COMPLEX Final Scientific Report, Volume 2
Non-linearities and System-Flips

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COMPLEX
Knowledge Based Climate Mitigation Systems for a Low Carbon Economy

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9. Coupled Environment-Ecology Modelling

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In various disciplines regime shifts (Folke 2006; Biggs *et al.*, 2009; Carpenter *et al.*, 2011), critical transitions (Scheffer, 2009), non-marginal changes (Stern, 2008) are the terms, which are used to denote an abrupt structural change (Andersen *et al.*, 2009). Such a non-linear systemic change may occur either due to a incremental change in some underlying variable(s) which gradually crosses a threshold, due to an external shocking event, or due to a combination of the two. While understanding of the nature of non-linear abrupt changes is essential for the proper estimate of cost and benefits of various policy actions, especially in the domain of climate change mitigation where impacts are intergenerational, the quantitative modelling of regime shifts in coupled CEE system is challenging. The literature on modelling coupled human-environment systems experiencing such non-linear dynamics identifies several critical issues (Filatova & Polhill, 2012; Schlueter *et al.*, 2012). They require a careful consideration when designing a software model, which is able to endogenously grow or capture non-linear responses of one of the subsystems or of a coupled system. On a model design stage it is vital to consider:

- the sources of regime shifts (endogenous or exogenous, originating in natural or social system, from a gradual change or a shocking event),

- the type of feedbacks between human and environmental systems (which could either amplify or absorb non-linear dynamics),
- methods for detecting and characterizing non-marginal change, a regime shift, and
- complexity aspects (thresholds, non-linearities and scales, including temporal scales to show if a phenomena is reversible or not).

The latter group is particularly relevant for this report. In what follows we review how various modelling approaches, which are most commonly used to design CEE models, treat the issues of non-linearity, thresholds and irreversibility. In particular, we look at Integrated Assessment Models (IAMs) including General Equilibrium Models, System Dynamics Models (SDs) and Agent-Based Models (ABMs).

Modelling non-linearities

Non-linear responses are strongly related with the feedbacks included in the modelling[2]; ultimately, all dynamics arise from the interaction of just two types of feedback loops, reinforcing (or positive) and balancing (or negative) loops. Among the high-resolution IA models the dominant approach has been the sequential (linear) representation from socioeconomic inputs to emission and climate impacts *without* considering feedbacks (Damage Function) to the "Human Activities" or "Ecosystem" modules (see Figure). In these models (e.g. MiniCAM/GCAM, POLES, MESSAGE)

[2] In welfare optimization models, the inclusion of non-linearities is in close relationship with the discount rate used.

feedbacks are usually restricted to the "Human Activities" module.

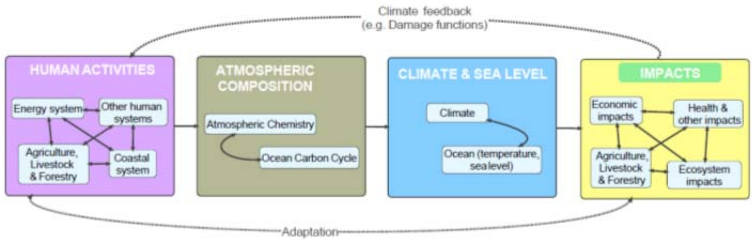

Figure 9.1: *Sequential characterization of IAMs.*

However, damage functions are implemented in some high-aggregated models such as DICE, FUND, PAGE, MERGE, etc. Damage functions have the form of non-linear equations mostly based on damage estimates related to doubling the CO_2 concentration from the pre-industrial level that are usually below the 2% of global GDP. The uncertainty on the damage functions currently used in IA models is extremely high (Arigoni & Markandya, 2009) and subject to concerns such as the degree of arbitrariness in the choice of parameters or the functional form which limit models' ability to portray discontinuities (Ackerman *et al.*, 2009; Pindyck, 2013; Stanton *et al.*, 2009; Stern, 2013).

Some models distinguish between economic impacts and non-economic impacts; only the former are included directly in the GDP (e.g. FUND, PAGE-09). However, many valuable goods and services (e.g. human health effects, losses of ecosystems and species) are not included in conventional national income, which suggests that usual damage functions may underestimate the damage costs of climate change. As an example, DICE, and a majority of its descendants, assumes that the exponent in the damage function is 2 –that is, damages are a quadratic function of temperature change: no damages exist at 0 ºC temperature increase, and damages equal to 1.8% of gross world output at 2.5 ºC (Nordhaus & Boyer, 2000; Nordhaus, 2008) (Figure). On the contrary, (Stanton et al., 2009) review of the literature uncovered no rationale, whether empirical or theoretical, for adopting a quadratic form for the damage function.[3] This is a key issue in IAM, since the results are significantly sensitive to this parameter (Dietz *et al.*, 2007; Roughgarden & Schneider, 1999).

Feedbacks to the socioeconomic variables are not considered by IA models. For example, large scale population movement with likely associate conflict could happen at high levels of climate impact, being surely unreasonable to assume that we can be confident that this scale will be very small and invalidating, for example, the regional population exogenous projections (Stern, 2013).

Also, very few models explicitly assess the relationships between climate and ecosystem services, although modelers and policy makers have recognized that climate change problems have to be solved in harmony with other policy objectives such as economic development or environmental

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[3] *This practice is endemic in IA models, especially in those that optimize welfare (e.g. DICE-family, MERGE, WITCH but also from other disciplines such as System Dynamics: ANEMI)PAGE2009 (Hope, 2011) uses a damage function calibrated to match DICE, but makes the exponent an uncertain (Monte Carlo) parameter.*

conservation (e.g., nonlinear impacts of temperature on crop yields (e.g. (Rosenzweig *et al.*, 2013)).[4] In this sense, IMAGE and AIM can be considered among the most prominent models incorporating ecosystems services. These modes display a great spatial resolution in their ecosystem modules and have participated in all the IPCC Assessments and in the Millennium Ecosystem Assessment (MEA, 2005). In the case of IMAGE 2.4 (Bouwman *et al.*, 2006), it includes the Nitrogen cycle and a Biodiversity module as well as changes in climate (precipitation and temperature) impacting crop and grass yields. Also, the Carbon cycle model includes different climate feedback processes that modify Net Primary Productivity (NPP) and soil decomposition (and thus NEP) in each grid cell (0.5 by 0.5 degree resolution).[5] However, even in these models climate feedbacks to ecosystem services have a partial scope, they do not consider explicitly fundamental impact feedbacks related with the albedo-effect, the increase in climate extremes or sea-rise impact in coastal zones.

System dynamic models represent real-world applications of the formal mathematical theory of nonlinear dynamic systems, and thus, by definition, are designed to represent non-linearities. Coupled climate–socioeconomic system dy-

[4] For an overview of IAM shortcomings in this field see (Calvin et al., 2013).

[5] *Also, the IIASA Integrated Assessment Modeling Framework (including MESSAGE-MACRO model) includes some feedbacks in terms of changes in agricultural production (Tubiello and Fischer, 2007) or in the corresponding changing water needs for agricultural production (Fischer et al., 2007).*

namics models applied to the study of the economics of climate change include numerous non-linearities both in the economic modules (e.g. economic crises, bubbles on asset markets etc.) and in the climate modules (e.g. abrupt climate change). As example, a simple climate-socioeconomic system dynamic model by Kellie-Smith and Cox (2011) integrated for a very long term (from year 2000 to year 3000) generated under certain scenarios pronounced persistent low-frequency nonlinear oscillations of climate and macroeconomic variables.

Some system dynamic modelling studies suggest that the pronounced non-linearity of the real-word climate system (and supposedly even more pronounced non-linearity of real-world socioeconomic system) could surprisingly be beneficial for global mitigation policies. For instance, simulations with actor-based system-dynamic model MADIAM (Weber *et al.*, 2005) revealed a strong non-linearity of the model towards properly designed mitigation strategies: revenues from a moderate carbon tax, when re-circulated into the economy in the form of investments in endogenous carbon and energy efficiency improvement, had a more than linear impact in slowing down the global warming and accelerating the transition to a sustainable economy.

ABMs are designed to model complex adaptive systems evolving along a non-linear path. Due to their technical ability to be implemented on a variety of spatial and temporal scales, they are naturally sited to be coupled with natural science models. In application to economics is it often realized either through technology diffusion on the supply side of a market or behavioural change on the demand side. Thus, ABMs have a high potential to simulate non-linear dynamics and responses in coupled CEE systems. Yet, it is not suited to model climatic systems, thus only non-linear response in socio-economic systems and energy markets can be considered. Abrupt shifts in climatic systems as a results of dynamics in energy and economy systems are never modelled with ABM.

While in other domains both technology diffusion and behavioural change have been studied, the applications of ABM to energy or climate mitigation, which also demonstrate non-linear response, are at their initial stage of development. A recent review of energy ABMs (Gerst *et al.*, 2013) concludes that existing models can be divided into 4 groups: (1) ABMs focusing on technology diffusion in a single market with little or no feedback to macro-economy, (2) ABMs having a broader focus on the electricity market or overall energy use with little or no macroeconomic feedback, (3) ABMs of entire macro-economy of a country or the world at the costs of omitting technological detail and household behaviour, (4) ABMs modelling interactions among countries with little or no feedback between domestic actors and international policy. While all ABMs have some sort of non-linear functions or rule-based behavior on micro-level, here we focus on non-linear macro-dynamics of the emergent phenomena.

The ENGAGE ABM by Gerst and colleagues (2013) is the most developed ABM of CEE system to date, which also tries to connect across the 4 level of energy ABMs mentioned above. ENGAGE simulates heterogeneous firms and households while having an evolutionary representation of economic growth, energy technology, and international negotiations regarding climate change. It goes beyond conventional economic assumptions of many IAMs and CGE models such as homogenous households and firms, perfect information and are perfect rationality. Yet, it still represents an economy in a stylized manner (firms cover only two sectors – producers of capital and consumer goods). Households and firms are connected via labor and commodity and services markets. Energy enters as a cost factor in the production of goods and machines and is also consumed by households. Energy supply is represented by three energy technology firms ('carbon-heavy', 'carbon-light', and 'carbon-free') and one energy production firm. On the energy demand side households use a certain floor space and a certain number of appliances and cars, while good-producing firms use energy to run machinery, which can be replaced when its lifecycle is over. ENGAGE is applied to study the effect of domestic actors energy-related behavior on international and domestic climate policies, including carbon tax. Simulated energy technology market shares and energy intensity (ratio of annual energy use to real GDP) trajectories exhibit abrupt shifts. Emergent average household energy consumption and CO2 emissions also follow non-linear trends. This happens due to endogenous energy technology evolution, and is highly influenced by a policy scenario. For example, only when carbon tax is used as an investment in carbon-free R&D, economy a swift transition away from carbon-based-energy technologies. In this case low-carbon-energy fuels exponential economic growth by the end of the 21st century.

Chappin and Dijkema (2007) design an ABM of a decentralized System of Electricity Production Systems (SoEPS) in the Netherlands to explore the impact of CO_2 emission trading (CET) to in reducing CO_2 emissions. Their ABM shows that the impact of CET is small and visible only in a long time. However, authors admit that technological innovation among electricity producers, which is one of the crucial elements driving GHG emission reduction in the presence of CET, was not included in the model. Thus, this ABM is able to model only long-history of incremental innovation leading just to a smooth change. If diffusion of new technologies is implemented, this would imply a dramatic non-linear shift from fossil-fuel-based electricity production.

Castesana and Puliafito (2013) propose an ABM of endogenous economic growth studying the influence of population dynamics and growth of physical capital consumption on energy use and CO_2 emissions. This one-sector model operates on a global level and is partially parameterized with empirical data. A population of heterogeneous individuals goes through various life-stages potentially deciding to invest in human capital (education and development of technologies) that correspond to the investments in R&D at macro level. Agents make choices regarding their reproductive, economic and energy development driven by personal preferences and family influence. The trajectories of energy consumption and corresponding CO_2 emissions do not have linear correlation with smooth curves of population and GDP growth. The latter follow more volatile dynamic paths due to the fact that increase in energy consumption is partially offset by the improvements in technology. Moreover, authors highlight that agent-level factors may speed up or slow down a certain trajectories of energy use and CO_2 emissions, potentially amplifying non-linearities. In general a likely pathway towards a drop in anthropogenic carbon emissions is to encourage investments in human capital through education and low-carbon technologies.

Chappin and Afman (2013) developed an ABM of a consumer behaviour regarding purchase of lamps. Their paper explores the nature and speed of possible transitions to low-electricity consumer lighting. This ABM explicitly model behavioral change on the demand side by assuming heterogeneous and dynamic preferences on lamps, which change with experience and through interactions via social network. As a result this ABM goes beyond simulating linear paths and is able to grow abrupt shifts to a non-conventional lightening technology under various policy scenarios. Authors highlight that complex market dynamics emerges as a result of interactions among consumers and bulb manufacturers, opinion exchange among consumers, and interactions between technologies. Non-linear transitions may not occur under specific assumptions about agents' heterogeneity and dynamics of individual perceptions.

Jackson (2010) designed an ABM to quantitatively evaluate electric utility energy efficiency and smart-grid programs. A forecast of annual electricity use and peak residential load over 15 years was simulated under an assumption of a residential customer growth rate of 1.2%. The results of a 'frozen' scenario (when equipment efficiencies and its utilization remain constant) show non-linear changes in annual electricity use (2.3% increase), while peak residential load changed almost linearly (1.3% increase). In contrast the 'baseline' scenario (smart grid 20% participation scenario) forecasts annual energy increases of 1.6% and annual peak load increases of 0.6%. In the 'smart grid 50% participation' scenario the peak annual growth is reduced to 0.2%. These non-linear response of the energy market driven by disaggregating the demand function into individual interacting consumers, which can be influenced by other agents leading to the dissemination of information on new technologies and utility programs. These complex dynamic is likely to be omitted when a traditional aggregated customer is used on the demand side.

The CITA ABM developed by Bravo and colleagues (Bravo *et al.*, 2013) explores the relationships between household consumption (of food, transportation and energy) and the related GHG emissions under carbon tax and information campaign policies. CITA explores the behavioural change towards green alternatives or absence of such due to self-reinforcement and social influence, where heterogeneous preferences of agents for 3 domains are parameterized using Eurobarometer data. The effect of price policies on GHG emission reduction is moderate in the domains of transport and energy (3% and 5% respectively) and only in the food domain the effect is a non-linear significant reduction in the adoption of the brown leading to 17% GHG emission reduction. However, the policies aimed at behavioural change (changes in households preferences) lead to abrupt structural changes in emission reduction: in the transport domain declined by 15%, in the energy domain by 24%.

Modelling thresholds

Stanton *et al.* (2009) in an IAM review finds that in only a few models damages are treated as discontinuous, with temperature thresholds at which damages show a major shift from lower temperatures. For example, DICE-2007 (Nordhaus, 2008) models catastrophe in the form of a specified (moderately large) loss of income, which is multiplied by a probability of occurrence (an increasing function of temperature), to produce an expected value of catastrophic losses. This expected value is combined with estimates of non-catastrophic losses to create the DICE damage function (i.e. it is included in the quadratic damage function discussed above). However, for much of Nordhaus's work using the DICE model the loss via the Damage Function at 5°C is *only* in the region of 5–10 percent GDP (see **Error! Reference source not found.**.2). In much of Tol's work (see e.g. (Dietz *et al.*, 2007)) on the FUND model damages at 5°C are still lower, around 1–2 percent of GDP (**Error! Reference source not found.**.2).

In the PAGE-2009 model (Hope, 2011), the probability of a catastrophe increases as temperature rises above a specified temperature threshold (3 ºC above pre-industrial levels). For every 1°C rise in temperature beyond this, the chance of a large-scale discontinuity occurring rises by 20%, so that with modal values it is 20% if the temperature is 4°C above pre-industrial levels, 40% at 5°C, and so on. The threshold at which catastrophe first becomes possible, the rate at which the probability increases as temperature rises above the threshold, and the magnitude of the catastrophe when it occurs, are all Monte Carlo parameters with ranges of possible values. PAGE-2009 assumes that only one discontinuity occurs, and if it occurs it is permanent, aggregating long-

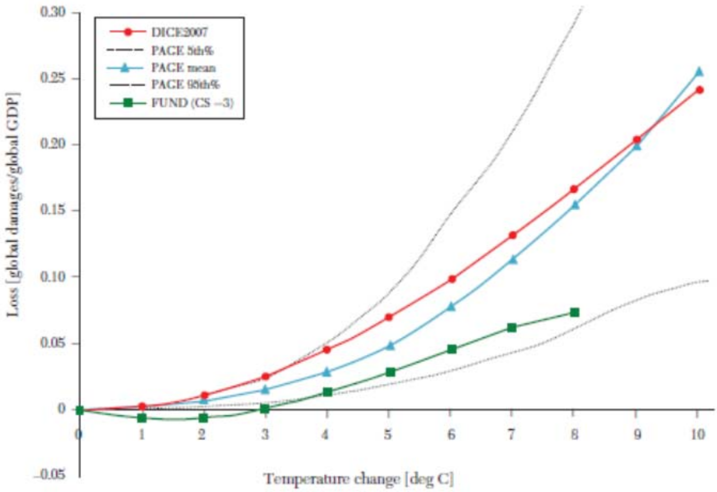

Figure 1.2. *Annual Consumption Loss as a Fraction of Global GDP 2100 due to an increase in annual global temperature in the DICE, FUND and PAGE models. Source: (Stern, 2013)*

term discontinuities, as ice-sheets loss, with short-term ones, such as monsoon disruption and thermohaline circulation. In fact, Nicholas Stern selected this model (PAGE-2002 version) for his Review “guided by our desire to analyse risks explicitly - this is one of the very few models that would allow that exercise” (Stern, 2007). However, still, climate feedbacks are poorly represented in this model in particular[6] and in climate IAMs in general (Whiteman *et al.*, 2013).

However, as stated by (Stern, 2013) "*most reasonable modelers will accept that at higher temperatures the models go beyond their useful limits; Nordhaus suggests that we have insufficient evidence to extrapolate reliably beyond 3°C*". Since the climate science states that there are major risks of temperatures well above 3°C, the main concern thus lies in the incorrect extrapolation of these damage functions (Pindyck, 2013; Stanton *et al.*, 2009; Stern, 2007). To illustrate this, whilst recognizing the wise cautionary advice of Nordhaus on making such extrapolations, (Ackerman *et al.*, 2010) show that in a standard model, such as DICE-2007, temperature increases of up to 19°C might involve a loss in output of only 50 percent, against a baseline where the world is assumed to be many times richer by 2100. This illustrates both the modest nature of damages and the perils of such extrapolation since such temperatures could even involve complete human extinction, indeed at much lower temperatures than that.

The key point is the exogeneity of a key driver of growth combined with weak damages. With exogenous growth that is fairly high (say at 1 percent or more over a century or more) and modest damages, future generations are more or less assumed to be much better off (Fig. 9.3). Exogenous growth of any long-term strength is challenged in the face of the scale of the disruption that could arise at these higher temperatures (e.g. potential large scale destruction of capital

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[6] Better models are needed to incorporate feedbacks that are not included in PAGE09, such as linking the extent of Arctic ice to increases in Arctic mean temperature, global sea-level rise and ocean acidification," (Whiteman et al., 2013)

and infrastructure, mass migration, conflict) (Pindyck, 2013; Stern, 2013).

Growth rate	With output loss				
	Yr 100	5%	10%	20%	50%
1%	270	256 (14)	243 (27)	216 (54)	135 (135)
2%	724	688 (36)	652 (72)	579 (145)	362 (362)
3%	1,922	1,826 (96)	1,730 (192)	1,538 (384)	961 (961)

Note: Table entries are output levels and losses are in parentheses (output in time zero = 100).

Figure 9.3. *Output after a Century relative to now (base value = 100). Source: (Stern, 2013)*

Some researchers have responded to the apparent absurdities of such weak damage functions by invoking higher order terms (see (Weitzman, 2012)), but the models still appear to suffer from the omission of the scale of damage that could arise from catastrophes, mass migration and serious conflict, most retain exogenous drivers of growth, and most have inherently narrow risk descriptions (Stern, 2013).

Coupled climate-economic models

There is relatively little discussion of threshold effects in the literature on coupled climate-economic models. Below we provide two interesting exceptions.

An interesting example is provided by Kellie-Smith and Cox (2011) for a highly stylized system dynamics model of a coupled global climate–socioeconomic system. With exogenous decarbonisation of the economy built into the model equations, projections of coupled climate-economic dynamics are computed for the 21st and 22nd century for two background economic growth rates: low (1% per year) and high (4% per year). For the low background economic growth rate, the global development is sustainable (a regime of "soft landing" at an equilibrium where the economy steadily grows at the decarbonisation rate). In contrast, for the high background economic growth rate, the global economy initially booms, but this is followed by an economic crash, and the resulting depression lasts for the entire 22nd century.

Another example of a threshold effect is the bifurcation of GDP losses caused by extreme weather and climate events simulated with the NEDyM model (Hallegatte *et al.*, 2007): GDP losses increase sharply beyond a certain threshold value of the intensity and frequency of extremes.

In the *ABM literature* in CEE domain thresholds are usually mentioned only with respect to the dynamics of socio-economic system and sometimes possible CO_2 emissions trajectories. Since ABMs are not directly used to model climatic systems (e.g. 2 degree Celsius threshold), there are no climate system thresholds considered directly. However, the latter may be used as a target for tested low-carbon policies entering ABM dynamics indirectly. The ABM examples below concern thresholds in energy-economy systems only.

The ABM of Chappin and Afman (2013) is driven by evolving preferences regarding low-cost electricity lams due to personal experiences and exchange of opinions with a social network. Yet, while agent's perceptions evolve incrementally over time, the dramatic shift in market shares occur when an endogenous threshold value of adopters is reached. Changes in consumer preferences can be amplified or suppressed by changes in individual cost-effectiveness moving towards certain threshold values, e.g. when a decrease in electricity costs outweighs a jump in lamp purchasing costs.

When studying CEE system dynamics with their ABM Gerst and colleagues (2013) admit that the effect of the carbon tax on machine and goods consumptions, and consequently large-scale technological change, is dependent on how tax revenue is invested. While there is a linear relationship between firms' R&D activity and economy-wide annual growth rates, the dynamic paths of market shares of various energy technologies under some policies (e.g. investing carbon tax into R&D) pass through certain threshold values. Various thresholds are also seen in aggregated energy intensities, which peak around year 2020. This is associated with lifecycle of machinery (20 years) and the fact that carbon tax is not high enough to trigger premature machine replacement.

Micro-level agent behaviour is sometimes designed to exhibit thresholds. For example the CITA ABM assumes that consumer agents have two exogenously defined thresholds for need satisfaction and uncertainty (which impacts the forecasting ability regarding the consequences of agents' choices) with respect to food, transportation and energy consumption (Bravo *et al.*, 2013). The threshold values were calibrated to match the empirical consumption trends. However, we are mainly interested in the thresholds in the response variables, i.e. macro-level dynamics. Such thresholds appear in the results of the CITA model under the scenario with households preferences change modeled as an information campaign to agents with low environmental preferences. Specifically, when the intensity of a policy reaches a certain value ($\sigma_3 > 0.5$) the brown consumption pattern disappears in all domains (food, transportation and energy use).

Modelling irreversibility

One of the most controversial conclusions to emerge from many of the first generation of *climate IAMs* was the perceived economic optimality of negligible near-term abatement of greenhouse gases. Typically, such studies were conducted using smoothly varying climate change scenarios or impact responses. Abrupt changes observed in the climatic record and documented in current models could substantially alter the stringency of economically optimal policies derived from IAMs. Such abrupt climatic changes—or consequent impacts—would be less foreseeable and provide less time to adapt, and thus would have far greater economic or environmental impacts than gradual warming (Mastrandrea & Schneider, 2001).

Despite critical uncertainties in the assessment of relationships such as climate sensitivity or damage functions (e.g. (Pindyck, 2013; Stern, 2013)), for the most part, IAMs adopt best guesses about likely outcomes (Ackerman *et al.*, 2009; Kelly & Kolstad, 1998; Lomborg, 2010; Nordhaus, 2007; Tol, 2002; Webster *et al.*, 2012). IPCC's focus in this issue has also being decisive: most visibly attention has been given to the communication of uncertainties by the natural scientists in the areas of climate science and impacts, and to a lesser extent, or at least very differently, by economic models and social scientists in the assessment of vulnerability, sources of greenhouse gas emissions, and adaptation and mitigation options (Pindyck, 2013; Stern, 2013; Swart *et al.*, 2009).

Uncertainty, if incorporated at all, is usually analysed by running Monte Carlo simulations in which probability distributions are attached to one or more parameters. For example, the *Stern Review* (Stern, 2007), using the model PAGE-02, represents a step forward over the standard practice in this respect, employing a Monte Carlo analysis to estimate the effects of uncertainty in many climate parameters. As a result, the *Stern Review* finds a substantially greater benefit from mitigation than if it had simply used "best guesses".[7] Another recent applications are (Webster *et al*., 2012) with MIT-IGSM or (Cai *et al*., 2013), who developed a stochastic dynamic programming version of the DICE model. But these are rather exceptions: (Stanton *et al*., 2009) review did not identify any model assuming fat-tailed distributions that reliably samples the low probability tails, thus failing into providing an adequate representation of worst case extreme outcomes.

The probabilities of eventual warming of 4°C or more, on current emissions paths, may be of the order of 20–60% (e.g., (Rogelj et al., 2012; WEO, 2012)); thus, if the damage functions are not included or calibrated to temperature increase until approximately 3 ºC (altogether with the common use of likely values instead of risk assessment), there is a wide range of possibilities currently outside the scope of the models. Therefore, it can be concluded that risk is understated in IAMs and models largely ignore the possibility of a

[7] Stern Review found that "without action, the overall costs of climate change will be equivalent to losing at least 5% of global gross domestic product (GDP) each year, now and forever." Including a wider range of risks and impacts could increase this to 20% of GDP or more, also indefinitely.

catastrophic climate outcome (Ackerman *et al.*, 2009; Pindyck, 2013; Stanton *et al.*, 2009; Stern, 2013). (Lenton & Ciscar, 2013) review the limitations of the models and state that there is a "…huge gulf between natural scientists' understanding of climate thresholds or tipping points and economists' representations of climate catastrophes in IAMs." (Stern, 2013) summarizes: "the economic models add further underassessment of risk on top of the underassessment embodied in the science models, in particular because they generally assume exogenous drivers of growth, only modest damages from climate change and narrow distributions of risk".

The problem of abrupt/irreversible climate change is has not been widely addressed in the existing literature on *climate-economic SD models*. Indeed, up to now most modeling exercises based on climate modules able to represent abrupt/irreversible climate dynamics or including discontinuous climate damage functions, have been performed within the utility maximization paradigm – a conventional wisdom of neoclassical economic growth theory. However, both of these climate modeling forms can be straightforwardly adopted in SD models. An interesting research agenda would therefore be to develop such system dynamic versions of traditional climate-socioeconomic models rooted in the utility maximization paradigm. These should then be able to provide a more realistic description of the impacts of abrupt/irreversible climate change and its interaction with the non-linear socio-economic system.

The problem of possible irreversible global change was originally addressed using system-dynamic modelling in the neighbouring area of environmental and resource economics. An example that received extremely high visibility (and at the same time was severely criticized by many mainstream economists) is the "Limits to Growth" report and its follow-ups (Meadows et al., 1972, 1992, 2002). The authors argued, on the basis of simulations with the SD model World3, that maintaining the exponential growth of population, capital, resource use and pollution on a finite planet is unsustainable and will inevitably lead to an irreversible catastrophe, unless the timely correction measures are implemented at the global level.

Many *ABMs* are characterized lock-in effects and strong path-dependency. Therefore the sequence of previous states constraint future states, and even gradual changes in behavior or technology may lead to irreversible changes in energy-economy system. As before irreversibility in climate systems is hardly ever considered in ABMs as they are not the best tools to simulate climatic systems.

The ABM of the carbon emission trading impact on shifting from carbon-intensive electricity production (Chappin & Dijkema, 2007) suggests that as soon as investments in new technology are made, the switch from the old technology is irreversible. Various scenarios produced by the ENGAGE ABM by Gerst and colleagues (2013) all produce irreversible transitions to low-carbon economy. While depending on a policy, the transition can be swift or more gradual, the return back to carbon-intensive economy is unforeseeable.

The ABM of transition to low-electricity lightening (Chappin & Afman, 2013) produces non-linear paths under various policies (banning, tax, subsidy). While this market system moves along transition pathways, this transition is irreversible. The shift to low-electricity lamps happen when either it becomes cost-efficient for consumers or when their dynamics preferences reach a certain level. There is no reverse dynamics modelled, also probably since it is unrealistic.

Discussions and conclusions

Occasionally, dramatic shifts occur in natural system as well social and economic systems. As reviewed in this report, the literature on critical transition theory suggests that such shifts can be associated to the existence of alternative stable state, thresholds and hysteresis in the system. For the management of such system and more specifically for the climate mitigation policies and measures, it implies a radically different view on policy options, and on the potential effects of global change on such systems. For instance, although the gradual changes in temperature might show little and proportional impact, once a threshold is reached and a flip occurred the large impact might be difficult or even impossible to reverse. Examples are the collapse of an overharvested population, ancient climatic transitions, and the collapse of Saharan vegetation. The critical transition in such systems can ultimately derive from how it is organized — and usually from feedback mechanisms, stabilizing or distabilising, within it.

In climate system, the critical transition is usually associated to the destabilising (positive) and stabilising (negative) feedbacks. For example, Rial *et al.* (2004)) proposes a metaphor of a net feedback. According to this metaphor, in unperturbed conditions the net negative climate-driving feedback of the Earth is slightly stronger than the net positive feedback, at least for small values of external/internal forcing.

However if the forcing grows beyond the point at which the two competing feedbacks are balanced, then the explosive amplification produced by positive feedbacks leads to strong nonlinear effects. Even below this critical threshold, the negative impacts of human induced climate change can become so strong at some critical adaptation threshold that societies are no longer able to respond to the climate change impacts at an acceptable cost. Thus mitigation policies should be implemented such that this critical adaptation threshold is not exceeded.

Predicting such critical thresholds in a system and occurrence of catastrophic shift before they are reached is extremely difficult as the state of the system may show little change before the bifurcation points. However, recent attempts to assess whether alternative stable states and hence critical transitions are present in a system are now converging in different fields such as desertification, limnology, oceanography and climatology. These studies are now suggesting the existence of generic early-warning signals that may indicate for a wide class of systems if a critical threshold is approaching. The theoretical studies show that the dynamics of systems near a critical point have generic properties, regardless of differences in the details of each system. Therefore, sharp transitions in a range of complex systems are in fact related. In models, critical thresholds for such transitions correspond to 'catastrophic bifurcations'.

Earlier we reviewed one of the prototype models of such systems, the lake system, and used it to analyse and classify the economic outcomes of such a shift.

Scheffer *et al.* (2009) reviews some of the generic early-warning indicators. The main indicator that is mentioned in the review is the so-called critical slowing down that might lead to three possible early-warning signals in the dynamics of a system approaching a critical threshold: slower recovery from perturbations, increased autocorrelation and increased variance in the resulting pattern of fluctuations. Although, these indicators are examined in some strong but stylized models, more work is needed to test the robustness of these signals. Also, detection of the patterns in real data is challenging and may lead to false results. In the Copenhagen Accord (UNFCCC, 2010) the critical threshold, based on recommendations, among others, of Bruckner *et al.* (1999), was set at 2 degrees C. Jaeger and Jaeger (2011) provide an interesting overview of the history of emergence of 2C target, including a review of the criticism of this target. Whether the 2C threshold is well justified as a mitigation policy target or not, there is now increasing scepticism on the chances of retaining the global mean surface air temperature at or below this limit (Anderson & Bows, 2011; Peters *et al.*, 2013). At the same time, some recent studies (Mann, 2009; Smith *et al.*, 2009) have revised the climate change impacts associated with 2C temperature rise above the pre-industrial level towards higher severity levels. On this basis, Anderson and Bows (2011) suggest redefining the 2C limit as a threshold not between "acceptable" and "dangerous" climate change, but between "dangerous" and "extremely dangerous" climate change.

In order to assess the economic impacts of climate change and the mitigation and adaptation related policies, the issue of non-linearity in the presence of tipping points is essential for the definition of optimal mitigation and adaptation strategies as the impact climate change could become extremely severe, however, there are a lot of uncertainties regarding the critical thresholds (Pindyck, 2007). Moreover, many climate impacts such as the damage to ecosystems may be irreversible. This means that adopting a policy now rather than waiting has a sunk benefit, that is a negative opportunity cost. This implies that traditional cost-benefit analysis will be biased against policy adoption (Pindyck, 2007).

While understanding of the nature of non-linear abrupt changes is essential for the proper estimate of cost and benefits of climate related policy actions, especially in the domain of climate change mitigation where impacts are intergenerational, the quantitative modeling of regime shifts in coupled CEE system and impact assessment models and tools is challenging. Current impact assessment models are not fully able to present non-linearities, thresholds and irreversibility or run catastrophe climate scenarios. Numerous studies have indicated that in the case of non-linear climate change impacts, optimal abatement increases substantially (Baranzini *et al.*, 2003; Gjerde *et al.*, 1998; Keller *et al.*, 2004; Kolstad, 1994; Mastrandrea, 2001; Tol, 2003; Yohe, 1996; Zickfield & Bruckner, 2003). The potential for non-linear and low-probability climate responses to anthropogenic greenhouse gas forcing, however, has received little attention in the climate change damage cost literature to date (Alley *et al.*, 2003; Higgins *et al.*, 2002; Tol, 2009; Wright & Erikson, 2003).

In this report we reviewed the shortcoming of various modeling approaches, which are most commonly used to design CEE models, treat the issues of non-linearity, thresholds and irreversibility. In particular, we look at Integrated Assessment Models (IAMs) including General Equilibrium Models, System Dynamics Models (SDs) and Agent-Based Models (ABMs).

As mentioned earlier, non-linear responses are strongly related with all dynamics arise from the interaction of just two types of feedback loops, destabilising (or positive) and stabilising (or negative) loops. Among the high-resolution IA models the dominant approach has been the sequential (linear) representation from socioeconomic inputs to emission and climate impacts without considering feedbacks (Damage Function) to the "Human Activities" or "Ecosystem" modules. In these models feedbacks are usually restricted to the "Human Activities" module. Moreover, Stanton *et al.* (2009) IAM review finds that in only a few models damages are treated as discontinuous, with temperature thresholds at which damages show a major shift from lower temperatures (see for example Nordhaus, 2008). In particular the review concludes that IAMs as well as GE models largely ignore the possibility of a catastrophic climate outcome (Ackerman *et al.*, 2009; Pindyck, 2013; Stanton *et al.*, 2009; Stern, 2013). (Lenton & Ciscar, 2013) review the limitations of the models and state that there is a "…huge gulf between natural scientists' understanding of climate thresholds or tipping points and economists' representations of climate catastrophes in IAMs." (Stern, 2013) summarizes: "the economic models add further underassessment of risk on top of the underassessment embodied in the science models, in particular because they generally assume exogenous drivers of growth, only modest damages from climate change and narrow distributions of risk".

Unlike GE modes and IAMs , ABMs have a high potential to simulate non-linear dynamics and responses in coupled CEE systems. Yet, it is not suited to model climatic systems, thus only non-linear response in socio-economic systems and energy markets can be considered. However, In the ABM literature in CEE domain thresholds are usually mentioned only with respect to the dynamics of socio-economic system and sometimes possible CO2 emissions trajectories. Since ABMs are not directly used to model climatic systems (e.g. 2 degree Celsius threshold), there are no climate system thresholds considered directly. Irreversibility, however, are addressed in ABMs. The ABM of the carbon emission trading impact on shifting from carbon-intensive electricity production (Chappin & Dijkema 2007) suggests that as soon as investments in new technology are made, the switch from the old technology is irreversible. Various scenarios produced by the ENGAGE ABM by Gerst and colleagues (2013) all produce irreversible transitions to low-carbon economy. While depending on a policy, the transition can be swift or more gradual, the return back to carbon-intensive economy is unforeseeable.

System dynamic models represent real-world applications of the formal mathematical theory of nonlinear dynamic systems, and thus, by definition, are designed to represent nonlinearities. Coupled climate–socioeconomic system dynamics models applied to the study of the economics of climate change include numerous non-linearities both in the economic modules (e.g. economic crises, bubbles on asset markets etc.) and in the climate modules (e.g. abrupt climate change). As example, a simple climate-socioeconomic system dynamic model by Kellie-Smith and Cox (2011) integrated for a very long term (from year 2000 to year 3000) generated under certain scenarios pronounced persistent low-frequency nonlinear oscillations of climate and macroeconomic variables. However, the problem of abrupt/irreversible climate change is has not been extensively addressed in the existing literature on climate-economic SD models. Indeed, up to now most modelling exercises based on climate modules able to represent abrupt/irreversible climate dynamics or including discontinuous climate damage functions, have been performed within the utility maximization paradigm – a conventional wisdom of neoclassical economic growth theory. However, both of these climate modelling forms can be straightforwardly adopted in SD models.

In order to tackle the aforementioned shortcomings of the current CEE impact models, the main goal of COMPLEX WP5 is to developed a system of models combining insights from different field of research such as critical transition and catastrophe theory, and IAMs, GEs, ABM, and SD modelling approaches with the emphasis on utilising the non-linear climate responses and regime-shifts of economic-ecological systems, modelling processes of diffusion and pervasive technical change and its implication, and representation of economic sectors with a significant potential for mitigation and resource efficiency. The system of model will be designed in such a way that it can serve as a so-called 'fully integrated assessment model' to evaluate mitigation policies, assessing the costs and inform policy makers in a more effective way. The next report will present the theoretical and conceptual framework for such a system.