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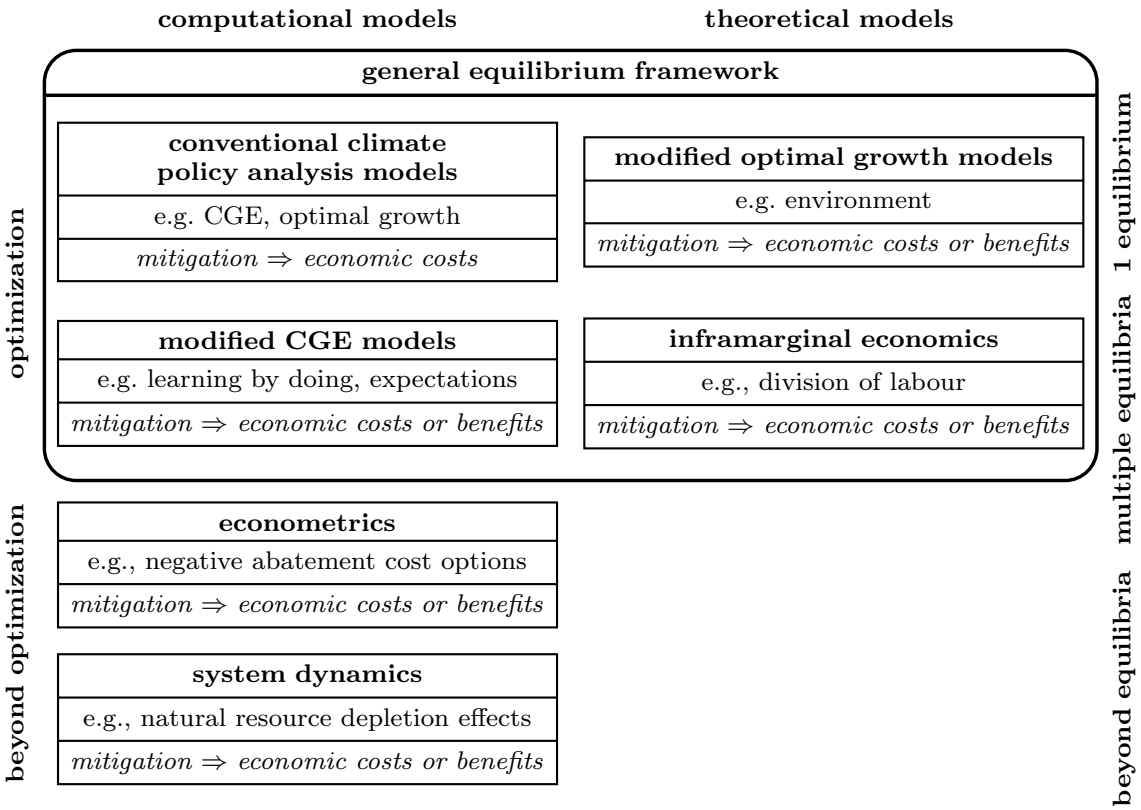

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The Possibility of Green Growth in Climate Policy Analysis Models – a Survey

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Abstract The concept green growth appeared on policy agendas of various countries and international organizations rather recently. Since it would provide a solution to the climate problem with positive economic effects, it deserves to be carefully researched in the climate policy analysis context. As a starting point for such research, this paper reviews models which can represent positive economic effects of climate and environmental policy. In particular, it points out how such models go beyond conventional climate policy analysis models that are grounded in the general equilibrium framework. The review indicates three directions for future research towards macroeconomic models for analysing a possibility of green growth: extending standard policy analysis models with insights from theoretical works, studying a transition from the current to a green growth path as a transition from one equilibrium of the economic system to another one, or using modelling approaches outside the general equilibrium framework.

Keywords Climate policy analysis · Green growth · Economic model structures · Optimization · Equilibria

1 Introduction

The general impression about climate change mitigation is that current generations have to pay for reducing emissions in order to avoid dangerous climate change in the future, or in other words that (short-term) economic costs have to be incurred for reaping (long-term) environmental benefits. In contrast, the concepts green growth and green economy contain the idea that there need not be a trade-off between economic and environmental well-being. For example, in the European context, green growth has been discussed as a solution to both the climate change problem and the Eurozone crisis (e.g. Schepelmann et al 2009; Zenghelis 2011). This paper focuses on the possibility of net economic benefits from climate change mitigation, and will refer to these with the term green growth, unless when reviewing works that refer to a green economy. We acknowledge that this considers a very specific one of the many aspects that these concepts – closely related but not synonymous – are associated with in their various definitions found in the literature. However, a detailed analysis of the concepts themselves is not relevant to the scope of this paper.

Traditionally, studies on the economic effects of climate policy report net mitigation costs, as summarized by the IPCC (2014); only recently, (economic) co-benefits of mitigation policy are also being discussed (e.g., Edenhofer et al 2015). Most macroeconomic models commonly employed to assess climate policy measures fall short of capturing possible economic benefits of mitigation, thus ruling out green growth by construction. It is therefore important to extend the climate policy analysis toolbox with models which are able to conceive net benefits of mitigation, and hence green growth. This paper presents a survey of the models used in the few works that have found such benefits and categorizes the corresponding model structures against the background of the general equilibrium framework, which underlies most previous climate economics. In doing so, we aim to clarify how the possibility of economic benefits from mitigation relates to the model structures used for assessing costs and benefits of climate policy from a macroeconomic perspective.

Other features that influence the possibility of economic benefits of mitigation include the choice of model parameters and of exogenous inputs to the models used for running simulations. A discussion of these is beyond the scope of this paper, however, see e.g., Rosen and Guenther (2015).

In previous green growth and green economy literature, that, for the time being seems rather detached from the field of climate policy analysis, (macroeconomic) models play a secondary role. The concepts originated in the policy sphere (see, e.g., Ho and Wang 2014; Jaeger 2014), and have been embraced by international institutions such as the OECD, UNEP and others, that provide platforms for green growth and related research via publications, websites and events.[1] Practice-oriented reports inform decision makers about the possibility of green growth and policy measures that could facilitate a shift to it (e.g., OECD, 2011; GCEC, 2014), and there is a pool of work on green growth strategies for specific countries[2] as well as on monitoring the success of such strategies (e.g. UNEP 2014). Further, theoretical considerations around green growth are discussed: for example, Scrieciu et al (2013) argue that the macroeconomic reasoning behind policy interventions for greening the economy remains ambiguous; Bowen and Fankhauser (2011) point out that the green growth narrative can draw on various perspectives in economic thinking (Keynesian, Schumpeterian, etc.) and thus provides a bigger picture than climate economics that focuses on marginal abatement costs; Jacobs (2013) categorizes different forms of green growth claims. A point that is variously mentioned throughout the emerging literature on green growth will be of particular interest to our analysis: given the current, fossil fuel based economy, green growth requires a structural transition of the economic system (e.g., Hepburn and Bowen 2012; Romani et al 2011; Zhang 2014), that needs to go beyond the energy sector alone (Zysman and Huberty 2012; Bowen et al 2014).

The paper is structured as follows: to ask what can be learned from conventional climate policy analysis modelling, it provides a brief recap in Section 2. Against this background, it then reviews models that can represent a possibility of green growth in Section 3. Section 4 concludes by summarizing research directions towards economic models for analysing green growth as revealed by the review of models.

2 Brief recap: climate policy analysis modelling

Many computational economic models and integrated assessment models, which combine an economic model with a climate model, are used in climate policy analysis (CPA). In order to analyse the effects of climate policy measures, the models are generally run to compare a so called business-as-usual (BAU) scenario, without climate policy measures, with a mitigation scenario, in which mitigation policy is implemented. Reductions in GDP growth, welfare, or similar criteria in the mitigation scenario as compared with the BAU scenario are conceptualised as the cost of mitigation; increases would be benefits. Both the use of economics in the climate policy context and the use of long-term scenarios can be discussed controversially, but without going into these debates, we refer the reader to DeCanio (2003) and Rosen and Guenther (2015), respectively.

Models applied in this way can be categorized according to different aspects, a few of which are summarized in Table 1. Estimated mitigation costs generally vary with these categories. For example, Scrieciu et al (2013) point out that for the criteria of optimization versus simulation and top-down versus bottom-up models (with related representation of technological progress as exogenous, endogenous or policy induced), projected mitigation costs are generally higher for the more common categories in climate policy analysis, that is, optimization and/or top-down models. This helps explain the general impression of a trade-off between economic and environmental well-being. As there are models which lead to lower cost estimates, and such, even if few, which find (short-term) benefits of

[1] See, e.g., http://www.oecd.org/greengrowth/, http://www.unep.org/greeneconomy/

[2] See, e.g., http://www.oecd.org/greengrowth/countries.htm

Table 1 Categories of climate policy analysis models

	conventional macroeconomic CPA models	**alternative approaches**
model structure	optimization single equilibrium	simulation / statistical multiple / out of equilibrium
agents	representative perfect foresight	many, heterogeneous expectations
resolution	top-down	bottom-up
technical change	exogenous	endogenous / induced
nature	implicit	explicitly valued
finance	intermediary	explicit

climate change mitigation beyond avoiding climate change, understanding fundamental assumptions underlying model results is crucial to the aim of this paper. To this end, the remainder of this section briefly describes basic structures of commonly used model types.

Most economic models used for climate policy analysis are grounded in the framework of general equilibrium theory. Despite wide criticisms, voiced especially since the financial crisis, no other approach has as yet been able to replace this overarching paradigm in economics (see, e.g. Krugman 2014). Therefore, our analysis considers this approach as a starting point and focuses on model elements and mechanisms that go beyond conventional climate policy analysis modelling practice. For detail on underlying economic theories, see Bowen and Fankhauser (2011); Scrieciu et al (2013).

Basic ideas in general equilibrium economics are that rational agents, in particular, households and firms, maximize utility, respectively profits. They take prices as given. Prices adjust to balance supply and demand, so that equilibrium is reached, that is, all markets clear. These ideas are formalized in the mathematical theory of general equilibrium as developed by Arrow and Debreu in the 1950ies. The theory shows that under certain mathematical conditions economic equilibria exist, and that these are Pareto optimal, that is, no agent in the system can be made better off while all others stay at least at the same level. The theory also shows that equilibria are generally not unique, and none of the possible equilibria is predetermined to prevail in a given economic system. In fact, the theory does not provide mechanisms for the dynamics of economic systems, or for equilibrium selection. A system of equations is solved, simultaneously, to find those prices at which equilibrium obtains, together with the respective quantities. The commonly told story of the auctioneer who reduces prices of goods for which there is excess supply and increases those of goods with excess demand until equilibrium is reached does not actually translate into price dynamics for the formal system, that, starting out from a given state would lead the system into equilibrium. Many mechanisms for price dynamics have been studied, but none has been found that would work reasonably well for a reasonably large class of economic systems (see Saari 1995).

Two types of computational models that are very prominent in climate policy analysis are based on these ideas: computable general equilibrium (CGE) and optimal growth models (see, e.g. Bowen et al 2014). The focus of optimal growth models is the allocation of a produced good in each time step (where often an infinite time horizon is considered) between consumption and investment in such a way that a representative household's lifetime utility – defined as an (infinite) sum of the discounted utilities derived from consumption at each time step – is maximized. CGE models add an optimization for the allocation of resources to different sectors using input-output tables at each time step to a similar intertemporal optimization structure for capital. Both model types use representative agents, an assumption which reduces the number of possible equilibria to a single one in the general equilibrium framework (for a critique of the representative agent, see Kirman 1992).

Conventional climate policy analysis models are thus located in the upper left corner in the graphical abstract on the title page of this paper: they are computational models that use an optimization approach and consider a single equilibrium.

With these models, the business-as-usual scenario is computed as an optimal trajectory of the system in the absence of climate change mitigation policy. Climate policy then enters as an additional constraint for the mitigation scenario, meaning that by construction the result can at most be as good as the BAU case. Within the given structure of the economy, provided by the single equilibrium that is being considered, the focus is on marginal changes induced by climate policy. Considering that green growth requires a structural transition of the economic system, it is not surprising that in this framework of marginal analysis, one finds mitigation costs rather than benefits, and that green growth is beyond the horizon of this modelling setup. The following section shows how going beyond it in various directions allows for the possibility of green growth.

3 Review – Green growth in economic models

In the following review, we consider theoretical and computational modelling works which find net economic benefits of mitigation. While computational models based on real-world data are used to assess policies, and a possibility of economic benefits from certain policy measures would have to be assessed using such an applied model for a certain area of the world at a certain point in time, we are also interested in theoretical models here, as computational models are based on given theoretical model structures. These represent the economy using some mechanisms and leaving out others. Which mechanisms are considered may influence whether green growth is a possibility.

This review is ordered, so to say, by increasing order of "distance" from the conventional approach: Section 3.1 considers theoretical extensions to optimal growth models that bring the possibility of positive economic effects of mitigation within their horizon – remaining in the optimization and single equilibrium approach. Section 3.2 reviews a theoretical and a computational approach which consider multiple equilibria – dropping the assumption of a single equilibrium, but keeping that of an optimization approach. Finally, Section 3.3 sketches computational works that are conceptualized independently from the general equilibrium framework – relaxing both optimization and equilibrium assumptions.

3.1 Extending optimal growth models

A list of works that include environmental policies in growth models is reviewed by Withagen and Smulders (2012), with a focus on natural resource inputs and technical change. We here sketch the framework by Hallegatte et al (2011) to illustrate which type of mechanisms are captured by this type of model (Section 3.1.1), and then consider a theoretical argument according to which mitigation should lead to a Pareto improvement (Section 3.1.2). In the graphical abstract (see the title page of this paper) these models are located in the top right corner: within the general equilibrium approach, using an optimization and single-equilibrium approach, we are here looking at theoretical models. Incorporating the extensions made in these models into computational climate policy analysis models could be one way towards allowing for the consideration of economic benefits from mitigation also in computational models.

3.1.1 How environmental policy affects growth

Hallegatte et al (2011) and The World Bank (2012) elaborate different channels through which environmental policy can influence production growth in an economy. Briefly summarized, potential output is conceptualized as a function of the inputs productivity, capital, labour and the state of the environment, and actual output is defined to be a fraction of that, meaning that the economy's state is not optimal if the fraction (represented by an optimality parameter) is less than one. Suboptimality is introduced to account for market

failures or inefficiencies, resulting from knowledge spillovers, behavioural biases, coordination failures etc. (see The World Bank 2012). All elements of actual output, i.e. inputs and the optimality parameter, can be influenced by environmental policy. Categorized by which of these elements a policy influences, the authors define the "channel" through which this policy works and provide examples for all channels. An example for the productivity input is that positive effects of an improved environment on health can lead to higher labour productivity.

Examples of environmental policy increasing the optimality parameter (and thus bringing the economy closer to a state where actual and potential output are equal) are further subdivided by Hallegatte and colleagues into an efficiency effect (correcting market failures, influencing behaviours, e.g. for energy efficiency) and a stimulus effect (of particular importance in situations of economic recession). The World Bank (2012) add an innovation effect, that is considered to shift the possible production frontier upwards, meaning that the original function describing potential output is modified, yielding larger output for the same inputs. Other examples of mechanisms that can be categorized as working through one of these channels will be seen throughout the review.

The framework further extends the type of utility function commonly used (in maximisation over an infinite sum of discounted utilities as described above) to depend not only on consumption but also on the state of the environment as well as on environmental policy, and introduces stochastic components into the production and the utility function. Thus conceptualized within an optimal growth model setting, environmental (and hence climate) policy can have positive or negative effects on growth, meaning that green growth is a possibility.

3.1.2 The external effect of emissions

The description of the general equilibrium framework in Section 2 did not mention an important detail: preferences of agents are assumed to depend only on their own actions. If one agent's utility or profit is influenced by another agent's actions, this is referred to as an externality. Climate change arises from a negative externality: producers of emissions do not take into account the effect these have on later generations through climate change. Standard economic theory tells that given externalities in an economic system, market outcomes (i.e. equilibria) are not optimal (see, e.g., Mas-Colell et al 1995, Chapter 11), in particular, activities related to a negative externality are generally overprovided.

Spelling out the details of a case in which environmental policy removes inefficiencies, as pointed out by Hallegatte et al (2011), Foley (2009) finds that internalizing the external effect, e.g. by putting a price on emissions, allows for a Pareto improvement. If the current generation compensates its increased investment into mitigation by reducing conventional investment, rather than consumption, he argues, both present and future generations can be better off with mitigation.

Even within the standard economic framework, the possibility of net short-term benefits from mitigation is thus not actually excluded, leading to the question why most works do not find Pareto improvements. A set of works by Rezai et al (2012); Rezai (2011, 2010) argue that the business-as-usual scenario commonly chosen as a reference is problematic. In the BAU case, an equilibrium of the economy with an externality, agents ignore the effects of their emissions. The competitive equilibrium diverges from the optimum because social costs of emitting are not taken into account. In the optimal case, agents are aware of these costs and choose the appropriate levels of mitigation. What is usually considered as BAU in the literature is labelled a "constrained optimal path" by Rezai and colleagues: agents know about the negative consequences of their emissions, but are constrained to "no mitigation". Their only means to avoid emissions is to accumulate less capital, that will then result in less production and therefore less emissions. The choice by current generations to invest less results in the corresponding choice to consume more, meaning that compared with the mitigation scenario, consumption is higher in this scenario.

With the help of a simple optimal growth model, Rezai et al (2012) show that comparing the actual BAU case with the optimal mitigation case, a Pareto-improvement is possible, that is, the total welfare gain can be distributed in such a way that all generations benefit.

3.2 Beyond a single equilibrium

While a single equilibrium approach dominates in conventional economic modelling, considering multiple equilibria is warranted by general equilibrium theory (as sketched in Section 2); empirical data also suggest the existence of several equilibria in economic systems, as for example shown by Ormerod et al's (2009) analysis of long time series of inflation and unemployment data, which finds that the US, the UK, and the German economic system from time to time switch between a steady and a weak pattern.

If one dispenses with the assumption of a single equilibrium – moving to the second row within the representation of the general equilibrium framework in the graphical abstract: optimization, several equilibria – the BAU equilibrium need no longer be optimal by assumption. It can be a local, but need not be the global optimum among one of several equilibria. Conceptualizing the current economic situation (the BAU case) and a green growth scenario as different equilibria, as is done by the works reviewed in this section, opens room for the possibility of economic benefits from climate policy, if mitigation can shift the system to a better equilibrium. Such a shift goes beyond marginal changes and can be considered a structural transition deemed necessary for green growth in the literature, as mentioned in the Introduction.

3.2.1 Multiple equilibria based on the division of labour

A set of works on green growth by Shi and Zhang (2012); Zhang and Shi (2014); Zhang (2013, 2014) consider multiple equilibria in the form of different structures of specialisation and division of labour. The underlying framework of inframarginal analysis generalizes the conventional framework of marginal analysis that focuses on resource allocation within a single one of these structures.

Shi and Zhang (2012) label the mechanism behind transitions from one structure to another the Smith-Young growth model, with reference to Smith (1776) and Young (1928). This model predicates that technical level, economic growth and industrial structure undergo non-continuous change as the division of labour evolves. In particular, increasing transaction efficiency increases market size which implies further division of labour that then leads to productivity increases and hence decreasing prices, which in turn leads to an increase in market size.

For studying consequences of mitigation policies, Shi and Zhang (2012) present an inframarginal general equilibrium model. One consumer good is produced using labour and energy, which can be generated using a high carbon technology ("dirty" energy), with labour as an input, or a low carbon one ("clean"), with inputs labour, specialized equipment, or both. A number of identical agents who are both producers and consumers decide whether to specialize in one product, in which case the market transactions involve a transaction cost, or choose autarky. Four equilibria, representing four stages in the evolution of the division of labour, are the possible outcomes. Initially, clean energy is more costly, and, in a laissez-faire setting, it is thus not used in equilibrium, corresponding to a high carbon structure with full division of labour. As long as agents do not consider effects of emissions, no shift to clean energy use will occur. If strong mitigation policies are enacted, equalizing the after policy costs of clean and dirty energy, some agents choose to produce clean energy, resulting in a structure where clean and dirty energy coexist, however, the division of labour for producing clean energy is incomplete. Clean energy can here be considered a demonstration project. As mitigation policies become stronger, only clean energy (with partial division of labour) is retained in the equilibrium structure. Then, due to

market expansion and increasing transaction efficiency, the clean energy sector's market structure jumps to a higher level of division of labour, implying higher productivity. This low carbon structure with full division of labour is an equilibrium with greater utility than the high carbon case, meaning that emission reduction can be beneficial to the economic system. Thus, by modelling structural change to the division of labour that results from mitigation policy, the inframarginal approach can acknowledge and analyse the possibility of green growth. Zhang and Shi (2014) point consider mitigation policy "just a catalyst" while green growth is a self-fulfilling process.

3.2.2 Multiple equilibria based on expectations and investment

Similarly, the study "A New Growth Path for Europe" by Jaeger et al (2011) finds this self-fulfilling property when analysing effects of moving the EU emission reduction target by 2020 from 20% to 30% as compared to 1990 levels. It concludes that bold climate goals, ambitious growth targets, and careful expectation management can trigger an investment surge mobilized by the perspective of sustainable development. Via a virtuous cycle of feedback effects between investment into green technology, learning by doing and the expectations of investors, this can steer the European economy onto a new growth path with lower emissions but higher employment and growth, in short, a green growth path. The micro-costs for mitigation measures, such as increased energy prices due to emission trading, can be more than compensated by the macro-benefits of this path. These results are obtained using a version of the GEM-E3 model, a CGE-model commonly used to analyse European climate policy, that is enhanced for representing a different equilibrium instead of considering the effects of climate policy in the context of the BAU equilibrium.

A follow-up study (Jaeger et al 2015b) comes to the conclusion that investment-oriented climate policy presents an opportunity for Europe to overcome the economic stagnation experienced since the recent financial crisis. Providing a credible green growth perspective for Europe, it can help solve a coordination problem of investors: profits of individual investors depend on whether they correctly estimate growth perspectives for the economy. These perspectives in turn depend on the expectations of the individual investors. In the current situation in Europe with low growth rates and low investment levels, that can be described as a "bad equilibrium" (see, for example, Draghi 2012), climate policies that increase total investment via a green investment impulse can combine the long-term benefits of avoiding climate damages with the short-term benefits of moving to a better equilibrium. These results are based on outputs from several models:

- The GEM-E3 model[3], modified to explicitly represent four mechanisms that are relevant for a transition to a green growth equilibrium: learning by doing, expectations, a labour market that need not clear, and an investment impulse.
- The IMACLIM-R model[4], a CGE model which considers learning by doing and incorporates frictions into the dynamics determined by general equilibrium.
- STOEMSys, an agent-based modelling system under development[5]. Model results are preliminary, but qualitatively support the pattern found in the CGE results.

3.3 Beyond optimization

This section reviews two examples of non-optimization approaches that have been used to analyse the possibility of green growth. Without going into theoretical foundations underlying these approaches here, briefly, the behaviour of the economic system is conceptualized

[3] See Capros et al (1999).
[4] See Cassen et al (2010).
[5] See Jaeger et al (2015a).

independently from the ideas of equilibrium or optimality – hence located outside the representation of the general equilibrium framework in the graphical abstract on the title page. (Macro)econometric models (example in Section 3.3.1) use a statistical approach for describing the economic system, and simulation models represent relevant mechanisms on a computer to analyse the system behaviour based on model runs – with a focus on aggregate characteristics in system dynamics models (example in Section 3.3.2) or on the agents constituting the system in agent-based models (very briefly discussed below in Section 4).

3.3.1 Investments at negative costs and a macroeconometric model

The inherent assumption in optimization approaches – that the reference scenario achieves the economic optimum – implies the assumption that all investment opportunities with a positive return are known and realized in the optimal scenario. Hence, following this model logic, there are no untapped investment opportunities and additional investments will be made at a net cost. According to Rosen and Guenther (2015), this tends to overstate the net costs and underestimate the net benefits of achieving the necessary level of mitigation relative to where the economy actually stands.

"Bottom-up" studies, such as the abatement cost curves by McKinsey & Company (2010), claim that a considerable amount of investments into GHG emission reductions can be realized at net negative costs (i.e., net benefits). Especially energy-efficiency investments, such as for example building insulation, lighting, air-conditioning and more fuel-efficient vehicles, are reported on the net negative abatement cost side.

Such negative cost investments can then be taken into account in a macroeconomic context, with the help of Non-optimization models. An example are macroeconometric models such as the E3ME model[6]. Its key characteristics include a non-optimal starting point and a non-equilibrium demand led approach. Irrational behaviour and imperfect information may lead to the availability of negative cost investment options, while at the same time, spare capacity may be present in the economy both in the form of unproductive factors of production, and in the form of untapped sources for additional investment. In terms of Hallegatte et al's (2011) framework, this corresponds to a mechanism which increases the fraction of actual to possible output. Based on these model features, positive macroeconomic effects of mitigation measures are possible in the short term (see, e.g., European Commission 2011; Sijm et al 2013; Cambridge Econometrics 2012).

3.3.2 Natural resources and a system dynamics model

Explicit consideration of natural resources is a main model ingredient of the United Nations Environment Programme (2011) Green Economy Report (GER), which finds that a green economy can grow faster than a brown economy over time, while maintaining and restoring natural capital. It uses the Threshold21-World model[7], a system dynamics model that keeps track of both monetary and physical quantities to account for natural resource stocks. Modelling the influence that the depletion or conservation of natural resources has on the macroeconomic evolution of the system corresponds to the environment-factor in Hallegatte et al (2011)'s framework.

Exploring impacts – in terms of GDP, employment, resource intensity, emissions, and ecological impacts – of additional investments (of 1 and 2% of world GDP annually) into greening the economy compared with BAU investments, the GER finds that under the BAU pattern, natural resource depletion and high energy costs lead to falling long-term growth rates, whereas natural resource use is decoupled from economic growth for the green scenarios.

Investments take effect via different mechanisms in different sectors: while in the primary sectors (agriculture, fishing, forests, and water) investments into natural capital are directed

[6] See http://www.e3me.com, and Cambridge Econometrics (2014).
[7] See http://www.millennium-institute.org/integrated_planning/tools/T21/

towards restoring and maintaining ecosystem services as well as making management more sustainable and equitable, for secondary sectors such as energy, transport, and manufacturing, investments target opportunities for saving energy and resources, relating back to the topic of efficiency in Section 3.3.1. As Hallegatte et al (2011), the Green Economy Report points out that environmental policies can drive inefficiencies out of the economy, for example when firms which exist only due to implicit subsidies in under-priced resources are removed. It further lists mechanisms through which (natural) resource pricing can provide an economic advantage (see UNEP, 2011, p. 22-23): efforts and expenditures are allocated according to relative prices, but relative prices are distorted when natural resources are not priced; and resource pricing drives investments into R&D and innovation, in particular for resource efficient production methods, and these investments may then generate innovation rents.

4 Conclusions – Towards economic models for analysing green growth

Models which can represent win-win options for climate and the economy are still rare in the literature, and simulation results that find economic benefits of mitigation are largely published in reports rather than scientific journal articles. The few models found, however, show a large spectrum of "distances" from conventional climate policy analysis modelling practice: from theoretical model extensions within the standard setting to models conceptualised independently from the general equilibrium framework. In particular, computational models, applied for policy analysis using real-world data, show a larger distance from the standard approach.

The review indicates three possible approaches for building macroeconomic policy analysis models applicable to studying green growth – again listed in the same order as in the previous section.

First, including theoretical results, from the extension of theoretical models as observed in Section 3.1, into conventional applied (that is, computational) models, is an approach close to the standard modelling setup. An example is technical progress: The literature points out that estimated mitigation costs decrease from exogenous to endogenous technical change in models, and further if technical change is conceptualized as induced by mitigation policy (see Rosen and Guenther 2015; Scrieciu et al 2013, and references therein). Technical change involves a positive externality: due to spillover effects, benefits of R&D do not only accrue to its providers, in other words, its social benefit is not taken into consideration, meaning that market outcomes generally underprovide this activity. Addressing this externality, Acemoglu et al (2012) show that directed technical change with "brown" and "green" activities offers a stable "green" growth path as an alternative to the present growth pattern. While the authors find costs of mitigation for a transition phase, directed technical change seems to be a direction for further research into a possibility of "abatement benefits".

Second, within a general equilibrium view but outside the standard marginal modelling approach that considers a single equilibrium, the current economic situation and one of green growth can be conceptualized as two different equilibria (as seen in Section 3.2). When analysing the possibility of a transition from one to the other equilibrium, the discontinuous jumps of the model by Shi and Zhang (2012) need to be filled in with real-world mechanisms. Considering the mechanism suggested by Jaeger et al (2011)'s virtuous circle of expectations, investment, learning-by-doing and growth, further research into expectation and convention dynamics is of interest for studying the possibility of a re-coordination of agents' (and in particular investors') expectations from the current to a green growth path. For example, self-fulfilling dynamics arising from feedbacks between agents' expectations and how these can be modelled within a macroeconomic setting, deserve further research.

Third, computational models outside the general equilibrium framework present an opportunity to analyse a possibility of green growth; examples were seen in Section 3.3. As an outlook, agent-based models (ABMs) are another simulation model approach that has been considered useful in the climate change context (see, e.g. Moss et al 2001; Giupponi et al 2013), however, no macroeconomic agent-based model reporting mitigation benefits was found for inclusion in the review. Examples of ABMs in the climate change context exist in particular at sectoral level: e.g., electricity (Reeg et al 2013; Chappin and Dijkema 2010) and emissions trading (Zhang et al 2011). A macroeconomic ABM presented by Janssen and de Fries (1998) models agents with different worldviews in combination with a standard representation of the economy and the effects of emissions on the climate system; while the paper shows the importance of agents adapting their worldview to what they observe, it corroborates the general idea that mitigation leads to less economic output. Macroeconomic ABMs for analysing green growth strategies seem to require further work[8], be it because agent-based modelling in economics is a relatively young endeavour, because the modellers' freedom which agents to represent and how[9] makes it less clear how to relate ABMs to economic data from national statistics etc., or simply because there is, as yet, no common practice for building and documenting economic ABMs (see, e.g. Wolf et al 2013).

While many further elements, such as the labour market or climate finance, could be discussed as relevant to models for analysing the possibility of a transition to green growth, this paper will here conclude by summarizing the main points. Green growth has appeared on various policy agendas, and, as it combines a solution to the problem of climate change with positive economic effects, it deserves to be carefully researched in the climate policy analysis context. Important tools in climate policy analysis, macroeconomic models for assessing the effects of different policies, are largely not up to this task: the conventional modelling approach excludes, by construction, the possibility of (short term) economic benefits from climate change mitigation, and thus also the possibility of green growth. In essence, this inadequacy can be traced to the fundamental assumption of a single, optimal equilibrium of the economy: climate policy, then introduced as an extra constraint, cannot improve the business as usual situation. A survey of works which find positive economic effects of climate policy – focusing on model structures used in these works and relating these to the underlying structure of the standard modelling setup – has pointed out extensions of conventional models, modelling structural transitions between multiple equilibria in economic systems, and modelling outside the general equilibrium framework as possible directions for such research in the future.

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[8] Some such work is in progress: see, e.g., the Symphony project (http://projectsymphony.eu/) and Jaeger et al (2015a).

[9] In particular, agents need not be omniscient optimizers of utility (see Table 1), but may be equipped with many kinds of decision rules.

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