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

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With contributions from the COMPLEX Consortium
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COMPLEX (EU Project n°: 308601) is a 48-month project. We began collecting material for this report in Month 38 and started editing it together in Month 40. This report is a snapshot of the project taken in its final year. Please check the COMPLEX website for updates, executive summaries and information about project legacy.

COMPLEX
Knowledge Based Climate Mitigation Systems for a Low Carbon Economy

Published by Sigtunastiftelsen, Sigtuna, Sweden
Human Nature Series
Editors: Nick Winder and Hans Liljenström
Graphic design: Regina Clevehorn, Sigtunastiftelsen
Printed by Kopieringshörnan I Uppsala AB, Uppsala 2016
ISBN: 978-91-976048-2-6
www.sigtunastiftelsen.se

8. Climate Mitigation Policies

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Climate change is a complex phenomenon plagued of uncertainties which are crucial for climate policy. Some of these uncertainties are related to the existence of non-linearities, thresholds, and irreversible events. The Stern report (Stern, 2007) points out three main non-linear changes and threshold effects from climate change.

First, global warning will increase the chance of triggering abrupt and large-scale changes. These abrupt and large-scale changes could potentially destabilise regions, generating mass migrations and increasing regional conflicts. For example, the thermohaline circulation of the North Atlantic ocean, suggests the existence of thresholds, multiple equilibria, and other features that may result in episodes of rapid change (Stocker & Schmittner, 1997). While there is still uncertainty over the possible triggers for such changes, the latest science indicates that the risk is more serious than once thought. Fig. 8.1 shows the consequences of climate change against increases in global mean temperature (°C) after 1990. Each column corresponds to a specific "reasons for concern" identified by the Third Assessment Report (TAR) of the IPCC (McCarthy *et al.*, 2001) and represents additional outcomes associated with increasing global mean temperature. The color scheme represents progressively increasing levels of risk (Smith *et al.*, 2009). The left hand side of the figure shows the risks as reported by the TAR while the right hand side reflects the update impacts associated to an increase in global mean derived from the Forth Assessment Report (AR4) of the IPCC (Parry *et al.*, 2007).

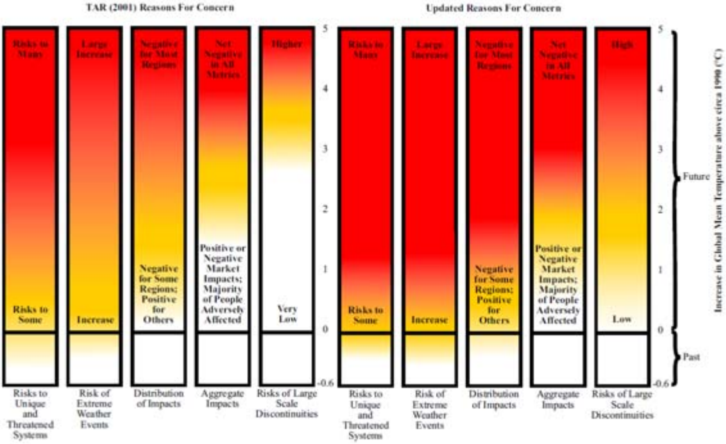


Figure 8.1*. Risks from climate change, by reason for concern—2001 compared with updated data. Source: (Smith et al., 2009)*

Second, melting of polar ice sheets would accelerate sea level rise and eventually lead to substantial loss of land, affecting around 5% of the global population. As temperatures rise, the world risks crossing a threshold level of warming beyond which melting or collapse of these polar ice sheets would be irreversible. This would commit the world to increases in sea level of around 5 to 12-m over coming centuries to millennia, much greater than from thermal expansion alone, and significantly accelerate the rate of increase. A substantial area of land and a large number of people would be put at risk from permanent inundation and coastal surges (Rahmstorf, 2007; Stern, 2007).

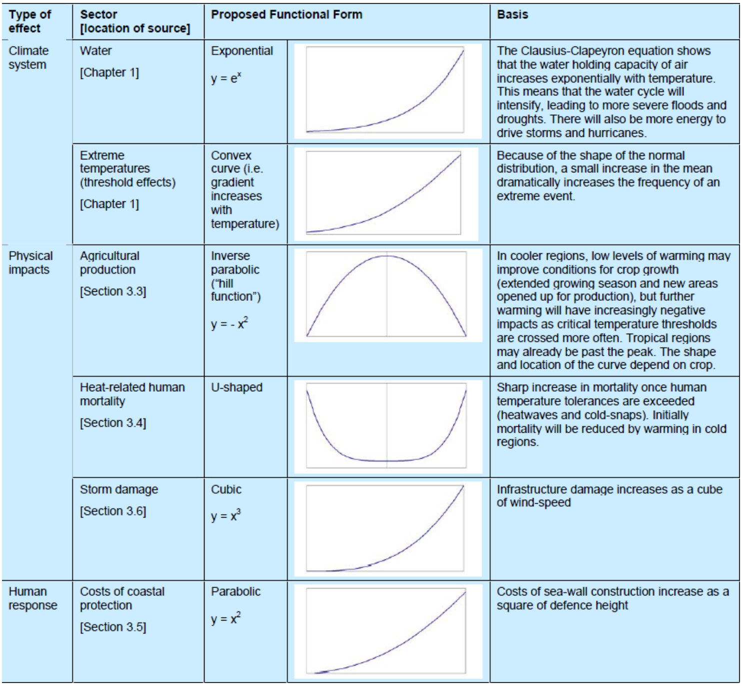
Finally, global warming may induce sudden shifts in regional weather patterns with severe consequences. The strongly non-linear nature and variability of some climatic systems, suggests that they may be particularly vulnerable to abrupt shifts. For example, recent evidence shows that an El Niño with strong warming in the central Pacific can cause the Indian monsoon to switch into a dry state, leading to severe droughts (Kumar et al., 2006). These types of shifts are temporary, but in the past, there is evidence that climate changes have caused such shifts to persist for many decades. If such abrupt shifts were replicated in the future, they could have severe impacts.

In this context, a critical issue is the definition of mitigation policies when the possibility for non-linearities, thresholds, and irreversible events is allowed. On the one hand, nonlinear phenomena characterize all aspects of global change dynamics: inputs and outputs are not proportional, change is often episodic and abrupt, rather than slow and gradual, and multiple equilibria are the norm (Rial *et al.*, 2004). Accordingly, the damage caused by climate change does not increase linearly with the level of emissions/concentration of GHGs. Thus, damage functions tend to be highly nonlinear, with insignificant damages for low levels of pollution which turn to be severe or even catastrophic once some uncertain thresholds are reached. Similarly, the cost/benefits of climate mitigation may be very low for the abatement of low levels of emissions and extremely high for higher levels. However, as we will show in the following sections, most modelling approaches ignore these catastrophic events when assessing the cost of climate change. To some extent this is due to the fact that there is not enough direct quantitative evidence on the impacts at higher temperatures (Stern, 2007). For instance, (Hitz & Smith, 2004) found increasingly adverse impacts for several climate-sensitive sectors but were not able to determine if the increase was linear or not. Indeed, in most cases the shapes of the damage functions are unknown (see Table 8.1).

The issue of non-linearity is essential for the definition of optimal mitigation and adaptation strategies, and is especially relevant in the presence of a threshold or "tipping point" at which the impact climate change could become extremely severe, but we do not know where that point is (Pindyck, 2007). The implications of the existence of these critical thresholds have been widely addressed in climate science (Schellnhuber *et al.*, 2006). Some climate researchers have argue that GHG emissions should be abated to avoid the high costs derived from exceeding climate thresholds (Rahmstorf, 1999), while others suggest that the trade-off between uncertain future climate damages and certain present costs for controlling emissions justify only low abatement levels (Tol, 1997). This discrepancy is close related to the parameter uncertainty about the threshold specific damages and the emissions level triggering a threshold (Keller *et al.*, 2004).

Irreversibility is also a major problem for the design and implementation of climate policy. There are two major sources of irreversibility relevant for climate policy (Pindyck, 2007, 2000). On the one hand, emissions abatement policies usually impose sunk costs on society in the form of discrete investments expenditure flows. In either case, if future costs and benefits of the policy are uncertain, these sunk costs create an opportunity cost of adopting the policy, rather than waiting for more information about expected impacts. Consequently, traditional cost-benefit analysis would be biased toward policy action. On the other hand, environmental damage is often partly or totally irreversible. For example, GHGs accumulate in the atmosphere for long periods; thus,

Table 8.1. *The types of relationship between rising damages and sectoral impacts. Source: (Stern, 2007).*



Type of effect	Sector [location of source]	Proposed Functional Form		Basis
Climate system	Water [Chapter 1]	Exponential $y = e^x$		The Clausius-Clapeyron equation shows that the water holding capacity of air increases exponentially with temperature. This means that the water cycle will intensify, leading to more severe floods and droughts. There will also be more energy to drive storms and hurricanes.
	Extreme temperatures (threshold effects) [Chapter 1]	Convex curve (i.e. gradient increases with temperature)		Because of the shape of the normal distribution, a small increase in the mean dramatically increases the frequency of an extreme event.
Physical impacts	Agricultural production [Section 3.3]	Inverse parabolic ("hill function") $y = - x^2$		In cooler regions, low levels of warming may improve conditions for crop growth (extended growing season and new areas opened up for production), but further warming will have increasingly negative impacts as critical temperature thresholds are crossed more often. Tropical regions may already be past the peak. The shape and location of the curve depend on crop.
	Heat-related human mortality [Section 3.4]	U-shaped		Sharp increase in mortality once human temperature tolerances are exceeded (heatwaves and cold-snaps). Initially mortality will be reduced by warming in cold regions.
	Storm damage [Section 3.6]	Cubic $y = x^3$		Infrastructure damage increases as a cube of wind-speed
Human response	Costs of coastal protection [Section 3.5]	Parabolic $y = x^2$		Costs of sea-wall construction increase as a square of defence height

were drastically reduced, it would take many years to reduce the concentration levels in the atmosphere. Carbon dioxide is removed from the atmosphere by terrestrial vegetation or by the oceans, but this is a long process (Fisher, 2003). Further, many climate impacts such as the damage to ecosystems may be permanent. 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).

These two kinds of irreversibilities (sunk costs associated with an environmental regulation, and sunk benefits of avoided environmental degradation) interact with two kinds of uncertainty (over the future costs and benefits of reduced environmental degradation, and over the evolution of ecosystems) affecting optimal policy timing and design (Pindyck, 2000).

All these uncertainties are aggravated by the long time horizon of climatic change. The costs and, especially, the benefits from an environmental policy can extend for a hundred years or more. This long time horizon exacerbates the uncertainty derived from non-linearities, thresholds and irreversibilities.

From the policy perspective, the existence of uncertainty about thresholds affects the timing and design of emissions abatement. In this sense, the uncertainty about the thresholds suggests that climate policy should be "precautionary" in the sense of favouring earlier and more intense intervention (Pindyck, 2007). However, due to this same uncertainty, it is not clear the level of precaution that should be adopted.

Policy and governance literature

The issue of a non-linear transition from fossil-fuel based to low-carbon economy, which goes through thresholds and exhibit irreversibilities, attracts the attention of policy-makers.

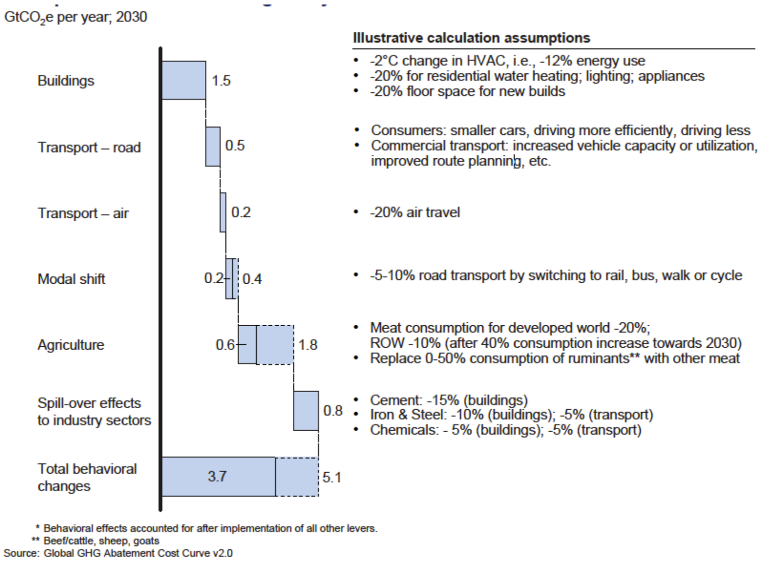
Firstly, policy discussion is structured around the fact that climate-energy-economy systems exhibit non-linear behavior with thresholds and irreversible pathways. Majority of climate mitigation policies worldwide are formulated using a “2 degrees Celsius” threshold as a target (McKinsey & Co, 2009). It is widely accepted that if global warming is held below this threshold, humanity will avoid irreversible climate change with catastrophic non-linear impacts on all sectors of economy. In addition to the “2 degrees Celsius” threshold the World Bank (2012) considers a “4 degrees Celsius” point, which if crossed will lead to irreversible catastrophic consequences in 2060 or 2100.

The EU Roadmap 2050 (European Commission, 2011) outlines an action plan to enable EU to achieve greenhouse gas reductions up to 80 to 95% agreed target by 2050 to avoid irreversible climate change. While policy discussions are often focused around non-linearities in climate system due to economic pressure, there is also a growing about non-linear changes in social and economic sphere systems due to changes in climate or our attitudes towards it. (Medhurst & Henry, 2011) highlight that economic systems are constantly undergo changes. However, while some changes can be incremental and smooth, others are unpredictable sharp changes in trajectories driven either by external events or gradual changes and amplified by feedbacks. This non-linear dynamics, which has been also associated with long-term economic cycles such as Kondratieff waves, should be considered when exploring transitions to green economy. According to IHDP (2012) a successful transition to low-carbon economy is possible only when society moves “beyond incremental technological change toward system innovation”. Thus, business-as-usual with gradual improvement of energy technology and efficiency is not enough to achieve a green economy.

Due to path-dependency complex climate-energy-economy systems are difficult to change, i.e. they are likely to be irreversible when on a certain development trend (Liu *et al.,* 2007). Thus, a transition to low-carbon economy is likely to undergo through a non-linear process of a system innovation and a paradigm shift (IHDP 2012). IHDP report highlights that a paradigm shift – a “change in the underlying social habits, beliefs, and assumptions that drive our behavior” – may break a traditional development path based on fossil-fuel-based economy. This systemic paradigm shift requires a deviation from the massive carbon-based production (energy supply side) as well as consumption (energy supply side).

Secondly, one of the most often discussed mechanisms that lead to non-linear responses in economic systems is emergence and diffusion of new low-carbon technologies. The Europe 2020 Strategy (European Commission, 2010) sets up a goal to reduce GHG emissions by at least 20% compared to 1990 levels through an increase the share of renewable energy sources in the final energy consumption to 20% and through a 20% increase in energy efficiency. Thus, technological measures are at the core of the transformation to a low carbon economy. European Commission (2011) highlights that future modelling efforts should better represent penetration of low-carbon technologies and improvements in resource efficiency. These two may lead to non-linear impacts on economy and CO_2 footprints. Naturally, it is expected that break-through technological innovation occur spontaneously and lead to "unforeseeable structural change". This rarely happens in a gradual way, which is used to justify marginal economic thinking in existing models.

Thirdly, another underlying mechanisms of non-linear response of socio-economic system frequently discussed in policy documents is behavioural change. In addition to supply-side effects driven by emergence and diffusion of low-carbon technologies, the demand-side effects also receive attention in policy documents. The implementation of the Energy Efficiency Directive of 2012 in EU relies on a change in consumer behaviour, in particular in energy consumption practices (EEA 2013). Behavioural changes at household level are expected to bring about 6% (4 $GtCO_2$ per year) of the required GHG emission reduction by 2030 (McKinsey & Co 2009). Yet, as McKinsey report highlights, this is a very low bound of estimate, which inherits a lot of uncertainty and would be higher if considered before the implementation of technical measures. Behavioural changes that make a difference in terms of GHG emission reduction include cutting on travel, reduction of domestic heating and cooling, reducing appliance use and meat consumption (McKinsey & Co 2009). Yet, the impacts of major lifestyle changes have not been systematically quantified and are still beyond the capabilities of the quantitative modelling tools for climate mitigation (European Commission, 2011).



Illustrative calculation assumptions

- -2°C change in HVAC, i.e., -12% energy use
- -20% for residential water heating; lighting; appliances
- -20% floor space for new builds
- Consumers: smaller cars, driving more efficiently, driving less
- Commercial transport: increased vehicle capacity or utilization, improved route planning, etc.
- -20% air travel
- -5-10% road transport by switching to rail, bus, walk or cycle
- Meat consumption for developed world -20%; ROW -10% (after 40% consumption increase towards 2030)
- Replace 0-50% consumption of ruminants** with other meat
- Cement: -15% (buildings)
- Iron & Steel: -10% (buildings); -5% (transport)
- Chemicals: - 5% (buildings); -5% (transport)

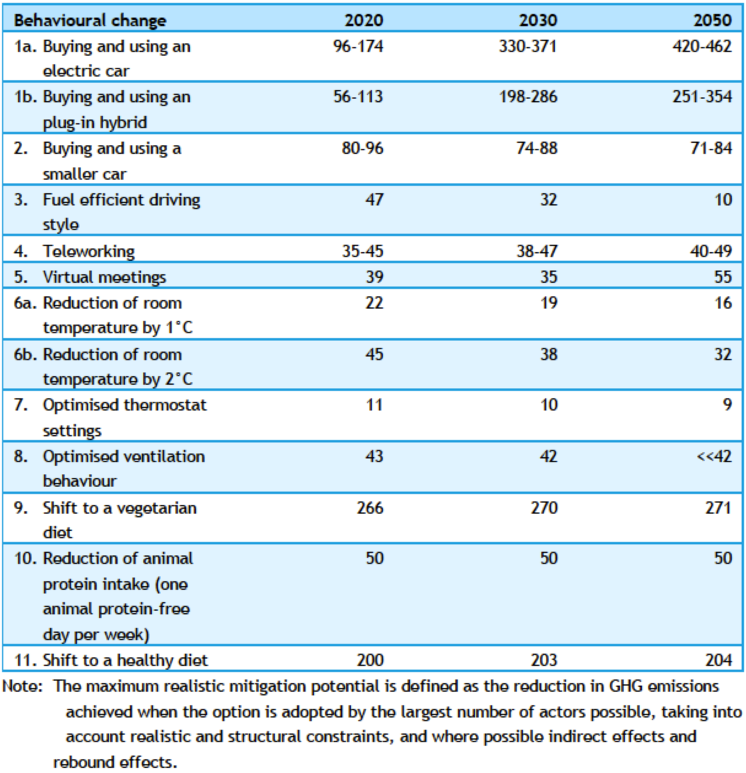
* Behavioral effects accounted for after implementation of all other levers.
** Beef/cattle, sheep, goats
Source: Global GHG Abatement Cost Curve v2.0

Figure 8.2. *Impact of various forms of behavioural change on GHG emission reduction. Source (McKinsey&Co 2009).*

Such behavioural changes at individual level are gradual. Yet, their impact on a societal level can experience social amplification effect, which is fuelled by social interactions and shifting social norms regarding energy use, leading to thresholds and eventually non-linear transitions. A difference between a discrete technological change within one regime (carbon-intensive economies) and a *shift to a qualitatively new regime* (low-carbon economies) lays in acceptance of new norms by a *massive* range of actors and institutions (IHDP 2012). This said, practice shows that path-breaking regime shifts to a low-carbon economy start small and have roots at the local level (IHDP 2012). Thus, many incremental changes cumulatively may lead to a regime shift.

Faber and colleagues (2012) distinguish two types of behavioural change with respect to reducing GHG emissions: habitual actions and intended behaviour. The former include frequently-repeated actions, i.e. habits. The latter is the outcomes of a planning process and conscious decision-making, e.g. a purchase of domestic appliances, and is usually a choice that does not occur on a daily/monthly or even annual basis. The impact of behavioural changes in routines as opposed to changes in one-time strategic choices on GHG emissions can be different. Fig. 8.3 presents a quantification of the impact of the first category of behavioural change on GHG reduction.

Behavioural changes would require energy-awareness programs supported by the governments and potentially economic stimuli. The EEA (2013) argues that active engagement of a consumer would require a range of changes in energy markets, including its form of functioning and possible changes in their regulation. Persistent change in energy consuming behaviour relies on long-term programs (educational, price, awareness, etc.) and should be studied in a dynamic way accounting for heterogeneity among households. As highlighted by EEA (2013) households and their behavioural change are not driven exclusively by economic reasoning. In contrast socio-demographic factors (age, education) as well as social norms, belief systems and cultural traits – which are changing over time – are prevalent. Quantification of the impact of a diffusion of 'green' beliefs and corresponding choices through society are vital.



Behavioural change	2020	2030	2050
1a. Buying and using an electric car	96-174	330-371	420-462
1b. Buying and using an plug-in hybrid	56-113	198-286	251-354
2. Buying and using a smaller car	80-96	74-88	71-84
3. Fuel efficient driving style	47	32	10
4. Teleworking	35-45	38-47	40-49
5. Virtual meetings	39	35	55
6a. Reduction of room temperature by 1°C	22	19	16
6b. Reduction of room temperature by 2°C	45	38	32
7. Optimised thermostat settings	11	10	9
8. Optimised ventilation behaviour	43	42	<<42
9. Shift to a vegetarian diet	266	270	271
10. Reduction of animal protein intake (one animal protein-free day per week)	50	50	50
11. Shift to a healthy diet	200	203	204

Note: The maximum realistic mitigation potential is defined as the reduction in GHG emissions achieved when the option is adopted by the largest number of actors possible, taking into account realistic and structural constraints, and where possible indirect effects and rebound effects.

***Figure** 8.3. Maximum mitigation potential for some categories of behavioral change for EU GHG emission mitigation targets, assuming all households adopt it (Mt CO2). Source: (Faber et al. 2012)*.

While considering behavioural change in a larger system of transition to low-carbon economy, Jevons Paradox (i.e. rebound effect) also requires attention (McKinsey & Co, 2009; EEA, 2013). Improvements in energy efficiency and emergence and diffusion of technological innovations may be bounced back by a behavioural response: as a unit of energy becomes cheaper and less harmful for the environment, a natural human response is to use more. This negative behavioural effect may reduce savings due to technical energy efficiency measures. Such feedbacks between technical and behavioral measures in coupled climate-energy-economy systems are likely to produce non-linear dynamics.

Lastly, another important factor, which is important when discussing potentially non-linear transitions to green economy, is impacts of transition for various economic sectors and their detailed representation in decision-support models. The feedbacks across sectors which may lead to non-linear economy pathways. The EU Roadmap 2050 (European Commission, 2011) underlines that changes in technology may lead to structural changes, which require detailed specificities of sectors and their interactions. Moreover, as any structural change, a (non-linear) transition to green economy driven by emergence and diffusion of low-carbon technologies is expected to impose benefits and costs of transition. As with majority of economic cycles, e.g. Kondratieff waves, an economic system will experience short-term costs of transition (e.g. bankruptcies of carbon-intensive businesses, unemployment in corresponding sectors) in exchange for long-term benefits (slow down of climate change, healthier environment, green jobs, opportunities to develop in an energy-efficient way etc.) (Medhurst & Henry, 2011). Costs and benefits will be unevenly distributes across sectors, demanding detailed representation of direct and indirect impacts of a transition to green economy. Some creative destruction as costs of transformation of energy use in various sectors, encourages path-dependence and attachment to the current fossil-fuel-based economy trend, which is difficult to reverse. Yet, a critical threshold on the expected future benefits and accumulating social commitment help to shift a system to a different trend (Medhurst & Henry, 2011).