ARTICLE IN PRESS
ECOLEC-04103; No of Pages 11
Ecological Economics xxx (2011) xxx–xxx
Contents lists available at SciVerse ScienceDirect
Ecological Economics
journal homepage: www.elsevier.com/locate/ecolecon

Pushing the boundaries of climate economics: critical issues to consider in climate policy analysis

S. Şerban Scrieciu [a,*], Terry Barker [b], Frank Ackerman [c]

[a] Economics for Equity and the Environment (E3) Network, United States & Department of Land Economy, University of Cambridge, UK
[b] Cambridge Centre for Climate Change Mitigation Research (4CMR), University of Cambridge, UK
[c] Stockholm Environment Institute-US Center, Somerville MA, United States

ARTICLE INFO

Article history:
Received 29 March 2011
Received in revised form 10 October 2011
Accepted 16 October 2011
Available online xxxx

Keywords:
New approaches to climate economics
Multi-dimensional valuation
Risk and uncertainty
Climate policy and technological change
Institutional barriers

ABSTRACT

Climate policy choices are influenced by the economics literature which analyses the costs and benefits of alternative strategies for climate action. This literature, in turn, rests on a series of choices about: the values and assumptions underlying the economic analysis; the methodologies for treating dynamics, technological change, risk and uncertainty; and the assumed interactions between economic systems, society and the environment, including institutional constraints on climate policy. We identify and discuss such critical issues, pushing at the boundaries of current climate economics research. New thinking in this area is gathering pace in response to the limitations of traditional economic approaches, and their assumptions on economic behaviour, ecological properties, and socio-technical responses. We place a particular emphasis on the role of induced technological change and institutional setups in shaping cost-effective climate action that also promotes economic development and the alleviation of poverty.

1. Introduction

The debate on whether climate change is happening or not, whether it is manmade or caused by natural factors, and whether it poses or not a long term real threat to human societies and the environment has largely concluded. The scientific climate community has clearly stated that: "most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations", and that "warming of the climate system is unequivocal" and due primarily to human interference via fossil fuel use, agriculture and land use change (IPCC, 2007). Though several counter claims continue to be made at different levels (Carter, 2010; Montford, 2010), these, in turn, have met their own systematic counter-argumentation (e.g. Carr et al., 2010; Rennie, 2009). Furthermore, other leading scientists have expressed concerns that IPCC projections are, on the contrary, too conservative, and that human-induced climate change may be occurring at a faster pace than previously thought (Hansen et al., 2008; Rahmstorf, 2007).

All in all, the scientific understanding of the climate change problem has advanced sufficiently to clearly convey the message that nations across the globe need to take prompt action in terms of both mitigation and adaptation. The risks of doing nothing are increasing rapidly as concentrations and emissions keep increasing, despite uncertainties in climate projections and tipping points. In addition, the precautionary principle embedded in the 1992 Rio Declaration on Environment and Development reminds us that uncertainty is not a reason to postpone or avoid action (Costello et al., 2009). The debate has moved on from "do we need to act now" to "how to act now in order to best mitigate and adapt to climate change". The work-load is being passed from climate scientists via politicians to economists, engineers, sociologists, ecologists and others involved in climate policy planning and analysis. Climate science will continue nevertheless to provide valuable input, such as understanding interactions between the carbon cycle and climate change, the impact of the latter on hazards, and refining climate change projections, particularly in terms of down-scaling impacts to national or local level with crucial implications for adaptation policy. Since action on the climate change front touches upon a myriad of inter-related and multi-dimensional aspects of societies, economies and the environment, any climate policy response would require interdisiciplinary analysis. The economic problem needs to be less concerned about choosing the targets themselves and focus instead on how to achieve political climate targets that are based on scientific evidence (Barker, 2008). What we *should* do about climate change is an ethical question involving conflicting interests; economic analysis helps out instead on the question of what we *can* do about climate change (Broome, 2008). This is not to say that economics should be decoupled from ethics and moral arguments. On the contrary, any new developments in climate economics need to acknowledge underpinning values and explicitly state their implications for policy and society.

New economic analysis is needed to provide answers in this respect not only by focusing on cost-effective strategies, but also by ensuring that any climate action is equitable and compatible with

* Corresponding author.
E-mail address: sss38@cam.ac.uk (S.Ş. Scrieciu).

0921-8009/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolecon.2011.10.016

context-specific development goals and priorities. As such, climate economics research has to break away from its own current disciplinary limitations, whilst developing stronger links with other relevant disciplines. To some extent this is already occurring with mainstream economic thinking on climate change shifting from a single-discipline focus of cost-benefit analysis preferred by traditional economists[1] to a new inter-disciplinary risk analysis approach (Ackerman, 2008; Barker, 2008; Dietz and Stern, 2008; Heal, 2009; Stern, 2007). This paper hopes to contribute along the lines of spurring new thinking in climate economics. It puts forward a series of what we consider critical issues for the economic analysis of climate policies,[2] with an emphasis on induced technological change (with reference to mitigation) and institutional barriers (applied to both mitigation and adaptation). It also recommends future pathways that research might follow towards a more realistic and comprehensive understanding surrounding the economic problem of climate action.

2. Fundamental Requirements for an Adequate Climate Economic Analysis

There is great uncertainty concerning the human, environmental, and economic impacts of climate change, and the arguments for and against potential policy responses. In order to formulate and adopt policies in a timely fashion, we are compelled to gaze deeply into a cloudy crystal ball, to look far into the uncertain future and project what may happen, what it may cost, and what responses could lead to better outcomes. Projections of future climate policy impacts and costs are based on both detailed empirical research, and structures of assumptions that frame the analysis. The "cost" of climate policy is not an observable market price; rather, it is a construct shaped by the modelling apparatus and its explicit and implicit assumptions.

As in any economic modelling, the future macro-level assumptions driving the analysis have important implications for the costs and impacts of climate policy. The anticipated growth of population and per capita production and consumption represent major influences on future emissions in a business-as-usual scenario. Higher baseline growth rates typically imply greater emissions and climate damages, but also greater potential for benefits (i.e. avoided costs) from emissions reduction. Higher oil prices increase the economic benefit of energy conservation measures, thereby inducing more energy saving technology. Major studies of climate impacts and policy costs have differed widely on this point, with climate policy "optimists" often assuming higher oil prices, and hence deducing lower net costs of mitigation, than "pessimists" (Ackerman et al., 2009). Baseline assumptions employed in modelling studies are often arbitrary and inconsistent with each other, particularly when projections are taken off-the-shelf from different sources. A complete model of climate policy costs and impacts should, in theory, make some of these data endogenous: climate damages can affect the rate of (business-as-usual) growth of per capita incomes; climate policies can change the price of oil. This, however, requires the development of a complex global system of energy-environment-economy interactions, with credible, endogenous dynamics of output, emissions, prices, and incomes.

Beyond the universal dilemmas of modelling uncertain futures, the economics of climate change poses unique challenges to orthodox styles of economic analysis. There are four fundamental requirements for an adequate economic framework for climate policy (Ackerman, 2008, 2009):

- Judgment about the importance of current versus future generations, with implications for discounting;
- Incorporation of multi-dimensional, often unmonetisable impacts, rendering cost-benefit analysis problematical;
- Recognition of the problems of catastrophic risks and irreducible uncertainty, leading to a precautionary approach to policy;
- Understanding the nature of implementation costs in dynamic and institutional settings grounded in empiricism, with multiple consequences for policy formation. This includes issues of induced technological change and institutional barriers addressed in more detail in the following two sections of this paper.

2.1. Discounting

Discount rates have been the focus of much debate in the literature, particularly with the publication of the Stern Review (Stern, 2007). Because the benefits of climate policy stretch over a longer time horizon than the costs, a lower discount rate makes the benefits relatively larger in present value, while a higher rate does the opposite. Disagreement is longstanding and inescapable.

Some argue for a significantly positive discount rate and criticise the use of a near-zero discount rate for climate policy analysis (e.g. Nordhaus, 2007). Their discounting should not be dismissed lightly. For financial decisions spanning a few years or decades, it is an indispensible tool for inter-temporal comparisons, appropriately weighing commensurable costs and benefits that are experienced by the same individual. If extended to cover the longer-term and multi-dimensional future costs and benefits of any climate policy action, discount rates have an important influence on decision-making. They simplify calculations and theories, follow the logic of financial markets, and prevent arbitrage and paradoxes of preference reversal.

However, others disagree and support the use of a near zero discount rate. The arguments are twofold. First there is the ethical or philosophical argument advocating for a zero utility discount rate (i.e. zero rate of pure time preference in the Ramsey equation) on the grounds that the welfare of all generations is of equal importance (Broome, 1994; Cline, 1992; Stern, 2007). Second, there are many "market" interest rates and for climate mitigation investments it is more appropriate to apply an interest rate for insurance-type investments rather than for ordinary capital investments. This is because climate mitigation efforts are better understood as social insurance against disaster rather than ordinary profit-seeking investments. As is typical for insurance, their returns are uncorrelated or negatively correlated with the broader market. This would argue for discounting at a risk-free rate of return, often averaging 1% or less in real terms (e.g. long-term government bonds issued by developed countries) (Howarth, 2003).

Whenever possible, outcomes that cannot be adequately expressed in monetary terms should not be discounted. This avoids paradoxes such as the devaluation of future lives: if one asserts that saving a human life is worth exactly €1,000,000, or any other fixed monetary amount, does that mean that one life today is worth about 20 lives, or 150 lives, a century from now (as would be implied by a 3% or 5% discount rate, respectively)? Nevertheless, since the practice of discounting is widely accepted, and even expected in climate analyses, choices must be made about the appropriate rates to use, at least for future quantities that lend themselves to monetary valuation. The arguments made by Stern and others for low discount rates, particularly for zero or near-zero rates of pure time preference, should be carefully considered. In addition, the assumption of constant discount rates could be

[1] We use the terms "traditional economics" throughout this paper to refer to the current orthodoxy or dominant school of economic thought, i.e. neoclassical economics. The latter may be summarised as "a combination of the emphasis on rationality in the form of utility maximisation; the emphasis on equilibrium or equilibria; and the neglect of strong kinds of uncertainty and particularly of fundamental uncertainty" (Dequech, 2008, pp.300, and similar characterisations in Hodgson, 1999, and Colander et al., 2004). It is also important to make the qualification here that "traditional" and "mainstream" are not interchangeable in this paper, as mainstream thinking may include increasingly accepted and influential non-neoclassical segments of research.

[2] Some preliminary work in this direction has already been initiated at the Energy Branch of UNEP's Division of Technology, Industry, and Economics in Paris under the auspices of the MCA4climate initiative "Multi-criteria analysis for climate change: developing guidance for pro-development climate policy planning" (UNEP, 2011a,b).

Please cite this article as: Scrieciu, S.Ş., et al., Pushing the boundaries of climate economics: Critical issues to consider in climate policy analysis, Ecol. Econ. (2011), doi:10.1016/j.ecolecon.2011.10.016

reconsidered. Arguments for fixed discount rates emerge from the analysis of short or medium-term financial calculations. For intergenerational public policy choices, however, there is less need for consistency with markets. As an alternative, discount rates that decline over time could be explored on the grounds of psychological research on individuals' time preferences, and separately on the basis of uncertainty about future interest rates and growth rates. Declining discount rates are starting to appear in climate policy analyses, e.g. in recent UK government guidance on such analyses (Lowe, 2008).

2.2. Multi-dimensional Valuation

Monetisation of the environment, health and other social issues has become a common practice, but it reduces transparency of the results, and raises a range of ethical and analytical dilemmas. Is it necessary to monetise every significant benefit? Are standard values available for non-market benefits? If the values are based on willingness to pay, do they vary with income? Economic logic suggests that they must depend on income; but are health and the environment worth more in a rich country? These and other problems arise from the attempt to put a price on intrinsically priceless values (Ackerman and Heinzerling, 2004).

Alternatively, can the most important damages or benefits be reported in natural (physical or medical) units as well as in monetary equivalents? Three approaches could be taken to the issue of incorporating marketed and non-marketed impacts in climate policy analysis. The first entails applying the best available estimates of monetary valuations of all health and environmental impacts. This has the advantage of internal consistency, and creates a bottom-line numerical estimate for any scenario; it is traditional in the economics literature, and is required for cost-benefit analysis. The second consists of applying only the most established, least controversial valuations of non-market benefits, such as the externality prices for common air pollutants used in energy sector analyses.[3] In addition, all major health and environmental impacts could be reported in their natural units; health impacts could be reported both in Disability Adjusted Life Years (DALYs) and in specific health outcomes. Finally, a third option would avoid all use of monetary valuations of non-market benefits. This would result in all market costs and benefits being reported in monetary terms, while health and environmental impacts are expressed in natural units. For health outcomes, DALYs, as well as surrogate prices, would be avoided. This has the advantage of avoiding the ethical and logical paradoxes of pricing the priceless values of life, health, and nature — at the cost of losing comparability with other studies.

The second option might be preferable to the third option, since it allows comparison to studies using now-standard monetary values for some externalities, and DALYs for health impacts. Having said this, it is important to establish from the start whether more relevant information is actually being created when reporting non-marketed impacts in both monetary terms and their natural units, compared to looking at only impacts expressed in natural units. This particularly applies for instance to DALYs that represent generalized health measures integrating morbidity and mortality and aggregating across diseases, age groups and gender. They have inbuilt controversial value judgments on disease and age-weights and bring together in one measure complex health or disability issues. If their assumptions are not clearly conveyed, their use might generate more disinformation rather than any added value or real contribution to the health improvements of a nation. Moreover, in a multi-criteria analytic framework it makes more sense to work with raw measures of health effects rather than with generalized measures of health, as value judgments can be introduced directly by stakeholders using a multi-criteria decision analysis (MCDA) approach (Chalabi and Kovats, 2011).

Both second and third option preserve and present, however, the essential information about impacts in natural units, which is required for transparency and communication with experts from other disciplines as well as with non-specialist readers. Both of these options are preferable to the first alternative. This is because an attempt at complete monetisation threatens to obscure the underlying information on climate impacts and policy action, while inevitably omitting some important categories.[4] The underlying information generated by the second or third option may be summarised in separate impacts for policy-makers or may be brought together for prioritisation and resource allocation decisions using formal methods for multi-dimensional evaluation.

2.3. Risk and Uncertainty

It is now widely recognised that the economics of climate change is centrally concerned with risk and uncertainty, a feature of the problem that has been evident from the early 1990s, when the scientific assessments began in earnest (Barker, 2008; Stern, 2007). Despite the immense accumulation of knowledge about climate science, there is continuing and perhaps inescapable uncertainty about fundamental questions such as the value of the climate sensitivity parameter (governing the overall magnitude of climate change). The traditional economics approach to such uncertainties converts them to “expected values” by assuming a probability distribution, which is used to construct a weighted average of likely outcomes. This approach, however, is not helpful in the face of catastrophic risks and deeply uncertain probabilities of worst-case scenarios, i.e. events which have very low probabilities of occurrence and very high impacts. Under such conditions the appropriate probability distribution may be so “fat-tailed” that the value of an incremental reduction in emissions could be, technically speaking, infinitely large (Weitzman, 2009).

The future development of climate economics research will need to take forward uncertainty analysis by developing stronger links with relevant (sub)disciplines within fields such as mathematics and risk analysis, as well as strengthening the dialogue with climate science and its treatment of uncertainty. Economies are highly complex non-linear systems and it is impossible to accurately predict their future evolution. For example, GDP growth trajectories are subject to considerable uncertainty; they may even at times be sensitively dependent on small events, as in the bursting of speculative bubbles, suggesting patterns that characterise chaotic dynamics (Rosser, 1999). Having said this, although future behaviour of economic systems cannot be accurately predicted, it is possible to be aware of a range of future states (Hayward and Preston, 1999, on chaos theory and economics).

Climate economic analysis would need to cover the entire spectrum of uncertainty ranging from unknown uncertainty (variations around expected system behaviour that cannot be quantified) to uncertainties that can be quantified, be they internal (relating to modelling assumptions and concepts used) or external (relating to the unpredictable variation in the phenomena under study). The latter are beyond the controlling capacity of the analyst, though they can be quantified, sometimes being referred to in the literature as aleatoric or chance events (Daneshkhah, 2004). In practice this might mean that for climate-related uncertainties, analyses and calculations could be performed for at least two distinct scenarios: one representing most likely outcomes, and one representing credible worst-case risks. For macro-level socio-economic uncertainties, which may be better understood than climate change, a fully-fledged uncertainty analysis, examining multiple possible

[3] The European Commission's ExternE research project is a well-known source of such valuations; see http://www.externe.info .

[4] The theoretical foundation of traditional cost-benefit analysis is compromised if benefits cannot be fully monetised or if the probabilities of worst-case outcomes are not known — as is the case in the analysis of climate change.

Please cite this article as: Scrieciu, S.Ş., et al., Pushing the boundaries of climate economics: Critical issues to consider in climate policy analysis, Ecol. Econ. (2011), doi:10.1016/j.ecolecon.2011.10.016

values or pathways, could in principle be undertaken — although climate and socioeconomic uncertainties are not necessarily separable in all possible futures. In other words, climate policy-making could draw more on scenario analysis (as is practiced in climate science) and robust strategies, and choose options that are most insensitive to future climate and socioeconomic conditions (e.g. Lempert and Collins, 2007). Current traditional optimisation algorithms based on well-posed objectives and known climate conditions are difficult to apply under uncertainty, and new methods supporting policy-making, favouring robustness and including uncertainty information need to be put forward (Hallegatte, 2009; Wilby and Dessai, 2010).

An alternative economic paradigm, used for low-probability catastrophic risks in other arenas, arises in insurance. People buy insurance to guard against things that don't usually happen, but would cause unaffordable losses if they did occur; the argument for fire insurance is not that you are sure that your house will burn down, but that you cannot be sufficiently sure that it will not. Insurance policies are thus driven by risk aversion, and always fail a simple cost-benefit test: an insurance company must charge its policy holders more than the present value of the payments it will make to them; to do otherwise would bankrupt the company. Public policy to guard against catastrophic climate risk could be viewed analogously: it insures society against the possibility of extreme losses, since we cannot be sufficiently sure that those losses will not happen. The analogy is not perfect; private insurance covers recurring individual risks with empirically known probability distributions, not fundamentally uncertain threats to human society as a whole. In the face of such threats, we can at best provide a form of collective self-insurance, through precautionary policies. This suggests setting safe minimum standards (e.g., 400 or 450 ppm CO_2-equivalent by 2100, not more than 2° warming, etc.), then seeking a least-cost strategy for achieving those standards. This cost-effectiveness framework may be less familiar to economists than a cost-benefit approach, but also appears to be more congruent with the main lines of climate policy discourse. Furthermore, low-cost climate strategies could be assessed against their contribution to other development priorities resulting in an array of potentially cost-effective and pro-poor climate measures.

2.4. Reframing Climate Policy Costs

Economic analysis is appropriately focused on reducing the costs of policy implementation. In the case of climate change, it is a complex and demanding research challenge to identify the least-cost pathway to the necessary levels of emission reductions or to more climate resilient systems. The task is all the more difficult because the costs of abatement or proofing play multiple economic roles. These costs, for example, representing the expense of adopting new energy technologies, are well-defined in monetary terms; that is, they are free of the extreme ambiguity surrounding the valuable but often unmonetised benefits of climate action, discussed above. Determining the current cost of a new technology, however, is only the beginning of the story. How should that cost be evaluated?

In an economy that is at or close to full employment, any new cost imposed by public policy might crowd out an equal amount of other expenditures. In that case, there is no net gain in employment or production; there is simply a shift from goods and services chosen by the private sector, to those required by public policy. This is often the implicit framework in traditional climate economics, leading to the treatment of abatement expenditures as a welfare loss, subtracted from desirable goods and services in models such as DICE (Nordhaus, 2008). On the other hand, in an economy that is far below full employment, expenditure on new energy technologies or other costs resulting from climate policies would be expected to provide a Keynesian stimulus to employment and output. In a very long-term analysis, the Keynesian benefits may appear transitory – since it seems unlikely that unemployment will be consistently high for time spans of many decades. The shorter the time frame of analysis, however, the more important the question of initial Keynesian effects may be (assuming a starting point of significant unemployment levels).

The costs of new technologies are also entwined with the future path of technological change and the dynamics of the economic system. Moreover, understanding the nature of climate policy implementation costs also requires understanding the various institutional factors that constrain or encourage the adoption of technologies for low-carbon or climate-proof developments. These two critical topics, technological change (with a focus on mitigation) and institutional barriers are the subject of the remainder of this paper.

3. Induced Technological Change

The reason that induced technological change (ITC)[5] is a critical issue for climate policy is that it offers a way of substantially reducing the costs of GHG mitigation and increasing the rate at which economies may be able to decarbonise. However, economic models for climate policy may not include ITC at all or include it with restrictive assumptions and in a partial form so that it has only weak effects. Furthermore, the models may not include all the policy instruments that affect ITC. In consequence, the results of the models exaggerate, from this perspective, the costs of mitigation and give the impression that stringent mitigation is not possible without economic collapse.

In this section, we address three features of the treatment of ITC, which suggest that the costs of mitigation may be much lower than supposed from the model results. (1) If all sources of ITC are covered together in the models the technological change will be greater and costs lower. (2) The assumption of full "crowding out" of GHG-emission-saving R&D has been found to be too restrictive and not justified theoretically or empirically. (3) The models generally fail to include all significant policy instruments that affect ITC in combination, especially regulation. The challenge for climate economics and policy is to bring together the disparate and fragmented knowledge about the processes involved, to assess the potential scale of the cost reduction and to design portfolios of policies in the light of this knowledge.

3.1. ITC in Top-down Economic Models

A substantial literature in representing ITC and the relevant policies in top-down economic models has been developing (see Barker et al., 2007; Gillingham et al., 2008, for surveys). The studies cover modelling the channels of ITC, such as private sector R&D and learning-by-doing, which may be influenced by climate policy, and climate policies that influence ITC, such as regulation, public spending on R&D, and carbon taxes or trading. Unfortunately, as Gillingham et al. (2008) conclude, there is no agreement as to how ITC should be modeled, although they add: "Despite these difficulties, with only a few exceptions most studies find that the ramifications and insights elucidated by incorporating [endogenous technological change] are important quantitatively" (p. 2750). In addition, most of the models have adopted the limiting assumptions of traditional economics about the working of the economy as well as for the representation of technology as noted above. In consequence there is a major problem in interpreting the results for climate policy when these assumptions do not hold, e.g. when economies are not at full employment, outcomes are uncertain, there is a widespread lack of information and expertise across consumers and firms, and non-market considerations are important. The

[5] In the context of this paper, "induced technological change" is technical change in demand and supply technologies associated with climate change mitigation and brought about by climate policy. Models for informing climate policy have been developed over the last 10 or so years to allow technological change to be affected by R&D spending, energy prices or accumulated use of or investment in technologies. In such models technological change is endogenous and if climate policies represented in the models lead to such change, this is defined as induced technological change.

Please cite this article as: Scrieciu, S.Ş., et al., Pushing the boundaries of climate economics: Critical issues to consider in climate policy analysis, Ecol. Econ. (2011), doi:10.1016/j.ecolecon.2011.10.016

rapid decarbonisation of the energy system implied by the internationally agreed 2 °C target calls for a non-marginal economic analysis involving radical adoption of low-GHG technologies in critical sectors.

Clarke et al. (2008) provide a framework for classifying the sources of technological change in GHG abatement. They divide the sources into R&D, learning by doing, and spillovers. These sources can be inside the GHG producing firms or sectors or those supplying the technologies for reducing GHGs, or outside, in other firms and sectors. The spillover effects from other sectors, usually taken as exogenous technological change, can be very important, e.g. from changes in information systems, materials or biotechnology. One of their main conclusions is that few if any of the models in the literature allowing for endogenous technological change include all these sources. The presumption is that the model results will tend to overestimate the costs of abatement by omitting one or more sources of cost-reducing technological change. If R&D effects are combined with learning-by-doing and spillover effects from other sectors, it is also conceivable that the transformed energy system could eventually be lower cost that the fossil-fuel-based system.

The introduction of a more complete specification of the channels for ITC in the models is a rich agenda for future research. Several of the models already include R&D and learning-by-doing effects, but with a weak empirical basis. As an example, Magné et al. (2010) include both effects in their application of the MERGE model but admit a lack of empirical estimates of the rates, relying on sensitivity tests to assess the uncertainty in their assumptions. The empirical "experience curves" of the literature (see surveys in Kahouli-Brahmi, 2007; Weiss et al., 2010) include the mixture of effects from all channels in the historical observations that unit costs of a new technology fall as the scale increases. The problem of combining R&D and learning-by-doing in the models is to be able to distinguish them without double counting and to identify empirically the different effects in the historical record. Progress has been made, however, specifically for wind power technologies. For instance, Ek and Soderholm (2010) provide econometric estimates for both learning-by-doing and R&D (learning-by-searching) in the case of the investment costs and the scale of public R&D in wind power in five European countries. Whilst the coefficient on the cumulated capacity (with an estimated rate for learning-by-doing of 17% a year) has been explored in other studies and is in agreement with other estimates (McDonald and Schrattenholzer, 2001), that on the R&D variable (giving an estimate of learning-by-searching of about 20% a year) makes an additional contribution to research in identifying the importance of public sector R&D in reducing costs.

3.2. The Crowding Out of Low-GHG R&D

One of the channels by which policy can influence technological change is that of R&D in the relevant technologies. There is support from traditional economics for public subsidies to R&D and other innovation in general as a response to the market failure that insufficient innovation is undertaken by private firms because they cannot capture all the benefits. In other words, the social returns to R&D are much higher than the private returns. However the literature (e.g. Newell 2010, p. 258) emphasises that, unless the R&D is primarily demand-driven by higher GHG emission prices, it is unlikely to lead to lower GHG emissions.

A critical issue is the extent of crowding out of other R&D by policy-induced R&D. Gerlagh (2008) has directly modelled the effects of including such change using a traditional economic approach and found that the carbon price is halved to achieve the same levels of mitigation. With induced technological change and R&D allowed to increase above base, consumption was less than 0.5% below base by 2100 for the 450ppmv scenario, compared to just over 6% below base without. Interestingly, consumption is slightly higher than base in 2050 in the 450 scenario with induced technological change. This is in contrast with the conclusion of Nordhaus (2002), who found a very small effect due to the crowding out of non-GHG R&D. The critical difference in the cost reduction comes from Gerlagh allowing for higher carbon prices to switch R&D out of high-carbon R&D and into low-carbon R&D. A study of US patents 1973–1997 (Popp and Newell, 2009) is consistent with Gerlagh's assumptions in that it finds no significant evidence of crowding out of non-energy R&D by energy R&D and some evidence of crowding out of carbon-intensive energy R&D by low-carbon energy R&D.

One suggestion for future work is much more research into the effects of additional R&D in the models. A reasonable conclusion from previous work is that the extension of the models that assume crowding out to allow switching between high- and low-carbon R&D will radically reduce their estimated costs of mitigation. If the models allow for additional R&D as well as switching, then costs are even lower and may become negative (i.e. benefits to aggregate consumption).

3.3. Modelling Portfolios of Policies

The issue for policy is how to design a portfolio of economic and regulatory instruments that induces rapid technological change to reduce costs over the long term. Addressing the problem of rapid reduction in GHG emissions becomes an interdisciplinary task involving, for instance, engineering and economics.

There are three main ways by which technological change can be influenced by climate policy: regulation to increase energy efficiency or reduce permitted GHG emission rates e.g. from vehicles or power stations; innovation policies to increase R&D spending in order to improve the emissions performance of existing technologies or develop new low-GHG technologies; and the effects of taxes or emission trading schemes in increasing fossil fuel and carbon prices, which in turn directly increase the take up of low-GHG technology. All three ways can lead to acceleration of technological change especially if they focus on technologies with more potential for learning by doing.

Regulation of standards in various forms is often adopted by governments to reduce energy use and GHG emissions (e.g. fuel and/or emission standards for the road vehicle fleets in Europe and USA). Traditional economic analysis for climate policy assumes that the economy is working at full efficiency. However, it takes time for new or improved technologies to be adopted. Actual equipment and practices can be far from the most efficient available. Regulation of markets to require higher standards of efficiency or reduced GHG emissions can induce technological change and shift the emission characteristics of energy use. One example is the regulations imposed to improve fuel efficiency in the US automobile industry (Lee et al., 2010).

Most traditional economic models assume that regulation will reduce economic welfare, but this may not always be the case. Just as in some cases health and safety regulations can restrict choice but improve welfare, so its extension to regulation for climate effects may be similarly beneficial. The critical issue for the costs of regulation is the lifetime of the capital stock affected. The period of transition to a low-carbon economy is some 40 years if the 2 °C target has a good chance of being achieved. This comparatively long time period means that technologies have time to be developed, diffused, and scaled to mass markets. Technological change via low-cost regulation, such as GHG-emission standards on new vehicles and electricity plant, has time to make a major contribution to reducing GHG emissions. In addition, if the regulation leads to substantial increases in investment, and there are unemployed resources, then the wider economy will benefit and unemployment will be reduced. If in turn long-term economic growth is demand-driven then the growth rate may even increase.

There is a notable contrast between the policies considered in the modelling literature and the portfolios of policies introduced and proposed by governments, including the International Energy Agency in

Please cite this article as: Scrieciu, S.Ş., et al., Pushing the boundaries of climate economics: Critical issues to consider in climate policy analysis, Ecol. Econ. (2011), doi:10.1016/j.ecolecon.2011.10.016

its projections of the 450 scenario (IEA, 2010) and the German government (Jochem et al., 2008). The modelling literature tends to focus on highly stylised carbon price assumptions via taxes or emission trading, with some studies including either R&D or learning by doing (Gillingham et al., 2008), but only a few (e.g. Magné et al., 2010) including both (so called "two factor" endogenous technological change). In contrast, the government scenarios include all three ways for policy to affect ITC, in varying mixes depending on sector and country-specific institutions. The German study uses a systems dynamics model, ASTRA, to assess the effects on GDP and jobs (Jochem et al., 2008).

One reason for a portfolio approach comes from recognising the feedback effects in the energy-environment-economy (E3) system. One feedback is the rebound effect associated with improvements in energy efficiency. The improvement will lower the real price of energy and hence this will lead to an increase in the energy demand, if the demand is not at saturation levels. The inclusion of increases in carbon and energy prices through taxes and trading alongside the efficiency regulation will offset this effect. However the main reason for including an increase in real carbon prices is that the modelling strongly suggests that without the price incentive the technological change will not be implemented and the costs will not fall. Newell (2010) addresses the issue directly and emphasises the importance of a GHG emissions price to encourage low-GHG innovation from both the demand and supply sides.

Fischer and Newell (2008) develop a ranking of policy instruments for a portfolio to reduce GHG emissions from the US electricity sector. They find that emissions price is most cost-effective, then emissions performance standard, a fossil fuel tax, a renewables share requirement, a renewables subsidy and finally R&D subsidy. The combination of instruments is expected to reduce emissions at significantly lower cost. Gerlagh and van der Zwaan (2006) comparing a similar list of instruments find that the emission performance standard, achieved through carbon taxes recycled as subsidies to non-fossil-fuel use, is the most cost-effective option. Barker et al. (2008) and Barker and Scrieciu (2010) develop and use a hybrid energy-environment economy model (E3MG) allowing for all the channels for ITC. They bring together several instruments of policy (carbon trading, carbon taxes, R&D subsidies, regulation) in a portfolio designed to accelerate technological change over the period to 2050 towards low-GHG technologies. They report that stringent abatement targets can be achieved with carbon prices rising to high levels, but with macroeconomic benefits. The carbon prices are much lower if regulation is included in the policy portfolio. The benefits come mostly from induced investment and lower unemployment, but also from higher technological change.

However, in order for climate policy portfolios to induce more rapid technological change and reduce costs over the long term, it is necessary that current institutional factors constraining their implementation or adoption are well understood and effectively addressed. The next section discusses such institutional constraints, including market and non-market barriers, transaction and transition costs, and the role of social institutions and collective action in delivering robust climate policy.

4. Institutional Constraints

In both mitigation and adaptation areas, there is a wide range of studies investigating the need for climate investments, identifying the sources of investment or exploring the policy mechanisms to raise the funds required (Haites, 2008). That is, a large body of the literature on climate economics is concerned with quantifying in monetary terms the investments necessary to mitigate and/or adapt to climate change. In the case of mitigation, a carbon price (typically expressed in US$ per tonne of CO_2 equivalent) is usually calculated that would reach a certain emissions reduction target. For example, a set of different simulation models point towards a 50% emissions reductions below baseline by 2030 (but with a wide range of 30–60%) that could be achieved with a carbon price set below 100 US$/t$CO_2$-eq (van Vuuren et al., 2009). For adaptation, targets are much more elusive, since adaptation policies are often intertwined with development strategies and relate to multi-dimensional wellbeing aspects of an entire community, city, area or sector. The concepts of "resilience" and "vulnerability" are multi-faceted terms open to ongoing debate. Despite such difficulties and complexities, financial values have also been attached to the adaptation investments needed in order to cope with increasing climate instability and more likely extreme weather events. Tens of billions of dollars per year of investments and financial flows are argued to be needed for overall adaptation several decades from now on (UNFCCC, 2007; World Bank, 2010a,b).

However, there continues to be a significant gap in the climate economics and policy analysis literature on the changes in institutional setups required or the policy-dependent structural barriers that need to be overcome, such that climate policy mechanisms are functional and investment needs are raised effectively. *Institutional setups* (varying in their degree of formality) or *institutions* are defined as "systems of established and prevalent social rules that structure social interactions" or, in short, "socially embedded systems of rules" (Hodgson, 2006). Or in more elaborate terms, "institutions are the prescriptions that humans use to organise all forms of repetitive and structured interactions including those within families, neighbourhoods, markets, firms, sports, leagues, churches, private associations and government at all scales" (Ostrom, 2005: 3). Economic and energy behaviours (such as our dependency on fossil-fuels) are grounded in the social and regulatory fabric of human interactions. Challenging established institutional structures is a pre-requisite for any radical or revolutionary (as opposed to marginal) change in the current mode of production, consumption and distribution of energy, as required for stringent mitigation, climate stabilisation, and bolder and more sustainable development pathways.

Though the concept of "adaptive capacity" is often referred to in economic assessment studies of adaptation needs, some of its determinants are less researched.[6] This particularly relates to institutions comprising the regulatory policy framework and societal norms that represent a key factor in enhancing or constraining adaptive capacity (Smit et al., 2001). For example, in the various models and scenarios employed in the UNFCCC (2007) study estimating adaptation costs or investment needs by sector, it is recognised that institutions are often not defined and their impact is either ambiguous or simply not accounted for. There is limited understanding of why climate adaptation investment actions are not implemented despite their no regret potential (e.g. controlling leakages in water pipes often brings net savings even in the absence of climate change), and this has been attributed to little research on relevant institutional and legal constraints (Hallegatte, 2009). The focus in the literature is instead mostly on economic resources, technologies and some market-related transaction costs (to which we will return below). Whilst these are important, they provide only a one-sided perspective and interpretation of the obstacles to climate policy implementation.

On the mitigation side, the range of carbon prices simulated in the literature is largely disjointed from the analysis of the institutional and social changes that would need to accompany any transition to a low-carbon world. For example, though it has been estimated that emissions savings from avoided deforestation in eight countries responsible for 80% of global emissions from deforestation could yield CO_2 reductions for under 5 US$/t$CO_2$, any large-scale reduction would need to be well monitored and carefully managed if it is to

[6] Six determinants of adaptive capacity in the context of climate change are typically cited in the context of climate change, drawing on Smit *et al.* (2001) as a contribution to the Third Assessment Report of the IPCC: economic resources, technology, information and skills, infrastructure, institutions, and equity.

become effective (Stern, 2007). It is this "carefully managed" part that requires more exploration and is frequently sidelined in the traditional economics literature, which instead has a preference for the homogenisation of institutions under its strong assumption of "representative agent".

4.1. Market and Non-market Barriers

Institutional changes for climate protection and adaptation are closely interlinked with issues of structural constraints in the shape of market and non-market barriers. Institutional factors may be regarded as including such barriers to widespread climate action, since the latter are mostly a result of dominant institutional systems and the status quo of ingrained social rules. Market (sometimes referred to as economic) barriers depend on the nature of markets under analysis, in turn influenced by various institutional arrangements. They prevent not only the smooth functioning of existing markets, but also any significant departure from the prevailing configuration of market players or rules of play. For instance, more than 80% of the economic mitigation potential of the buildings sector has being identified at negative costs (Barker et al., 2007). However, such mitigation potentials might prove in reality smaller or the costs higher since "significant barriers need to be overcome to achieve these" (Barker et al., 2007). Amongst mitigation areas of intervention, the building sector is argued to present one of the highest number of institutional barriers (Iwaro and Mwasha, 2010). In this case, market barriers may relate to: restricted access to credit and lack of funding, subsidies on energy prices, lack of proper incentives (landlords versus tenants), fragmentation of the building industry, and the often high costs associated with gathering information on energy efficiency measures (Levine et al., 2007). In other words, market barriers may significantly influence differences between economic and market potentials or the amount of mitigation or adaptation that could be realised.

Non-market (or non-price) barriers to effective climate action have also been typically downplayed in the traditional economics literature. This is because, in general, neoclassical theory has had an exclusive preference for attaching market prices to all sorts of non-marketed capital, which distorts understandings on the nature of social, environmental, informational, attitudinal, behavioural and other non-market barriers. While there is no doubt that market-based policies and pricing mechanisms play a significant part in solving the climate problem, it is also important to acknowledge the contribution of non-market elements to explaining economic behaviour. As an example, the demand for vehicles, vehicle travel and fuel use are significantly price inelastic, and as a result only large increases in prices or taxes often, politically infeasible will make a relevant dent in GHG emissions from the transport sector (Kahn Ribeiro et al., 2007). Non-market barriers have been signalled, as well, when attempting to scale up electricity provision from wind sources, such as difficult grid access or convoluted administrative procedures (Pfenninger, 2010). They have also been emphasised when implementing climate change adaptation and risk management activities, particularly in poor countries lacking the knowledge on climate change risks and the institutional capacity to address the challenges at the local level (UNEP-UNDP, 2011). Lack of information and low awareness are prevalent, as well, in mitigation efforts, such as energy efficiency improvements and renewable energy investments, particularly in developing countries (Iwaro and Mwasha, 2010; OECD/IEA, 2010). In many cases, price and technology-based policy options need to be complemented with non-price and non-technological options accounting for relevant cultural, behavioural and other social choices. Despite a poor understanding in the traditional economics literature of the potential leverage of the latter, available evidence suggests that they do represent important preconditions to fully operating climate policies (Levine et al., 2007). This would argue for embedding climate economics research in more active and engaging intra- and interdisciplinary work, i.e. both within and across disciplines.[7] Moreover, pricing policies could support non-price policies and reduce the costs of climate action. Carbon taxes or an emissions trading scheme based on carbon permit auctioning could raise revenue to help remove barriers to mitigation and adaptation lowering climate policy costs (Barker et al., 2007).

4.2. Transaction and Transition Costs

Market and non-market barriers for an effective climate policy implementation may also be interpreted in terms of transaction and transition costs associated with removing the respective (institutional) constraints. The transaction cost concept has been associated in the broader economics and organisation theory literature with multivalent definitions and often ambiguous conceptualisations (Klaes, 2000; Musole, 2009). The term has varied from the cost of using the price mechanism or carrying out transactions on the market (i.e. market transaction cost as defined by Coase, 1992), to the costs internal to an organization (see Williamson, 1981, undermining the neoclassical theory of the firm), or the cost of running and adjusting the institutional framework of the polity (Levi, 1988 as cited in Musole, 2009). Transaction costs are inherent to any system. They cannot be easily set aside as it has been practiced in neoclassical economic theory, which often assumes a purely theoretical world almost devoid of frictions (Furubotn and Richter, 1997) or, when transaction costs are considered, leads to contradictory assumptions (Kaufman, 2007).

Transaction costs and appropriate institutional responses vary across economic sectors, partly depending on the behaviour of demand with respect to prices. In sectors where demand is price inelastic (e.g. transport sector) or where there are important market and non-market barriers (e.g. efficiency improvements in the buildings sector), climate action may be better achieved through a combination of regulatory changes, command & control instruments, information-based measures, and market-incentives. However, the sequencing of policy measures or policy pathway is also critical for achieving the stated objectives (Wilby and Dessai, 2010).[8] The climate economics literature on the links between sectoral demand behaviour, institutional constraints and climate policy responses, including sequencing is nevertheless limited, and more research is required in this area.

Most importantly, transaction costs tend to be much higher when the transformations required involve systemic changes, and, generally, higher levels of novelty and uncertainty. In other words, a transition from one type of prevailing dynamics or operating environment to another (e.g. from fossil-fuels to low-carbon energy sources) incurs a switch in the nature and magnitude of transaction costs, sometimes referred to as a "transition cost". As an example, financial support for climate policy needs to target not only the actions *per se* (e.g. capital expenditures of low-carbon technologies), but also changes in the regulatory environment and institutional profiles required to render those actions effective (e.g. promoting labour skills to service new technologies, setting up new institutional bodies and legislative frameworks, creating mechanisms for

[7] A possible agenda for a "new" economics of climate change could follow a twin track. First, one needs to accept and interact more with different perspectives within economics itself. There is a wide and rich diversity of schools of economic thinking relevant to climate change already out there that requires more tapping into, for example, evolutionary economics, ecological economics, complexity economics, post-Keynesian economics, behavioural economics, experimental economics, institutional economics, Austrian economics and feminist economics. Second, one needs to foster closer cooperation between economists and experts from other relevant disciplines, such as climate scientists, sociologists, engineers, moral philosophers, ecologists, historians, political scientists and sociologists.

[8] Also see the example of policy sequencing for energy efficiency improvements in Canada's commercial building sector (NRTEE and SDTC, 2009).

Please cite this article as: Scrieciu, S.Ş., et al., Pushing the boundaries of climate economics: Critical issues to consider in climate policy analysis, Ecol. Econ. (2011), doi:10.1016/j.ecolecon.2011.10.016

monitoring, reporting and verification, understanding social attitudes, ensuring social safety nets).[9]

If such transition costs are overlooked and climate policy actions are prioritised according to the orthodox least cost way of delivering, then many of the trigger points that could facilitate long-terms transitions and more sustainable development pathways will be missed (Neuhoff et al., 2009). For instance, a country not having a credible lasting legislative framework that supports low-carbon investments and transcends the short-term interests of political parties in power, would increase the policy risk and diminish profitability prospects of potential climate investors. This would mean that "a significant share of the risk associated with low-carbon investments relates to the stability of the regulatory framework" (Neuhoff et al., 2009: 10).[10]

4.3. Social Institutions and Collective Action

A further lacuna in large parts of the climate economics literature is the neglect of the role of multi-level collective action, particularly that engaging the third (civic) sector in its broader sense.[11] Most research efforts have been instead focusing either at the state policy level (public sector) or at business/firm scale (private sector). Yet, the importance of bottom-up participatory action in the social management of many externalities or the governance of the commons has been frequently highlighted in other parts of the literature on institutional economics, political economy, political science or sociology (Bromley et al., 1992; McKean, 2000; Ostrom, 1990; Ostrom et al., 1994, 2002). Measures for coping with climate change may be better off by taking a polycentric approach at multiple local, regional and national levels involving different stakeholders rather than focusing on single top-down policies (Ostrom, 2009). Whilst not downplaying the role of governmental regulatory institutions for managing climate change (particularly for international mitigation efforts), it is also relevant to account for social institutions in the form of locally-initiated civic forms of action or grassroots associations. From a mitigation standpoint, the climate is a global common good and emissions reduction efforts represent a classical collective action problem. The same logic applies for adaptation to climate change, at least in areas that involve the governance of the commons. Examples include increasing ecosystems resilience to more intense climate variations, and improving the management of water or common land resources confronted with additional climate instability. Having said this, a challenge is how any community-based environmental governance initiatives may be scaled-up at the national level. Research avenues on multi-level nested governance systems drawing on the principles of subsidiarity and decentralisation (e.g. Marshall, 2008) may also provide useful insights in the climate change arena.

Local-community driven institutions for collective action may also push governments towards making credible commitments towards mitigation and adaptation. Social actors could be well placed to achieve mutual monitoring and verification, and may play a critical role in the supply of new or reformed institutions (Ostrom, 1990). Developing societal resilience to climate change requires building social diversity and supporting a strong civic community, which in turn reproduces itself, generates economic development, and alleviates poverty (Rayner and Malone, 2001). In large parts of the economics literature, mitigation and adaptation options are assumed, meaning that the underlying causes or conditions impacting the effectiveness of climate policy options and influencing their outcomes are not sufficiently explored. Participatory approaches are important for the feasibility and practicality of climate change measures, and local initiatives in this sense need to be integrated into or consistent with the wider transformations of geo-political-economic systems (Smit and Wandel, 2006). Closer links could be developed, for instance, between climate adaptation economics research at the national level (mostly focusing on planned adaptation) and community-based adaptation studies at the local level (focusing on autonomous adaptation and local adaptive behaviour) (Adger et al., 2003; Jones, 2010). Ultimately, social capital and collective action based on trust and reciprocity are pre-conditions for the success of climate action and economic development in general (Adger, 2003; Rayner and Malone, 2001).

Traditional economic modelling approaches (under their typical form of optimal growth models or computable general equilibrium models) to climate mitigation and adaptation policy analysis need to be thoroughly checked and empirical tested for their assumptions on the multitude of institutional barriers that may dampen climate efforts or even result in undesired impacts, i.e. "malmitigation" or "maladaptation". These generally rely on perfectly or fully rational economic agents who are delinked from social bonds in their decision-making. However, considerable experimental evidence, not to mention common sense, has shown the relevance of social norms in people's decision making and the context-specific heterogeneity of their preferences (Patt and Siebenhüner, 2005). Also, the validity of the representative agent assumption often made in traditional economic models (i.e. the behaviour of an economic group is adequately represented by each member of the group having the identical characteristics of the average) is not grounded in empirical evidence. Data, on the contrary, has been suggesting that economic behaviour is differentiated by industry and region (Barker and de-Ramon, 2006).

New avenues of climate economics research may spread towards a better understanding of the role that heterogeneous actors play in complex dynamic systems and their contribution towards meaningful climate action. These may include advances in economic modelling grounded in interdisciplinary innovation in knowledge that would simulate the complexity of interactions between different actors both at a local level and at a macro-scale. For instance, macro-econometric models simulating energy-environment-economy interactions relevant for climate mitigation continue to be very sparse in the literature despite their ability to capture the behaviour of heterogeneous agents and sectors grounded in empirical analysis. Examples in this sense include the global E3MG model (Barker and Scrieciu, 2010; Barker et al., 2006; Köhler et al., 2006), the global GINFORS model (Lutz et al., 2010) and the country-level PANTA RHEI model (applied to Germany, Meyer, 2005). Another novel approach is represented by agent based models (ABMs). These simulate complex systems and allow the modeller to investigate both the potential for and the sources of emergent properties, with underlying principle that the behaviour of the system is quite different from the behaviour of any of the elements within it (Patt and Siebenhüner, 2005). Examples include ABMs linked to system dynamics techniques and applied to sustainable transport (Bergman et al., 2008; Schilperoord et al., 2008), or the MASON model tackling "swarm"-style multi-agent systems research also applicable to relevant climate policy issues such as urban traffic modelling (Luke et al., 2005) or climate variability, food security and health (Cioffi-Revilla et al., 2010). Other relevant interesting numerical simulation approaches relate to system dynamic models, such as the ASTRA model applied for the integrated assessment of transport and low-carbon policy strategies within Europe (Köhler et al., 2010; Schade, 2005).

[9] The body of transition theory and research focusing on radical or systemic change spurred by the growth of socio-economic-technical niches may also bring some useful insights to the climate change economics literature (Rotmans et al., 2001). The theory argues that if a transition or a socio-technical transformation process (e.g. towards a low-carbon energy infrastructure) is to occur, a niche must arise and either grow to form a new regime or force the existent regime to change to adopt the new technology and practices of the successful niche (Köhler et al., 2010).

[10] Credit guarantees backed by governments could remove some of the risks of investing in new technologies under uncertain regulatory investment regimes (Neuhoff et al., 2009).

[11] For instance, to include quasi-public or quasi-private organisations such as cooperative associations, green banks or other specialised credit institutions carrying out activities for public purposes (e.g. a list of quasi-public institutions or public-private partnerships in finance in US, covering clean-energy is provided in Lind, 2010).

Please cite this article as: Scrieciu, S.Ş., et al., Pushing the boundaries of climate economics: Critical issues to consider in climate policy analysis, Ecol. Econ. (2011), doi:10.1016/j.ecolecon.2011.10.016

The role of economic modelling would thus be to capture the effects of collective action and to inform decision-makers at all levels and the public in general as to what action may be most effective and with what consequences. Furthermore, the likely performance of proposed climate policy options could be assessed against a set of institutional criteria highlighting the various institutional constraints that might be at play. These could be framed in terms of policy feasibility, including, for example, required institutional capacity and legislative changes, social acceptability of proposed actions, or social engagement and stakeholder participation.[12] However, even for more data-intensive models departing from traditional neoclassical models, a critical challenge remains their ability to simulate the past or generate a set of observed data. To some extent the empirical validation of such simulation models has progressed (see Windrum et al., 2007 for ABMs), though far more work needs to be done in this area. In addition, interesting alternative approaches to the empirical validation of socioeconomic simulation models have emerged, for example the French school of "companion modelling" (e.g. Barreteau et al., 2003), whereby stakeholders are engaged in the modelling and validation process (Moss, 2008).

"Understanding institutions is a serious endeavor" (Ostrom, 2005: 3). When riddled with uncertainties, long term perspectives and cross-boundary effects, as induced by the climate change problem, the challenges of understanding endogenous institutional development and achieving the desired institutional change are even greater. Accounting for institutional constraints along the lines discussed above may lead to more robust and socially acceptable climate policy design and implementation. It may reveal greater costs of achieving the emissions reductions or climate proofing desired, but also result in important opportunities for institutional regime change towards improved socioeconomic and environmental governance. Drawing on alternative economic approaches with a greater propensity towards inter-disciplinarity and exploring the institutional aspects of climate action may go a long way forward in this respect. New climate economics research could take forward investigations on the interrelated nature of economic institutions and behaviour, the interdependence between market relations and social relations. This would represent an important break from the traditional perspective that often "de-institutionalises", "de-historicises" and "de-contextualises" economic policy responses.

5. Concluding Remarks

Climate policy planning and decision-making is influenced by the economics literature exploring the implications of climate action and supporting different strategies. Simulating the impacts and costs of climate policy is based, in turn, on varying assumptions and theories that frame the economic problem. The paper has highlighted some of the knowledge gaps on climate economics research that warrant further research efforts and directions. The economics of climate change poses unique challenges to orthodox styles of economic analysis, placing their rigid assumptions in the spotlight.

Critical requirements for an adequate economic framework for climate policy could be fourfold. First, one needs to explicitly state the value judgements underlying the economic analysis, particularly judgements about the importance of current versus future generations, with implications for discounting. Second, climate policy induced interactions between the economy, environment and society would need to be considered in their multi-dimensional, often unmonetisable integrity. This renders the traditional cost-benefit analysis approach problematical, warranting its replacement by other methodologies, such as those based on multi-criteria analysis. Third, the problems of catastrophic risks and irreducible uncertainty need to be fully recognised, resulting in a collective insurance-based or precautionary approach to climate policy. Fourth, it is important to understand the nature of implementation costs in dynamic and institutional settings, with multiple consequences for policy formation. This would render not only increased empiricism to the characteristics of economic systems under analysis (e.g. accounting for unemployment and underemployment versus merely assuming full employment), but also improved treatment of policy-induced technological change and the context-specific institutional barriers that might constrain climate policy implementation.

The roles of technological change and institutional constraints have been in particular identified in this paper as essential in shaping robust and effective climate policy responses. The stylised models of economies working at optimal efficiency and full employment in which prices clear markets and reflect marginal costs are inadequate for analysing system-wide global technological change, where diversity of institutional and technical responses across economies at different stages of development is to be considered and regulation is an important policy option. One of the implications for future climate economics research, in this respect, is that more attention should be given to modelling system-wide change to include all the main channels for induced technological change effects, and all the main policy instruments that affect induced technological change. Another implication is that more research needs to be geared towards understanding and capturing current institutional setups that favour or hamper the adoption of new technologies or the implementation of climate policy portfolios. Such analysis could explore the market and non-market barriers, or the transaction and transition costs of policy implementation, as well as the contribution of social institutions and the civic sector towards effective action.

It is difficult to predict what it would take for new approaches to have a real and wide-reaching impact on thinking about climate economics. In fact, contemporary global man-made crises (climate crisis, financial crisis) have triggered scholars and practitioners to rethink their understanding of the issues involved and explore new avenues of research. Greater and sustained investments into innovative research that fill the gaps identified would be a start. Increased transparency of new information produced from different perspectives would help build a more diverse and solid base of evidence. This would support policy makers and civil society in making more informed choices and contributing to progress towards more sustainable futures. The potential for change towards a new consensus on climate economics has already been building up for last few decades. It remains to be seen whether this will gather pace and reach the critical mass required to break-through to new horizons that would redefine economics and change its methods of investigation and proof.

Ultimately progress in economics is measured by the shaping of better working solutions to existing and emerging problems. New ideas emphasising the role of economics as a problem-solving activity could replace old ideas clinging onto supposedly value-free notions. There is a need for a break in the pattern of economic thinking away from approaches that have contributed to the climate problem and unsustainable modes of production and consumption in the first place. This could be achieved if those pursuing economic theories and approaches that better represent the realities of the climate change problem were to form a common platform and advance research along the lines suggested in this paper. Climate change policies need not be seen or undertaken at the expense of development or poverty alleviation. On the contrary, they can act as a catalyst for shifting the development process towards economic outcomes that are compatible with social and environmental goals.

Acknowledgements

Useful and constructive comments from Reinhard Mechler and Zaid Chalabi are gratefully acknowledged. We would also like to

[12] A methodological framework for climate policy planning at a strategic level based on multi-criteria analysis including institutional constraints has been developed, for instance, at UNEP (2011a), see www.mca4climate.info.

Please cite this article as: Scrieciu, S.Ş., et al., Pushing the boundaries of climate economics: Critical issues to consider in climate policy analysis, Ecol. Econ. (2011), doi:10.1016/j.ecolecon.2011.10.016

thank the anonymous reviewers of our manuscript who have provided us with very detailed comments and useful suggestions for improvement. Terry Barker wishes to acknowledge funding from the Three Guineas Trust, one of the Sainsbury Family Trust for supporting new thinking in climate economics.

References

Ackerman, F., 2008. Climate economics in four easy pieces. Development (Cambridge, England) 51 (3), 325–331.

Ackerman, F., 2009. Can We Afford the Future? Economics for a Warming World. Zed Books, London.

Ackerman, F., Heinzerling, L., 2004. Priceless: On Knowing the Price of Everything and the Value of Nothing. The New Press, New York.

Ackerman, F., Stanton, E.A., DeCanio, S.J., Goodstein, E., Howarth, R.B., Nordgaard, R.B., Norman, C.S., Sheeran, K.A., 2009. The Economics of 350: The Benefits and Costs of Climate Stabilization. Economics for Equity and Environment. E3 report, Portland OR, United States http://sei-us.org/Publications_PDF/SEI-E3-Econ350BenefitsCostsClimateStabilization-09.pdf.

Adger, N.W., 2003. Social capital, collective action and adaptation to climate change. Economic Geography 79 (4), 387–404.

Adger, N.W., Huq, S., Brown, K., Conway, D. And, Hulme, M., 2003. Adaptation to climate change in the developing world. Progress in Development Studies 3 (3), 179–195.

Barker, T., 2008. The economics of avoiding dangerous climate change. An editorial essay on The Stern Review. Climatic Change 89 (3–4), 173–194.

Barker, T., de-Ramon, S.A., 2006. Testing the representative agent assumption: the distribution of parameters in a large-scale model of the EU 1972–1998. Applied Economics Letters 13 (6), 395–398.

Barker, T., Scrieciu, S.Ş., 2010. Modelling low stabilization with E3MG: towards a 'new economics' approach to simulating energy-environment-economy system dynamics. The Energy Journal 31, 137–164 (Special Issue on "The Economics of Low Stabilization").

Barker, T., Pan, H., Köhler, J., Warren, R., Winne, S., 2006. Decarbonizing the global economy with induced technological change: scenarios to 2100 using E3MG. The Energy Journal 27, 241–258 (Special Issue on "Endogenous Technological Change and the Economics of Atmospheric Stabilisation").

Barker, T., Bashmakov, I., Alharthi, A., Amann, M., Cifuentes, L., Drexhage, J., Duan, M., Edenhofer, O., Flannery, B., Grubb, M., Hoogwijk, M., Ibitoye, F.I., Jepma, C.J., Pizer, W.A., Yamaji, K., 2007. Mitigation from a cross-sectoral perspective (chapter 8 in) In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK & New York, NY, pp. 619–690.

Barker, T., Foxon, T., Scrieciu, S.Ş., 2008. Achieving the G8 50% target: modelling induced and accelerated technological change using the macro-econometric model E3MG. Climate Policy 8, S30–S45 (Special Issue on 'Modelling long-term scenarios for low-carbon societies').

Barreteau, O., Le Page, C., D'Aquino, P., 2003. Role-playing games, models and negotiation processes. Journal of Artificial Societies and Social Simulation 6 (2)http://jasss.soc.surrey.ac.uk/6/2/10.html (url: URL:).

Bergman, N., Haxeltine, A., Whitmarsh, L., Köhler, J., Schilperoord, M., Rotmans, J., 2008. Modelling socio-technical transition patterns and pathways. Journal of Artificial Societies and Social Simulation 11.

Bromley, D.W., Feeny, D., McKean, M., Peters, P., Gilles, J., Oakerson, R., Runge, C.F., Thomson, J. (Eds.), 1992. Making the Commons Work: Theory, Practice, and Policy. ICS Press, San Francisco.

Broome, J., 1994. Discounting the future. Philosophy and Public Affairs 23 (2), 128–156.

Broome, J., 2008. The ethics of climate change. Scientific American 97–102 (June).

Carr, M.-E., Anderson, R.F., Brash, K., 2010. Climate Change: Addressing the Major Skeptic Arguments", report prepared for DB Climate Change Advisors, Deutsche Bank Group. (September) .

Carter, R.M., 2010. Climate: The Counter-Consensus. Stacey International, London.

Chalabi, Z., Kovats, S., 2011. Reducing human health impacts and risks. Contribution to the UNEP's initiative MCA4climate: A Practical Framework for Planning Pro-Development Climate Policies. Energy Branch, Division of Technology, Industry and Economics, United Nations Environment Programme, Pariswww.mca4climate.info.

Cioffi-Revilla, C., Luke, S., Rogers, J.D., Schopf, P., Trimble, J., 2010. Agent-based modelling of climate change, ecosystems, and security: a research programme", paper prepared for the 250th Anniversary Conference on "Climate Change and Security. The Royal Norwegian Society of Sciences and Letters, Trondheim, Norway, 21–24 June 2010.

Clarke, L., Weyant, J., Edmonds, J., 2008. On the sources of technological change: what do the models assume? Energy Economics 30, 409–424.

Cline, W.R., 1992. The Economics of Global Warming. Institute for International Economics, Washington DC.

Coase, R.H., 1992. The institutional structure of production. The American Economic Review 82 (4), 713–719.

Colander, D., Holt, R., Rosser Jr., B., 2004. The changing face of mainstream economics. Review of Political Economy 16 (4), 485–499.

Costello, A., Abbas, M., Allen, A., Ball, S., Bell, S., Bellamy, R., Friel, S., Groce, N., Johnson, A., Kett, M., Lee, M., Levy, C., Maslin, M., McCoy, D., McGuire, B., Montgomery, H., Napier, D., Pagel, C., Patel, J., de Oliveira, J.A.P., Redclift, N., Rees, H., Rogger, D., Scott, J., Stephenson, J., Twigg, J., Wolff, J., Patterson, C., 2009. Managing the health effects of climate change. Lancet 373, 1693–1733 (Lancet and University College London Institute for Global Health Commission).

Daneshkhah, A.R., 2004. Uncertainty in Probability Risk Assessment: A Review. BEEP Working Paper: Bayesian Elicitation of Experts' Probabilities, Sheffield, UK: University of Sheffield.

Dequech, D., 2008. Neoclassical, mainstream, orthodox, and heterodox economics. Journal of Post Keynesian Economics 30 (2), 279–302.

Dietz, S., Stern, N., 2008. Why economic analysis supports strong action on climate change: a response to the Stern review's critics. Review of Environmental Economics and Policy 2 (1), 94–113.

Ek, K., Soderholm, P., 2010. Technology learning in the presence of public R&D: the case of European wind power. Ecological Economics 69 (12), 2356–2362.

Fischer, C., Newell, R.G., 2008. Environmental and technology policies for climate mitigation. Journal of Environmental Economics and Management 55 (2), 142–162.

Furubotn, E.G., Richter, R., 1997. Institutions and Economic Theory: The Contribution of the New Institutional Economics. The University of Michigan Press, Ann Arbor, MI.

Gerlagh, R., 2008. A climate-change policy induced shift from innovations in carbon-energy production to carbon-energy savings. Energy Economics 30, 425–448.

Gerlagh, R., van der Zwaan, B.C.C., 2006. Options and instruments for a deep cut in CO_2 emissions: carbon capture or renewables, taxes or subsidies? The Energy Journal 27, 25–48.

Gillingham, K., Newell, R.G., Pizer, W.A., 2008. Modeling endogenous technological change for climate policy analysis. Energy Economics 30 (6), 2734–2753.

Haites, E., 2008. Investment and Financial Flows needed to Address Climate Change", Breaking the Climate Deadlock Briefing Paper. The Climate Group, London.

Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. Global Environmental Change 19 (2), 240–247.

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D.L., Zachos, J.C., 2008. Target atmospheric CO_2: where should humanity aim? The Open Atmospheric Science Journal 2, 217–231.

Hayward, T., Preston, J., 1999. Chaos theory, economics and information: the implications for strategic decision-making. Journal of Information Science 25 (3), 173–182.

Heal, G., 2009. Climate economics: a meta-review and some suggestions for future research. Review of Environmental Economics and Policy 3 (1), 4–21.

Hodgson, G.M., 1999. Evolution and Institutions: On Evolutionary Economics and the Evolution of Economics. Edward Elgar, Cheltenham, UK.

Hodgson, G.M., 2006. What are institutions? Journal of Economic Issues XL (1), 2–4http://www.geoffrey-hodgson.info/user/bin/whatareinstitutions.pdf (available online at).

Howarth, R.B., 2003. Discounting and uncertainty in climate change policy analysis. Land Economics 79 (3), 369–381.

IEA, 2010. World Energy Outlook. International Energy Agency, Paris.

IPCC, 2007. Summary for Policymakers. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK & New York, NY.

Iwaro, J., Mwasha, A., 2010. A review of building energy regulation and policy for energy conservation in developing countries. Energy Policy 38 (12), 7744–7755.

Jochem, J., Jaeger, C., et al. (Eds.), 2008. "Investments for a Climate-Friendly Germany", Study commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). Synthesis Report, Berlin, Germany (June).

Jones, L., 2010. Overcoming social barriers to adaptation", ODI Background Note. Overseas Development Institute, London.

Kahn Ribeiro, S., Kobayashi, S., Beuthe, M., Gasca, J., Greene, D., Lee, D.S., Muromachi, Y., Newton, P.J., Plotkin, S., Sperling, D., Wit, R., Zhou, P.J., 2007. Transport and its infrastructure (chapter 5 in) In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK & New York, NY, pp. 323–385.

Kahouli-Brahmi, S., 2007. Technological learning in energy-environment-economy modelling: a survey. Energy Policy 36 (1), 138–162.

Kaufman, B.E., 2007. The impossibility of a perfectly competitive labour market. Cambridge Journal of Economics 31 (5), 775–787.

Klaes, M., 2000. The birth of the concept of transaction costs: issues and controversies. Industrial and Corporate Change 9 (4), 567–593.

Köhler, J., Barker, T., Anderson, D., Pan, H., 2006. Combining energy technology dynamics and macroeconometrics: the E3MG model. The Energy Journal 113–134 (vol. "Hybrid Modelling" (special issue 2)).

Köhler, J., Wietschel, M., Whitmarsh, L., Keles, D., Schade, W., 2010. Infrastructure investment for a transition to hydrogen automobiles. Technological Forecasting and Social Change 77 (8), 1237–1248.

Lee, J., Veloso, F.M., Hounshell, D.A., Rubin, E.S., 2010. Forcing technological change: a case of automobile emissions control technology development in the US. Technovation 30 (4), 249–264.

Lempert, R.J., Collins, M.T., 2007. Managing the risk of uncertain threshold responses: comparison of robust, optimum, and precautionary approaches. Risk Analysis 27 (4), 1009–1026.

Levi, M., 1988. Of rule and revenue. University of California Press, Berkeley, CA.

Levine, M., Ürge-Vorsatz, D., Blok, K., Geng, L., Harvey, D., Lang, S., Levermore, G., Mongameli Mehlwana, A., Mirasgedis, S., Novikova, A., Rilling, J., Yoshino, H., 2007. Residential and commercial buildings (chapter 6 in) In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK & New York, NY, pp. 387–446.

Lind, M., 2010. Public Purpose Finance: Investing in America's Future with Regional Economic Development Banks. Economic Growth Program Policy Paper. New America Foundation, Washington, DC (September).

Please cite this article as: Scrieciu, S.Ş., et al., Pushing the boundaries of climate economics: Critical issues to consider in climate policy analysis, Ecol. Econ. (2011), doi:10.1016/j.ecolecon.2011.10.016

Lowe, J., 2008. Intergenerational wealth transfers and social discounting: Supplementary Green Book guidance. HM Treasury, UK Government, London. (online) http://www.hm-treasury.gov.uk/d/4%285%29.pdf.

Luke, S., Cioffi-Revilla, C., Panait, L., Sullivan, K., 2005. MASON: a Java multi-agent simulation environment. Simulation: Transactions of the Society for Modelling and Simulation International 81 (7), 517–527.

Lutz, C., Meyer, B., Wolter, M.I., 2010. The global multisector/multicountry 3-E model GINFORS. A description of the model and a baseline forecast for global energy demand and CO2 emissions. International Journal of Global Environmental Issues 10 (1–2), 25–45.

Magné, B., Kypreos, S., Turton, H., 2010. Technology options for low stabilization pathways with MERGE. Energy Journal 31, 83–107 (Special Issue 1 on "The Economics of Low Stabilisation").

Marshall, G.R., 2008. Nesting, subsidiarity, and community-based environmental governance beyond the local level. International Journal of the Commons 2 (1), 75–97.

McDonald, A., Schrattenholzer, L., 2001. Learning rates for energy technologies. Energy Policy 29 (4), 255–261.

McKean, M.A., 2000. People and Forests: Communities, Institutions, and Governance. MIT Press, Cambridge.

Meyer, B., 2005. The Economic-Environmental model PANTA RHEI and its Application. GWS Discussion Paper Series 2005/3. Institute of Economic Structures Research, Osnabrück.

Montford, A.W., 2010. The Hockey Stick Illusion: Climategate and the Corruption of Science. Stacey International, London.

Moss, S., 2008. Alternative approaches to the empirical validation of agent-based models. Journal of Artificial Societies and Social Simulation 11 (1) (url) http://jasss.soc.surrey.ac.uk/11/1/5.html.

Musole, M., 2009. Property rights, transaction costs and institutional change: conceptual framework and literature review. Progress in Planning 71, 43–85.

Neuhoff, K., Fankhauser, S., Guerin, E., Hourcade, J.-C., Jackson, H., Rajan, R., Ward, J., 2009. Structuring international financial support to support domestic climate change mitigation in developing countries. Climate Strategies report, Cambridge, UK.

Newell, R.G., 2010. The role of markets and policies in delivering innovation for climate change mitigation. Oxford Review of Economic Policy 26 (2), 253–269.

Nordhaus, W.D., 2002. Modeling Induced Innovation in Climate Change Policy (chapter 9 in) In: Grubler, A., Nakićenović, N., Nordhaus, W.D. (Eds.), Modeling Induced Innovation in Climate Change Policy. Resources for the Future Press, Washington, D.C, pp. 259–290.

Nordhaus, W.D., 2007. A review of the stern review on the economics of climate change. Journal of Economic Literature 45, 686–702.

Nordhaus, W.D., 2008. A Question of Balance: Weighing the Options on Global Warming Policies. Yale University Press, New Haven, CT.

NRTEE & SDTC, 2009. "Geared for Change: Energy Efficiency in Canada's Commercial Building Sector", a report by National Round Table on the Environment and the Economy (NRTEE) and Sustainable Development Technology Canada (SDTC), Ottawa, Ontario, Canada.

OECD/IEA, 2010. Energy Efficiency Governance. International Energy Agency, Paris, France.

Ostrom, E., 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press, Cambridge.

Ostrom, E., 2005. Understanding Institutional Diversity. Princeton University Press, Princeton NJ and Oxfordshire, UK.

Ostrom, E., 2009. A polycentric approach for coping with climate change. Policy Research Working Paper 5095 (Background Paper to the 2010 World Development Report). The World Bank, Washington, DC.

Ostrom, E., Gardner, R., Walker, J., 1994. In: Agrawal, A., Blomquist, W., Schlager, E., Tang, S.Y. (Eds.), Rules. Games, and Common-Pool Resources. The University of Michigan Press, Ann Arbor.

Ostrom, E., Dietz, T., Dolšak, N., Stern, P.C., Stonich, S., Weber, E.U. (Eds.), 2002. The Drama of the Commons. National Academy Press, Committee on the Human Dimensions of Global Change, Washington DC.

Patt, A., Siebenhüner, B., 2005. Agent-based modelling and adaptation to climate change. Vierteljahrshefte zur Wirtschaftsforschung 74 (2), 310–320.

Pfenninger, S., 2010. Renewable electricity in the EU: the road to 2020. SEFEP paper, Berlin: Smart Energy for Europe Platform.

Popp, D., Newell, R.G., 2009. Where does energy R&D come from? Examining crowding out from environmentally-friendly R&D. NBER Working Paper No. 15423. National Bureau of Economic Research, Cambridge, MA.

Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. Science 315, 368–370.

Rayner, S., Malone, E.L., 2001. Climate change, poverty, and intragenerational equity: the national level. International Journal of Global Environmental Issues 1 (2), 175–202.

Rennie, J., 2009. Seven Answers to Climate Contrarian Nonsense: Evidence for human inteference with Earth's climate continues to accumulate", Scientific American. (November 30) . (online) http://www.scientificamerican.com/article.cfm?id=seven-answers-to-climate-contrarian-nonsense.

Rosser Jr., J.B., 1999. On the complexities of complex economic dynamics. The Journal of Economic Perspectives 13 (4), 169–192.

Rotmans, J., Kemp, R., van Asselt, M.B.A., 2001. More evolution than revolution: transition management in public policy. Foresight 3 (1), 15–31.

Schade, W., 2005. Strategic Sustainability Analysis: Concept and application for the assessment of European Transport Policy. NOMOS-Verlag, Baden-Baden, Germany.

Schilperoord, M., Rotmans, J., Bergman, N., 2008. Modelling societal transitions with agent transformation. Computational & Mathematical Organization Theory 14 (4), 283–301.

Smit, B., Wandel, J., 2006. Adaptation, adaptive capacity and vulnerability. Global Environmental Change 16, 282–292.

Smit, B., Pilifosova, O., Burton, I., Challenger, B., Huq, S., Klein, R.J.T., Yohe, G., 2001. Adaptation to climate change in the context of sustainable development and equity (chapter 18 in) In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), Climate Change 2001: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 876–912.

Stern, N., 2007. The economics of climate change: The Stern Review. Cambridge University Press, Cambridge.

UNEP, 2011a. MCA4climate: a practical framework for planning pro-development climate policies. MCA4climate brochure / UNEP document. Energy Branch, The Division of Technology, Industry and Economics, United Nations Environment Programme, Parishttp://www.mca4climate.info.

UNEP, 2011b. New Climate Economics: Methodological choices and recommendations. Additional guidance supporting UNEP's MCA4climate initiative / UNEP document. Energy Branch, The Division of Technology, Industry, and Economics, United Nations Environment Programme, Paris (authored by F. Ackerman, with contributions from Z. Chalabi, R. Mechler and Ş. Scrieciu) http://www.mca4climate.info/_assets/files/New-Climate-Economics-Final-report(1).pdf.

UNEP-UNDP, 2011. CC DARE: Climate Change and Development – Adapting by Reducing Vulnerability", a joint UNEP/UNDP programme for Sub-Saharan Africa (funded by the Danish Ministry of Foreign Affairs), Maiden Volume - January.

UNFCCC, 2007. Investment and Financial Flows to Address Climate Change. United Nations Framework Convention on Climate Change, Bonn.

van Vuuren, D.P., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S., Chateau, J., Scrieciu, Ş., van Vliet, J., Masui, T., Blok, K., Blomen, E., Kram, T., 2009. Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. Energy Policy 37 (12), 5125–5139.

Weiss, M., Junginger, M., Patel, M.K., Blok, K., 2010. A review of experience curve analyses for energy demand technologies. Technological Forecasting and Social Change 77, 411–428.

Weitzman, M.L., 2009. On modelling and interpreting the economics of catastrophic climate change. The Review of Economics and Statistics 91 (1), 1–19.

Wilby, R.L., Dessai, S., 2010. Robust adaptation to climate change. Weather 65 (7), 180–185.

Williamson, O.E., 1981. The economics of organization: the transaction cost approach. The American Journal of Sociology 87 (3), 548–577.

Windrum, P., Fagiolo, G., Moneta, A., 2007. Empirical validation of agent-based models: alternatives and prospects. Journal of Artificial Societies and Social Simulation 10 (2) (url) http://jasss.soc.surrey.ac.uk/10/2/8.html.

World Bank, 2010a. Economics of adaptation to climate change: Synthesis report. World Bank, Washington DC.

World Bank, 2010b. The cost to developing countries of adapting to climate change: new methods and estimates. Consultation Draft, World Bank, Washington DC.

Please cite this article as: Scrieciu, S.Ş., et al., Pushing the boundaries of climate economics: Critical issues to consider in climate policy analysis, Ecol. Econ. (2011), doi:10.1016/j.ecolecon.2011.10.016