they supersede the direct technical costs, making up for negative abatement costs. Notwithstanding the academic debate whether they should be attributed the merit of it or not, carbon policies can be crafted to lift some of the inefficiencies that are to be found in any economy, thereby reducing decarbonisation costs.

I.3. Limits to carbon pricing

We have so far outlined two types of 'second best' constraints to the development of carbon policies: uncertainty about the manifold future terms of the carbon equation, and the distortions caused by pre-existing tax and subsidies and openness to international trade. A cautiously differentiated set of carbon taxes or quota trajectories, backed by some clearly anticipated normative pricing trajectory, tentatively emerges as a policy portfolio up to the challenge of these second best conditions. However, the recent literature devoted to low carbon scenarios describes many instances of failure of pricing policies to induce the most ambitious quota objectives (Tol, 2009 ; Rao et al., 2008 ; Clarke et al., 2009; Edenhofer et al., 2010). Clarke et al. provide some insight on these inabilities, identifying (beside more straightforward international participation issues, solving limitations and the availability of technological options[16]) "decline or expansion constraints" in key aspects of the decarbonising process: in most models the penetration rate of techniques is bounded by asymptotes that are in some instances explicit, and in others drawn by constant depreciation rates of the initial carbon-intensive capital stock.[17]

It is hard to draw any robust policy conclusion from such evidence. There is indeed no theoretical reason why extreme prices should not end up impacting on some of these "decline and expansion constraints", e.g. by gradually inducing the early retirement of the existing capital stock—although the practical question of calibrating such fundamental shifts is certainly on the frontier of current climate policy research. In that sense the unreachable nature of some targets could be attributed to modelling limitations rather than to a shortcoming of the specific pricing instrument. This is implicit in the use by some modelling teams of exogenous scenario assumptions on alternate development patterns.[18] On a similar note it should be mentioned that the widespread use of carbon pricing in models is to some extent ambiguous: some studies explicitly state that carbon pricing is only meant as a proxy to some unspecified policy portfolio better apt to trigger abatement, especially for the most ambitious emission cuts, which require carbon prices reaching heights that raise serious implementation issues.

In a different body of literature, stemming from the seminal paper of Jaffe and Stavins (1994), a number of energy market failures have nonetheless been explicitly identified that warrant resorting to policy instruments beyond the market-based ones (cf. e.g. Bennear and Stavins, 2007). Out of the three types of market failures pinpointed by the Stern review (Stern, 2007), putting a price on carbon indeed only addresses the first and most straightforward one, the environmental externality, by forcing agents to take into account some measure of the environmental damage caused by their economic activity. Two other broad categories of market imperfections elude the grip of market instruments.

To begin with, a series of market imperfections tend to drive a wedge between the socially optimal and the effective innovation effort on low-carbon technologies. Among these, knowledge spillovers prevent the innovator from capturing the full return of its investment; the lack of infrastructure constitutes a barrier to the penetration of some technologies; fragmented technological markets provide little economic leverage to engage in R&D programmes characterised by high initial costs, while historical operators on energy markets may have less incentive to innovate.

Another series of market failures hamper the adoption of low carbon technologies or behaviours on the side of energy demand. First, information is fragmented and in some instances sparse on the particulars of the available technology options, when facing a replacement decision because some equipment has reached the end of its life, and all the more so when some anticipated retirement might prove profitable even accounting for the opportunity cost of untimely retirement.

16. This latter point is also stressed by Edenhofer et al. (2010): some of the models of the ADAM European project, whose findings Edenhofer et al. synthesise, had to be extended with Carbon Capture and Storage (CCS) and combined biomass and CCS options to reach the most ambitious targets of the study.

17. Clarke et al. (2009) insist on the methodological difficulties of pinpointing the exact causes of modelling failures. It would indeed call for a thorough examination of some mathematical and parametrical particulars that are out of reach of anyone but the modellers themselves. This is another example that crafting conclusions on any simulation requires a deep understanding of the underlying modelling tool.

18. Cf. e.g. FONDDRI (2009), who resorts to a set of exogenous assumptions to picture a 'non-mimetic' scenario, where developing countries let the carbon constraint influence their funda-mental development patterns, rather than pursue the northern hemisphere 'way of life' with only marginal changes.

Secondly, capital constraints prevent the more modest households and firms from investing into end-use equipments that, despite high initial investment costs, would prove profitable over their lifetime. A third market failure is caused by misaligned incentives, whereby the direct beneficiaries of some abatement actions are not in a position to perform them, cf. e.g. the owner/tenant problem, or the split incentives between professional drivers and their companies. At last, some intangible costs, linked to real or perceived non-monetary characteristics of technology options, limit the adoption of seemingly cost-effective technologies.

It is again doubtful that any of the abatement actions hampered by these market failures could not be triggered by sufficiently high carbon prices. It is reasonable to think, though, that more targeted, not necessarily market-based policies could tap this abatement potential at a lower social cost, and thus should complement any carbon pricing measure if the least-cost option is to be struck. But this conclusion is at the most glimpsed at in peer-reviewed literature, and comprehensive assessments of policy portfolios are sorely missing,[19] either because the issue is not clearly identified and the uniform pricing rationale still prevailing, or because of modelling limitations—on which we will come back. 'Grey' literature, on the contrary, offers studies and reports that insist on the necessity to combine a wide range of specific policy instruments to achieve high rates of decarbonisation, and propose such combinations.

II. Addressing 'market failures': the case for policies and measures

The set of recent studies and reports matching complex policy portfolios with high rates of decarbonisation at the middle of the century is conveniently split between works commissioned or carried out by public bodies, and works produced by non-governmental organisations (NGOs).

In the first of these categories, France, Germany and the United Kingdom (UK) have each recently produced a study focusing on the way to comply with their national commitments, a factor 4 cut in emissions by 2050 for France, and a factor 5 cut for Germany and the UK.[20] The French report (CAS, 2006) was commissioned by the French government to an advisory body, the Centre d'Analyse Stratégique (CAS) under the editorial authority of Christian de Boissieu, and leans on pre-existing expertise. The German report (BMU, 2008) was commissioned by the German federal environment ministry to a consortium of 4 research centres, which produced original scenarios, but on exogenous energy demand assumptions. The British report (CCC, 2008) emanates from the Committee on Climate Change, an independent advisory body to the British government, and also developed original scenarios on exogenous energy demand assumptions. Prior to the de Boissieu report, France had also issued a shorter note on the Factor 4 objective (Radanne, 2004); besides, the CAS recently reported on French energy perspectives to 2020 and 2050 under the editorial direction of Jean Syrota (CAS, 2008), and the document contains a large number of climate policy recommendation. .

19. Many energy and carbon policy instruments other than the simple carbon tax and TEP systems (e.g. green and white certificates, performance standards, etc.) have been devoted a large body of specific literature, sustained by partial equilibrium modelling. What is missing is the comparative assessment of the aggregate social cost of complex policy portfolios.

20. The German and British targets are with reference to 1990 levels, echoing the Kyoto commit-ments. The French target is more loosely established; CAS (2006) assumes it is also with refer-ence to 1990, but it could end up being pinpointed as against 2003, 2004 or 2005 levels, the years in which the target made its way into the French political agenda.

Some policy measures beyond carbon pricing can also be gleaned from the previously quoted Quinet report on the shadow price of carbon (CAS, 2009).

In the second category, Greenpeace issued a report focusing on EU-25 that envisages a 70% emission cut in 2050 from 2000 levels (Greenpeace, 2005). In 2008 the same NGO published a much expanded report at the global level, which describes a 78% emission cut in 2050 from 1990 levels for OECD Europe (Greenpeace, 2008). Another set of quite less extended scenarios to 2050 is proposed by the INFORSE network, and includes an EU-27 regional scenario that envisages a phase-out of fossil energy by 2050 (INFORSE, 2008). INFORSE is itself a network of NGOs, among which a militant Zero Carbon Britain, which produced an extensive report specific to the UK (more precisely to the island of Britain per se, as the name hints) describing a provocative total phase-out of carbon emissions in the course of 20 years only (ZCB, 2007). A more synthetic report for France was published in 2006 by the Negawatt association (Negawatt, 2006).

Before turning to the detail of their policy recommendations, it is capital to stress that all of these studies blatantly lack support from both (i) micro-economic expertise, which could assert the wide array of advocated measures match the often dramatic impacts that are attributed to them, and (ii) a macro-economic integrating framework, in which the manifold policy actions that are promoted could be built into a consistent economic and energy system picture. The somewhat consensual policy portfolio that emerges from them is thus at best a tentative answer to the question of the policy path to low-carbon societies, which would require due assessment to be confirmed—a third and last section will comment on the research agenda this outlines. As a side note, it should be underlined that most if not all studies advocate carbon pricing as a core mitigation measure, although the future prices are rarely pinned down, and at exogenous levels when so (e.g. by BMU, 2008, or Greenpeace, 2008), with the only exception of CCC (2008). The most precise pricing policy description is proposed by Zero Carbon Britain (ZCB, 2007): a multigas cap-and-trade system strictly enforcing the phasing-out promoted, with 40% of the yearly quota freely allocated to households on a per capita basis, to correct distributional impacts, while the remaining 60% is auctioned to firms and public institutions, and the auction revenue "ring-fenced for use in easing the tran-sition to a zero-carbon economy". This indeed offers the most striking example of the imperious necessity of economic assessment: while ZCB cautiously avoids providing estimates it is quite likely that auction prices for such drastic carbon constraints would reach unsustainable heights, inducing such shifts in the relative prices (including vis-à-vis international prices) as to cause entire sectors of the British economy to collapse—or more likely the policy action to be abandoned under public pressure.[21]

This important caveat behind laid, we will turn to the description of the recommended policy instruments, divided in three subsection detailing in turn measures concerning energy supply, energy demand, and a set of other actions.

II.1. Energy supply

21. Combet et al. (2009) assess substantial GDP and employment losses induced by terms of trade effects for schemes close to ZCB's proposal, in the case of France, and for a 100 to 400€ per tonne CO_2 carbon tax. It is doubtless that the prices induced by ZCB's proposal would rapidly exceed 400€ per tonne CO_2.

The stress on energy supply is put first and foremost on the production of electric power, and the necessity of a much increased penetration rate of renewables to meet ambitious concentration targets. The main barrier to the development of renewable energies is identified by all studies, explicitly or implicitly (considering their policy recommendations), as the historical heritage of state-funded, planned, massively subsidised, power production.

To overcome the implied barriers the first obvious move identified by most studies is to create a 'level playing field' (BMU, 2008; Greenpeace, 2005) by putting an end to any subsidy to conventional electricity production—Greenpeace quotes OECD figures of an estimated $250-300 billion per year in subsidies worldwide (Greenpeace, 2005), which heavily distort markets in favour of fossil- and nuclear-based electricity.[22] Policy action should lift the existing subsidies rather than align the subsidies granted to renewables on those existing for conventional power production: it is essential to energy efficiency improvements that the real cost of electricity should be passed through to consumers—which also requires that an end be put to regulated prices, as CAS (2008) advocates in the case of France. On top of this obvious move, some studies insist on the necessity to level the field between the renewable options themselves (and more broadly to align the incentives created by the wide array of energy policies that are currently in force): the existing incentives should be thoroughly reviewed, and brought into consistency (BMU, 2008). The analyses by CAS (2009) and DECC (2009) of the existing supporting instruments in respectively France and the United Kingdom reveal indeed large discrepancies in the implicit 'private' value of carbon—this should be taken as a hint that the social values, which we have seen do not necessarily correspond to the private ones, also mismatch.

But for most studies creating a level playing field is just a prerequisite, and does not suffice to overcome the consequences of decades of public support, firmly anchored in the existing technologies and infrastructure. This makes the case for a series of complementary policies and measures, as:

• Feed-in tariffs, extensively supported (Greenpeace, 2005, 2008; ZCB, 2007; BMU, 2008, which more specifically supports the German Renewable Energy Sources Act of 2000 and its 2004 amendment). To reduce uncertainty and avoid inefficient 'stop-and-go' markets, these should be guaranteed to a mid-term horizon—Greenpeace (2005) stipulates a 20-year horizon. BMU (2008) however stresses that the tariffs can be gradually phased out, starting as early as 2015 in the German case, as the combined forces of productivity gains from market developments and steady increases in fossil fuel prices make them economically viable.[23] In 2023 the portfolio of renewables projected by BMU is self-financing, at least from an aggregate perspective.[24] A similar general argument is found in Negawatt (2006).

• Legally binding renewable targets (Greenpeace, 2005; CCC, 2008). As a extension and strengthening of the Renewables Directive of 2001, the share of renewables in electricity production should be imposed for further time horizons to form a 'renewable share pathway'.

22. Cf. OECD (1998). Greenpeace also quotes a Worldwatch Institute estimate that the subsidies to coal production reach $63 billion worldwide, while in Germany alone they total €21 billion, including direct support of more than €85,000 per miner.

23. This is notwithstanding the benefits from building industrial export capacity, underlined, if not assessed, by BMU (2008).

24. The costs of the still substantially more expensive solar photovoltaic technology being com-pensated by the competitiveness of all other renewable technologies envisaged. BMU advocates that solar photovoltaic is to be supported, despite a considerable mark-up in current market con-ditions, to create the conditions for it to take up a large market share from 2030 on.

• Simplification and acceleration of the administrative procedures surrounding electricity production and access to the grid (Greenpeace, 2005; BMU, 2008, CCC, 2008). Administrative barriers should be removed at all levels and a ‘one-stop-shop’ system, complemented by clear timetables for project development, should be introduced (Greenpeace, 2005; BMU, 2008). On the particular question of the grid this requires due transposition of the existing European legislation by Member States, among others regarding an effective unbundling of historical utilities into separate generation and distribution companies. A grid authority should guarantee similar, transparent conditions to all producers, and carry the costs of infrastructure development rather than bill it to renewable energy projects.

Some studies insist on the fact that both the renewable targets and the feed-in tariffs should be expressed in a way that preserves technological diversity, which should play a crucial role in attaining the most ambitious targets (Greenpeace, 2005). This obviously constitutes quite a challenge for tariffs, as it implies a thorough prospective on the future relative costs of the renewable technologies.

The targeted increase in renewable energy supply calls for improvements in the electric grid, in the three dimensions of storage, transport and distribution. Electric grids are to be upgraded to ‘smart grids’ to allow for balancing power production by decentralised and intermittent units (ZCB, 2007; CAS, 2008, specifically targeting electric heating). Greenpeace (2005) thus advocates that the level and timing of demand for electricity could be managed by providing consumers with financial incentives to turn off some of their appliances at periods of peak consumption—a technical solution also envisaged by CAS (2008). Furthermore ZCB suggests heterogeneous electricity pricing: consumers should be given the choice between uninterruptible, expensive contracts, and discounted rates where energy companies can control appliance use to balance demand; they should indeed be allowed to sell the use of their onboard power and battery storage back to utility companies while these are not being used—a most innovative “vehicle to grid (V2G)” system is promoted.

The development of a smart grid would obviously be most efficient if it were coordinated at a European level. This is essential to integrate large quantities of renewable-generated electricity in power supply systems, as it allows an efficient mobilisation of the renewable potentials specific to countries, and guarantees the balance of the system (BMU, 2008; CAS, 2008, which stresses the difficulties of the European grid to accommodate the current levels of renewable contribution in Germany and Denmark). The stakes are outlined by BMU, which forecasts massive reliance on imports of solar energy to Germany in 2050: 26% of the German electricity generation from renewables, and 21% of the total German energy generation (BMU, 2008, Table 1, Table 2). CAS (2008) also underlines that an integrated European grid could greatly contribute to further open to competition some national markets as the French one.

A second key compartment of policy intervention in the field of energy supply regards the quite specific question of combined heat and power. BMU (2008) explicitly underlines that the most ambitious abatement targets cannot be met if the huge potential gains in energy return that result from heat collection are not duly tapped. BMU indeed stresses that the German market for heat generation systems based on renewables must undergo even more dynamic growth than comparable systems in the electricity sector have recently experienced. It is all the more necessary to give the heat sector careful attention as it is rarely given the consideration it deserves. This accounts for the lack of experience about the policy instruments that should be implemented to build a consistent, efficient market out of the myriad of decentralised investment decisions happening (every single property owner would be an actor on such a market).

Still, BMU (2008) supports the German CHP Act (in its latest amended version), particularly for the promotion of the modernisation of existing CHP plants alongside the building of new ones, as well as the crucial expansion and creation of heat grids. It however questions the level of support to heat providers based on two German studies. It also promotes the German Renewable Energies Heat Act of 2007 and the corresponding act in Baden-Württemberg as preliminary measures at least, that should be speedily extended to all types of building—the national act is restricted to new buildings, while the regional one includes them but covers residential buildings only—, while the mandatory use of renewables should be extended to the building stocks. Finally it stresses the role that local authorities will have to play to accelerate the structural change in grid-connected heat supply it envisions.

To conclude this section on energy supply, it is worth mentioning that none of the surveyed studies place a strong emphasis on biofuels. The general stance is rather one of cautious support, considering both the uncertainties regarding the life-cycle assessment of that energy carrier (CAS, 2008), especially when imported from outside the EU (BMU, 2008), and the potential undesired side-effects on food prices prompted by the competition with food production in the use of land (BMU, 2008). Nonetheless BMU (2008) identifies tax exemptions for biogenic fuels, and the German Biofuel Quota Act of 2006, as highly effective measures that have allowed the share of biofuels to rise steeply in the German context.

II.2. Energy demand

The 'efficiency gap' in energy demand must be fully tapped to reach the ambitious 2050 objective of a -60% to -80% in GHG emissions compared to 1990. Greenpeace (2008) thus estimates that current European energy demand can be cut by as much as 30% in a cost-effective manner. Beyond this potential a thorough rethinking of energy services, starting from scratch rather than composing with the constraints embedded in the current stocks, is deemed capable of cutting back energy needs by a factor four to ten (Greenpeace, 2008). ZCB (2007) and Negawatt (2006) also insist on the necessity of energy savings as a third major component of a transition to a low-carbon society.

Mandatory energy efficiency targets could pave the way to this objective (Greenpeace, 2005): Greenpeace criticises the low mandatory European targets for annual energy savings, which equal just 1% of private customer energy use and 1.5% of the amount distributed to the public sector, and advocates annual targets of at least 2.5% for the private sector and 3% for the public sector.

More specific measures detailed by the various reports are understandably in line with the main contributors to energy savings they envisage. Buildings and transportation thus receive the main focus, while appliances and end-use equipments are also significantly targeted. Industry, however, is consistently viewed as sensitive enough to market signals to restrict the policy measures targeting it to carbon pricing.

Buildings are stressed by many studies as one if not the major source of potential energy savings, and indeed one that cannot be left untapped if ambitious targets are to be met (ZCB, 2007; CAS, 2008; Radanne, 2004). A strong emphasis is placed on the slow dynamics of the building stocks (ZCB, 2007; crucial to Radanne, 2004—one of his "interdits" i.e. cannot do without; CAS, 2008). CAS also stresses the highly decentralised nature of decision making in the building sector, and the financial constraints weighing on many of its actors—ZCB insists on the latter as well, and advocates that some of the proceeds of the quota auction it promotes be used to finance investment by the poorer households.[25] This makes the case for a vast, strong, coordinated and continued public action.

General recommendations include a strengthened and accelerated de-velopment of building regulations for new construction (Radanne, 2004; ZCB, 2007; CAS, 2008; Greenpeace, 2005 and 2008; INFORSE, 2008; BMU, 2008). INFORSE (2008) more specifically proposes to raise mandatory building-codes to current low-energy housing levels as early as 2010, and to require that all major renovation include a major energy renovation—but does not precise how such a prescription should be enforced. As regards energy efficiency it explicitly targets passive houses, that are to be the subject of a massive R&D programme, and once developed are to be the basis of updated energy standards. CAS (2008) goes as far as propose that any new building should be constrained to be equipped with either heat pumps, renewable heating, or solar thermal hot water. Greenpeace (2008) recommends a similar mandatory share of renewable sources to heating and cooling, while CCC (2008) calls for some appropriate framework to support the wide-scale deployment of renewable heat. A couple of studies insist on the necessity to monitor these constraints and liabilities (ZCB, 2007; CAS, 2008), based on surveys revealing the 'implementation gap' between regulations and actual performances.

The existing stock should also be subjected to an ambitious refurbishment programme (BMU, 2008; Negawatt, 2006), with a view to hasten convergence between the efficiency of the stock and that of new constructions (Radanne, 2004). One way to implement this convergence is suggested by ZCB (2007), which proposes "mandatory energy efficiency improvement at exchange of contract on sale, and when letting". Less targeted measures include tax rebates in exchange for the installation of efficiency measures, and a VAT exemption for refurbishment expenses. ZCB expresses support to the British Warm Front programme (grant programme directed to the poorer households) and the Decent Homes programme (refurbishment of social homes). CAS (2008) and CCC (2008) voice support for the certificates mandated by the EU directive on the energy performance of buildings, as these concretise the constraint on real estate markets. Among other provisions based on energy performance certificates (EPCs) CAS (2008) proposes that

• firms could be required to publish an indicator of the energy performance of the buildings they own or occupy,

25. Although it is specifically pregnant in the building sector where investment costs are high, limited investment capacity also impacts end-use equipments.

• landowners could be forbidden to increase the rents of the properties that belong to the lowest categories of EPC,

• an accelerated amortisement of the acquisition or refurbishment costs of a building could be allowed in case this building belongs to the higher EPC categories.

CAS also develops a collection of measures more specific to the French economy (extension to landlords of the tax credits earned by energy savings and renewables investments, effective implementation of the obligation of individual accounting for collective heating systems, suppression of the reduced VAT rate on cooling systems). Alternatively, ZCB (2007) supports a transition of energy companies to energy services companies, which charge for the provision of energy services (lighting, warmth, hot water, etc.) rather than energy units, with the advantage of trusting to such specialised companies the complex optimisation problems of energy systems. The shift to such market organisation is tentatively started by the Supplier Obligation in the UK, which is strongly supported by CCC (2008). The second main energy demand sector identified as a target of specific policies and measures is transportation, for the obvious reasons of its continued growth and reliance on fossil fuels (CAS, 2008).

A first series of recommendations regard a 'systemic approach' to the transportation problem: it is only through a concerted reform of a broad range of public policies related to urban planning, land settlement, business supply chains organisation, etc., that the challenge of containing the growth of transport services, and reorienting it to the least emissive modes, can be met (Radanne, 2004; Negawatt, 2006; CAS 2008b, although cautiously subordinating such changes to public acceptance). Radanne (2004) particularly urges for early action, considering the dynamics at work in such fields of public intervention. ZCB (2007) advocates some infrastructure changes in the sense of improved cycle lanes (also supported by Greenpeace, 2005) and pedestrian facilities to help reduce vehicle usage and encourage alternative modes of transport. The need for some specific instruments to foster telecommuting and car-sharing is underlined by Negawatt (2006) or CAS (2008), although these instruments are not pinpointed. CAS still stresses the need to lift the legal obstacles hampering car-sharing (insurance, expenses eligibility). Greenpeace (2005) points out at Japan as a 'best practice' country for passenger transport, considering the large share of rail in total passenger kilometres it exhibits (29% in 2004), thanks to a strong urban and regional rail system; and at Canada for freight transport, but without detailing specific policy measures.

More targeted measures concern first and foremost passenger cars. Greenpeace (2008) advocates strict technical standards on vehicles, together with measures to guarantee that the size of vehicles decreases. CAS (2008) pinpoints an objective of 120g/km in 2012 for new personal cars—10g/km stricter than the EU objective, and CCC (2008) one of 100 g/km in 2020—both studies agree that standards should be imposed on all other classes of motor vehicle as well. CAS (2008) also suggests that already existing efficiency improving equipments could be made mandatory (instant fuel consumption display, tyre pressure gauge, cruise control, etc.). To downsize vehicles Radanne (2004) supports a bonus/malus scheme akin to the one introduced in France in 2008,[26] highlighting it as a good use of the fiscal

26. The buyer of a new car is subject to a range of taxes or subsidies depending on the car's average CO2 emissions per kilometre.

instrument as a leverage on consumer behaviour rather than a source of public money. CCC (2008) supports a similar incentive, although in less precise terms. Radanne also suggests a mandatory tie down of engines at a European level, stating this could reduce fuel consumption by 20%—but without addressing the problem of heterogeneity of speed limits in Member States. CAS (2008) does, and advocates that a harmonised upper limit of 130 km/h should be enforced, not so much for its direct impact on fuel consumption, as for its indirect impact on the power of cars, which would allow for reduced consumption in all driving cycles alike. CAS also stresses the role that training drivers to 'eco-driving' and information campaigns could play, advocates the development of urban tolls, but also of time-dependent toll pricing (implying reduced fuel waste through congestion), suggests that a vignette should be reintroduced on a CO2 emission basis, based on a €100 carbon value and on an average 14,000 km per year. CCC (2008) also mentions the potential impact of a CO2-based vignette, without pinpointing levels.

Targeted measures on other transportation modes are few. On road freight CAS (2008) recommends a kilometre-fee that could be enforced thanks to GPS data. Negawatt advocates a specific taxation of low-cost air transport, without more precision. ZCB, in line with its extreme scenario of a 20-year carbon phase out for UK, goes as far as suggesting that the nationalisation of coach and railways could be required to meet its ambitious objective of a fourfold development of rail and coach transportation. Simultaneously, it advocates that the rail network should be completely electrified (one third remaining to be done in the UK).

A third series of measures address the specific problem of appliances and end-use equipments, whose responsibility in residential energy consumption has consistently increased over the last decades. Recommendations include:

• In line with the 2005 EUP Directive, an extension of environmental labelling to provide more product information (Greenpeace, 2008; CAS, 2008; ZCB, 2007; CCC, 2008). ZCB further specifies that energy ratings should be permanent and clearly visible, to play on reputation effects; and should be split in two to reflect active versus standby power consumption, considering the growing number of equipments with permanent plug-in requirements.

• On top of the labelling, strict technical standards are advocated (Radanne, 2004; Greenpeace, 2008; CAS 2008b) to guarantee that the least efficient appliances are denied access to market. Radanne (2004) underlines that this should help cutting down the costs of the more efficient appliances by guaranteeing them larger markets. CAS (2008) specifically mentions the case of light bulbs.

II.3. Policies and measures beyond the energy markets

Most studies promote a set of measures to complete those directly targeting energy demand and supply. A first field of policy intervention, still strongly connected with the energy markets, is R&D support. The need for a strong, coordinated and immediate R&D effort is consistently stressed, to foster technical change in the energy producing technologies and end-use equipments alike. Radanne (2004) indeed explicitly addresses the timing issue, stressing that standard 2050 technologies must have hit market competitiveness around 2030, which means that they must reach the stage of prototypes by 2020, and should thus proceed from programmes launched in the very few years to come. Some studies put the stress on particular fields of research, that can be split in two:

• specific end-uses and end-use equipments: cooling (Greenpeace, 2008); personal cars (Radanne, 2004); positive energy buildings (CAS, 2008),

• ancillary technologies: heat storage (Greenpeace, 2008), electricity storage, transport and distribution (ZCB, 2007; CAS, 2008); carbon sequestration (Radanne, 2004; CAS, 2008, with mention of the potential global market to seize; CCC, 2008), although some studies exclude it as a non-sustainable option (ZCB, 2007; BMU, 2008).

Although most if not all studies advocate support to renewable technologies CAS (2008) is the only one identifying a priority, namely second generation biomass, stressing that support cannot be generalised if it has to be efficient, considering the current state of public budgets.[27] On the contrary ZCB (2007) stresses that R&D programmes should strive to balance their support to competing technologies and let the market elect the most efficient ones.

A second policy recommendation regards public awareness campaigns. Such campaigns are advocated by many reports, either on loose terms ("energy efficiency"), or on more specific issues, including driving behaviour, heating and cooling practices, and standby power consumption. In a similar line of thought demonstration projects are advocated on the particular questions of building efficiency by Greenpeace (2008), and on the CCS technology, by CCC (2008).

A third and last field of policy intervention regards the implementation of ambitious training programmes, that are required to face the escalating demand induced by low-carbon policies on many job markets. The first and foremost of these markets is the construction market, in a broad rather than a narrow sense, i.e. from building conception to consultancy on energy performance to refurbishment and construction proper (CAS, 2008; Greenpeace, 2008; ZCB, 2007). Again, some stress is put on the timing issue, considering the time required to organise and develop the appropriate training courses (CAS, 2008).

III. A blueprint for further research

The above panorama of the state-of-the-art of low-carbon policymaking makes a clear call for extensive further research. Some lineaments have been laid in both the section about carbon pricing, and the section about supplementary policies and measures, that can now be developed and weaved into a research agenda.

III.1. On a normative carbon value trajectory

The first field of research that emerges from our survey regards the es-tablishment of a carbon pricing trajectory. It is quite illusory to set the objective of pinpointing 'the' optimal trajectory, considering the multiple uncertainties that characterise global climate mitigation

27. CAS also advocates strong public support to 4th generation nuclear and nuclear waste treatment. We have deliberately left out the nuclear phase-out question, which is clear cut in the NGO reports, and strictly echoing national agendas for the French and German public reports.

over the next decades. To begin with, the research objective can probably be narrowed to a cost-efficiency framework that takes stock of the existing European abatement objectives, at least the longer term one of -60% to -80% from 1990 levels in 2050. On this truncated agenda there is still room for improvement of the current approaches. Section I.1 indeed identified that most available studies adopt such a cost-efficiency framework with exogenous concentration targets, that are met following a transposition of Hotelling's rule, i.e. applying to some tâtonnement-determined initial price a growth rate equal to the discount rate (cf. e.g. Tol, 2009; Gurney et al., 2009). The rationale for that is explained at length in the Quinet report (CAS, 2009), but again it applies to a first best setting that disregards four paramount determinants of the development of the mitigation potential:

• Demographics will weigh heavily on European growth in decades to come. Their impact is on the available manpower, on public budgets in many European countries where pension systems are public, and also on the av-erage savings rate. Ultimately they strongly influence growth and hence emissions on the one hand, but also the available income from which abatement action is financed on the other hand, together with the induced financial flows.

• Fossil fuel prices interact with carbon pricing policies in obvious ways. Their specific dynamics, for conventional fuels as well as for unconventional ones, constitute another price signal that will impact mitigation measures all the more strongly as resources deplete.

• The existing capital stock, in the energy sector but also in the rest of the economy, has an embodied degree of flexibility in input consumption that is a major driver of abatement costs. It is obvious that the multiple specific stock dynamics of end-use equipments, energy production, the building stock and ultimately urban and transportation infrastructures, shape the de-velopment of the mitigation potential.

• Technical progress, at last, defines how the flexibilities of the capital stock evolve with each new generation. It is itself driven by both research and development activities, and learning-by-doing. The former activity and the latter phenomenon must be accounted for to determine, even if only tentatively and in a stochastic framework, the 'carbon intensity' embodied in successive capital vintages.

It is likely that the combination of these four intertwined dynamics with that of carbon emissions disqualifies a simple application of Hotelling's principle to carbon pricing. The accumulation of technical progress questions indeed the very notion of systematically increasing carbon prices: as the innovations spurred by carbon pricing increase their market shares they will benefit from returns to scale that will allow decreasing their supporting measures—this is well illustrated by the call for a phasing out of feed-in tariffs over time (cf. section II.1). Besides, the policy-induced price signal will all the more be allowed to decrease as the depletion of fossil fuel resources will increase their prices, providing a signal of their own.

To clarify these interactions the five concomitant dynamics should be integrated in some intertemporal optimisation framework, that in the European case could target a 2050 emission objective with carbon pricing and public R&D trajectories as variables. The task is not out of reach of some models currently in use, and indeed some of the dynamic interactions at play have already been touched upon—particularly as regards trajectories of R&D investment, cf. e.g. Bosetti et al., 2009. Of course the resulting pricing pathways, as any modelling outcome, would be dependent on a particular set of assumptions (including some on the discount rate, which attracted great attention in the wake of the Stern review), but at least these could be explicitly discussed, and the policymaker allowed more informed decisions.

III.2. On the Terra Incognita beyond first best policy design

It is in fact firmly established, as echoed by section I.2, that the uniform pricing rationale is a challenge to enforce in real world 'second best' economies, where market distortions can be large enough to significantly increase the costs of uniform pricing under the standard assumptions of cost distribution (taxes or auction proceeds rebated lump-sum to households, grandfathered permits). Böhringer et al. (2009a) identify two such distortions:

• Pre-existing taxes and subsidies. These impact public budgets, and the shift in their fiscal bases or beneficiary activities induced by carbon pricing must be accounted for: some carefully differentiated pricing could lower the social cost of the carbon constraint by minimising its impact on the pre-existing public financing structure.[28]

• Terms-of-trade effects. The degree of exposure to international competition is highly variable across sectors, from say poorly differentiated raw materials to local services. It is hard to rule out that some moderate increase of the carbon price laid on unexposed activities to compensate for carbon price cuts granted to exposed sectors could lower the social cost of a mitigation objective.

These two types of distortion are easily modelled as they rest upon the interplay of readily observable relative prices. More controversial distortions regard some 'imperfect' features of e.g. labour markets in many European countries, where numerous regulations and transaction costs prevent full clearing through prices.

The consequences of such second best features on policymaking do not receive the attention they deserve, considering the stakes of significantly reduced if not inverted abatement costs illustrated by the formerly quoted IPCC survey (IPCC, 2001, section 8.2.2.1). They should be explored in a pragmatic way, notwithstanding the unsettled academic dispute whether the benefits from alleviating distortions should be attributed to the climate policy per se or not—a point arguably irrelevant to the policymaker. Case studies firmly anchored in some dominating traits of the real world economies can contribute to elicit them. To be thorough these should give greater attention to the rebating option that closes the loop of any price-based policy. In that regard attempts at pinpointing 'the' optimal recycling scheme through modelling are probably vain, as they are likely to point at some corner solution blatantly ignoring the strong political constraints that weigh on public decision making. Still, it should be made clearer to the policymaker how contrasted recycling options lead to

28. This is further complicated by the varying possible assumptions about public budget constraints. A standard assumption is that of the 'budget neutrality' of the reform, mostly defined as a maintained budget balance under the constraint of constant real public expenditures. This implies selecting some adjustable tax rate that allows balancing the induced variations. It is obvious that the cost of any abatement target will depend on the selected adjustable rate and the induced shift in any pre-existing distortions.

contrasted welfare and distributional impacts.

III.3. On a microeconomic elicitation of incentive overlaps

As testified by section II the available literature on low-carbon policy portfolios is more a catalogue of policy measures than anything else, with little attempts if any at rationalising the corresponding wide array of incentives. It is thus quite probable that these incentives overlap to some extent. On a strict efficiency ground this comes at the risk of exaggerating the incentives to some forms of abatement, thereby incurring unnecessary costs. It is also a threat to policy implementation, as it manifestly contradicts the 'pedagogy' principle that an ambitious carbon policy should be stripped down to the most simple possible expression if it is to gather public acceptance.

A body of literature exists that compares the merits of different policies aimed at the same carbon abatement options (for a survey cf. Duval, 2008), mostly in an analytical microeconomic framework (Acemoglu et al., 2009, provide a recent instance of such work). It should be systematically extended to more of the policy options identified in the grey literature on low-carbon societies, under the requirement that each of these options could be pointed at a particular market failure that could be analytically qualified as well. It should also be complemented by numerical analyses simulating the particular conditions of the current economies, and indeed exploring some of the anticipated trends of the relevant set of parameters, along the lines of Goulder et al. (1999) or Fisher and Newell (2008).

The ultimate objective of this line of research is to outline a set of alternative policy portfolios offering a consistent, rational combination of incentives capable of addressing the main market failures hampering abatement activities, while avoiding as much as can be costly overlaps.

III.4. On an integrated framework of analysis

It is quite striking that the most detailed low-carbon policy studies, namely the BMU (2008) and ZCB (2007) studies, rely on accounting models that picture little economic behaviour, if any.[29] Energy demand is explicitly described as a parameter of scenario building, which means that the impacts of the collection of policy measures envisioned are an exogenous, undocumented, 'guestimate'. The consequence is that both studies, and particularly ZCB considering its more-than-extreme target, could be accused of 'wishful modelling'. The expertise developed by Greenpeace, also quite comprehensive, originates in 4 different institutes for energy supply, energy demand, biomass potential and car technologies. But no description is available of the arguably problematic convergence process that could have lead to the figures eventually published. There is indeed no guarantee that the 4 scenarios are consistent on major drivers as demographics, GDP, energy prices, investment trajectories, etc.

What both these limitations outline is the necessity of an integrated framework of analysis that could be applied to policy assessment: it is necessary that the carbon pricing trajectories resulting from the first and second line of research, and the policies and measures emerging from the third, should be assessed simultaneously, lest some significant interac-

29. Detailed descriptions of the modelling tools underlying those studies could regretfully not be accessed.

tions and feedbacks be disregarded, at the cost of economic efficiency.

This last task is probably the most daunting: even if their numbers are cut down by the elicitation of a rational combination of incentives, most of the recommendable policies and measures play at a scale, and are justified by market imperfections, that comprehensive modelling structures will be hard put to model. The hybridising methods that were explored to bridge the gap between bottom-up and top-down energy modelling (cf. e.g. Hourcade et al., 2006, and the articles in the same journal issue) offer the beginning of an answer to these challenges, but the beginning only. Their further development is essential to construct from the current fragmented economic expertise a comprehensive vision of future carbon policy portfolios.

References

Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D. (2009), "The En-vironment and Directed Technical Change", NBER Working Papers 15451, National Bureau of Economic Research, 66 p.
http://www.nber.org/papers/w15451.pdf (accessed April 2010).

Bennear, L., Stavins, R. N. (2007), "Second-best Theory and the Use of Multiple Policy Instruments", Environmental Resource Economics 37, pp. 111-129.

Bernard, A., Vielle, M., (2009) "Assessment of European Union transition scenarios with a special focus on the issue of carbon leakage", Energy Economics 31, pp. S274–S284.

BMU (2008), Lead Study 2008: Further development of the 'Strategy to increase the use of renewable energies' within the context of the current climate protection goals of Germany and Europe, Nitsch, J. (ed.), German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), Division KI III 1 (General and Fundamental Aspects of Renewable Energies), 188 p.
http://www.bmu.de/files/pdfs/allgemein/application/pdf/leitstudie2008_en.pdf
(accessed April 2010).

Böhringer, C., Löschel, A., Moslener, U., Rutherford, T. F. (2009a), "EU Climate Policy up to 2020: An Economic Impact Assessment", Energy Economics 31, pp. S295-S305.

Böhringer, C., Rutherford, T. F., Tol, R. S. J. (2009b), "The EU 20/20/2020 targets: An overview of the EMF22 assessment", Energy Economics 31, pp. S268-S273.

Bosetti, V., Carraro, C., Duval, R., Sgobbi, A., Tavoni, M. (2009), "The Role of R&D and Technology Diffusion in Climate Change Mitigation: New Perspectives using the WITCH Model", OECD Economics Department Working Paper 664, OECD publishing, Paris, 53 p..
http://www.olis.oecd.org/olis/2009doc.nsf/LinkTo/NT00000B66/$FILE/JT03259340.PDF
(accessed April 2010).

Capros, P., Mantzos, L., Papandreou, V., Tasios, N. (2008), Model-based Analysis of the 2008 EU Policy Package on Climate Change and Renewables, Report to the European Commission - DG ENV, 49 p. + 914 p. appendixes.
http://ec.europa.eu/environment/climat/pdf/climat_action/analysis.pdf and
http://ec.europa.eu/environment/climat/pdf/climat_action/analysis_appendix.pdf
(accessed April 2010).

CAS (2006), Division par quatre des émissions de gaz à effet de serre de la France à l'horizon 2050, de Boissieu, C. (ed.), report of the Conseil d'Analyse Stratégique, La Documentation Française, Paris, 144 p.
http://lesrapports.ladocumentationfrancaise.fr/BRP/094000195/0000.pdf
(accessed April 2010).

CAS (2008), Perspectives énergétiques de la France à l'horizon 2020-2050, Syrota, J. (ed.), report 12 of the Conseil d'Analyse Stratégique, La Documentation Française, Paris, 326 p.

http://lesrapports.ladocumentationfrancaise.fr/BRP/074000659/0000.pdf
(accessed April 2010).

CAS (2009), La valeur tutélaire du carbone, Quinet, A. (ed.), report 16 of the Conseil d'Analyse Stratégique, La Documentation Française, Paris, 424 p.

http://lesrapports.ladocumentationfrancaise.fr/BRP/094000195/0000.pdf
(accessed April 2010).

CCC (2008), Building a low-carbon economy – the UK's contribution to tackling climate change, The Stationery Office, Edinburgh, 480 p.

http://www.theccc.org.uk/reports/building-a-low-carbon-economy (accessed April 2010).

CGP (2001), Transports : choix des investissements et coûts des nuisances, Boiteux, M., Baumstark, L. (ed), report to the Commissariat Général du Plan, La Documentation Française, Paris, 328 p.

http://lesrapports.ladocumentationfrancaise.fr/BRP/014000434/0000.pdf
(accessed April 2010).

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M. (2009), "International Climate Policy Architectures: Overview of the EMF 22 International Scenarios", Energy Economics 31, pp. S64-S81.

Combet, E., Ghersi, F., Hourcade, J.-C., Thubin, C. (2009), Economie d'une fiscalité carbone en France, report to the Confédération Française Des Travailleurs, 139 p.

http://www.cfdt.fr/content/medias/media22714_HrHvNGySSxrNUTA.pdf

DECC (2009), Carbon Valuation in UK Policy Appraisal: A Revised Approach, Climate Change Economics, Department of Energy and Climate Change, 128 p.

http://www.decc.gov.uk/en/content/cms/what_we_do/lc_uk/valuation/valuation.aspx
(accessed April 2010).

DEFRA (2007), The Social Cost of Carbon and the Shadow Price of Carbon: What they are and How to Use them in Economic Appraisal in the UK, DEFRA Economics Group, 24 p.

http://www.decc.gov.uk/en/content/cms/what_we_do/lc_uk/valuation/shadow_price/shadow_price.aspx (accessed April 2010).

Duval, R. (2008), "A Taxonomy of Instruments to Reduce Greenhouse Gas Emissions and their Interactions", OECD Economics Department Working Papers 636, OECD Publishing, Paris, 42 p.

http://www.oecdilibrary.org/docserver/download/fulltext/5kzdcszwd79t.pdf?expires=1272033668&id=0000&accname=freeContent&checksum=092E338BDC4FE7539097301EF404A72B (accessed April 2010).

Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M., Koehler, J. (2006), “Induced Technological Change: Exploring its Implications for the Economics of Atmospheric Stabilization: Synthesis Report from the Innovation Modeling Comparison Project”, The Energy Journal, Special Issue: Endogenous Technological Change and the Economics of Atmospheric Stabilization, pp. 57-107.

Edenhofer, O., Carraro, C., Hourcade, J.-C., Neuhoff, K., Luderer, G., Flachsland, C., Jakob, M., Popp, A., Steckel, J., Strohschein, J., Bauer, N., Brunner, S., Leimbach, M., Lotze-Campen, H., Bosetti, V., de Cian, E., Tavoni, M., Sassi, O., Waisman, H., Crassous-Doerfler, R., Monjon, S., Dröge, S., van Essen, H., del Río, P., Türk, A. (2009), RECIPE - The Economics of Decarbonization, Synthesis Report, 96 p.

http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/research-act-intl-climate-pol/recipe-groupspace/working-papers/recipe-synthesis-report/
(accessed April 2010).

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magné, B., Scrieciu, S., Turton, H., van Vuuren, D. P. (2010) “The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs”, The Energy Journal 31, Special Issue 1: The Economics of Low Stabilization, pp. 1-38.

Fischer, C., Newell, R.G. (2008), Environmental and Technology Policies for Climate Mitigation, Journal of Environmental Economics and Management 55 (2), pp. 142-162.

FONDDRI (2009), Carbon-constrained scenarios, joint research project, 89p.

http://www.iddri.org/L’iddri/Fondation/FONDDRI_Full_Report_Carbon_constrained_scenarios_EN.pdf (accessed April 2010).

Goulder, L.H., Parry, I.W.H., Williams, R.C., Burtraw, D. (1999), “The cost-effectiveness of alternative instruments for environmental protection in a second-best setting”, Journal of Public Economics 72, pp. 329–360.

Greenpeace (2005), Energy Revolution: A Sustainable Pathway to a Clean Energy Future for Europe. A European Energy Scenario for EU-25, 32 p.

http://www.greenpeace.org/raw/content/eu-unit/press-centre/reports/energy-revolution-a-sustaina.pdf (accessed April 2010).

Greenpeace (2008), Energy Revolution: A Sustainable Global Energy Outlook, 212 p.

http://www.energyblueprint.info/fileadmin/media/documents/energy_revolution2009.pdf
(accessed April 2010).

Gurney, A., Ahammad, H., Ford, M. (2009), “The economics of greenhouse gas mitigation: Insights from illustrative global abatement scenarios modelling”, Energy Economics 31, pp. S174-S186.

Hourcade, J.-C., Ghersi, F. (2009), "Interpreting Environmental Policy Cost Measures", in Gerlagh, R., Bosetti, V., Schleicher, S. (ed.), Modeling Sustainable Development, Edward Elgar, Cheltenham, pp. 62-83.

Hourcade, J.-C., Jaccard, M., Bataille, C., Ghersi, F. (2006), "Hybrid Modeling: New Answers to Old Challenges", The Energy Journal, Special Issue Hybrid Modeling of Energy-Environment Policies: reconciling Bottom-up and Top-down, pp. 1-12.

INFORSE (2008), Vision for a sustainable energy development for EU-27, 2000-2050, A European vision based on INFORSE's Sustainable Energy Vision, 11p.

http://www.inforse.org/europe/pdfs/EU27-vision-note.pdf (accessed April 2010).

IPCC (2001), Climate Change 2001: Mitigation: Contribution of Working Group III to the third assessment report of the Intergovernmental Panel on Climate Change, Metz, B., Davidson, O.R., Swart, R., Pan, J. (ed.), Cambridge University Press, Cambridge, 700 p.

IPCC (2007), Climate Change 2007: Mitigation of Climate Change: Contribution of Working Group III to the fourth assessment report of the In-tergovernmental Panel on Climate Change, Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (ed.), Cambridge University Press, Cambridge, 851 p.

Jaffe, A. B., Stavins, R. N. (1994), "The Energy-Efficiency Gap: What Does It Mean?", Energy Policy 22 (10), pp. 804-810.

Kretschmer, B., Narita, D., Peterson, S. (2009), "The economic effects of the EU bio-fuel target", Energy Economics 31, pp. S285-S294.

Negawatt (2006), Scénario négaWatt 2006, pour un avenir énergétique sobre, efficace et renouvelable, 15 p.

http://www.negawatt.org/telechargement/Scenario%20nW2006%20Synthese%20v1.0.2.pdf (accessed April 2010).

OECD (1998), Improving the Environment through Reducing Subsidies, OECD Publishing, Paris, 168 p.

http://www.oecdbookshop.org/oecd/display.asp?lang=EN&sf1=identifiers&st1=971998091p1 (accessed April 2010).

Radanne, P. (2004), La division par 4 des émissions de dioxyde de carbone en France d'ici 2050, report to the Mission Interministérielle de l'Effet de Serre, 36 p.

http://www.developpement-durable.gouv.fr/IMG/ecologie/pdf/Facteur4-franc_BAT.pdf (accessed April 2010).

Rao, S., Riahi, K., Stehfest, E., van Vuuren, D., Cheolhung, C., den Elzen, M., Isaac, M., van Vliet, J. (2008), IMAGE and MESSAGE Scenarios Limiting GHG Concentration to Low Levels, IIASA report IR-08-020, Laxenburg, 57 p.

http://www.iiasa.ac.at/Admin/PUB/Documents/IR-08-020.pdf (accessed April 2010).

Stern, N. (2007), The Economics of Climate Change: The Stern Review, Cambridge University Press, Cambridge, 712 p.

Tol, R. S. J. (2009), The Feasibility of Low Concentration Targets: An Application of FUND, ESRI Working Paper 285, 29 p.
http://www.esri.ie/UserFiles/publications/20090326110224/WP285.pdf
(accessed April 2010).

Weitzman, M. (1974), “Prices vs. Quantities”, Review of Economic Studies 41 (4), pp. 477-491.

ZCB (2007), Zero Carbon Britain, An Alternative Energy Strategy, CAT Publications, Llwyngwern, 105 p.
http://www.zerocarbonbritain.com/images/process.php?file=zerocarbonbritain.pdf
(accessed April 2010).

Les Cahiers de la Chaire

Chaire Modélisation prospective au service du développement durable

Contact

Nadia MAÏZI
Directrice du Centre de Mathématiques Appliquées (CMA)

MINES ParisTech / CMA
Rue Claude Daunesse
BP 207
06904 Sophia Antipolis

Tel: +33(0)4 97 15 70 79 / Fax: +33(0)4 97 15 70 66
Courriel: nadia.maizi@mines-paristech.fr

Jean-Charles HOURCADE
Directeur du Centre International de Recherche sur l'Environnement et le Développemenr (CIRED)

CIRED
Campus du Jardin Tropical
45 avenue de la Belle Gabrielle
94736 Nogent sur Marne Cedex

Tel: +33(0)1 43 94 73 63 / Fax: +33(0)1 43 94 73 70
Courriel: hourcade@centre-cired.fr

Site Web: http://www.modelisation-prospective.org
Contact de la Chaire: contact@mail.modelisation-prospective.org