COMPLEX WP4 Final Scientific Report

Towards a Fossil-Free Society

In the Stockholm-Mälar Region

Edited by Hans Liljenström and Uno Svedin

With contributions from the COMPLEX WP4 team

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Foreword

This volume describes the "Swedish part" (WP4) of the EU project COMPLEX, which has been dealing with pathways to a low carbon society with the Stockholm-Mälar region in focus. COMPLEX started on 1 October 2012 and ended after four years, on 30 September 2016. The central theme of the WP4 research has been to use the Stockholm-Mälar region as a sort of a "laboratory" for modelling and stake-holder interactions, but also for providing backgrounds, perspectives, tools and suggested policy outlines.

The time horizon was chosen to be up to 2050 when the transformation of society is considered to have been achieved. This choice has been guided by the EU, but also by Swedish considerations about the probable time frame for achieving the low carbon goals. The time frame is also given by the strong pressure from constant climate change, calling for distinct, or even drastic, measures all over the world. When the COMPLEX project was conceived by a relatively large number of researchers in Europe (COM-PLEX consisted of 17 institutional partners), in response to a EU call, the Paris UN meeting on climate change December 2015 was neither planned nor manifested. The motivation for our project was high already from the beginning, but has been further enhanced since then, also in terms of global agreements about the needs for strong actions. It is interesting to note that the multi-scalar nature of both the problem and its potential solution has also been strengthened during this time. This includes an increased emphasis on the regional level and its role – i.e. just the focus chosen for the Swedish case study.

Indeed, the emphasis here is to highlight the role of stakeholders in the region, as very important contributors to the development of insight, stressing the "co-production of knowledge". This implies closeness to the societal transformation aspects, to the need for qualified elaboration of knowledge needs, and support to decision makers at many levels, as well as a plurality of chosen approaches dealing with scientific and political issues at heart. Thus, in the beginning of the project we scanned the possible relevant concerns, given a needed transformation of Sweden, specifically the Stockholm-Mälar region, by 2050, and starting up a variety of model exercises as future support to the solution landscape. In the end, the synthesis and food for thoughts for acting stakeholders, particularly in the form of policy advice, provide connections between scientific investigation and support to decision making frameworks.

In this volume, we provide some glimpses of what we have learnt during the project period, from 2012 to 2016. Our hope is that our work may serve as support for the process of handling the urgent contemporary challenges, in terms of strong and informed actions to combat climate change at its source. Our intention has all the time been to respond to the need to change our societies in a fossil-free direction with deliberateness and speed. We hope our work has contributed, at least a little bit, to a greater understanding of the complexity of the problems involved, and the challenges we, as scientists and stakeholders, are facing when interacting and striving for a sustainable society.

Sigtuna, 30 September 2016

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The sculpture "Fractal Cloud" on the SLU campus in Uppsala, which has served as a symbol for the COMPLEX project. Photo: H. Liljenström

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I. INTRODUCTION

With the choice of a specific region as the research domain, in our case the Stockholm-Mälar region in Sweden, follows a number of considerations about possible approaches. In addition, the overriding task, i.e. to pave the way for a constructive transformation to a low carbon society by 2050, provides directional methodological choices.

First of all, we consider a multi-layered approach to governance, i.e. we operate from the level of the individual to the sub-national regional level, with all its historical decision making mechanisms and connections. We also have to consider that the region in turn is embedded in a national and an EU context – and in the end also in a global one. These levels are of different kinds and thus have to be treated in different ways.

Old Town in the center of Stockholm City, on the Baltic Sea side.
Photo: H. Liljenström

Secondly, the region is the home base for actors of many different types, e.g. citizens, economic actors of private and public kinds, educational entities, such as universities or research institutes and schools, representatives of different cuts of the public in terms of NGO:s, trade unions and the media. The value bases are often different due to the tasks and the nature of the constituencies. They also have different agendas, perspectives and roles. Indeed, they mostly operate at different spatial and time windows.

Thirdly, the relationship between humans and the environment has to be given some research based form, e.g. maybe within a sustainability framework, whatever that may mean post Brundtland Commission (WCED, 1987).

Fourthly, the different time horizons are not only an issue for diverse actors, but also have to do with the type of outlook the actors have for their operations and thus in which way policies can or cannot be framed. This, in turn, is connected to the view different actors may hold on issues as what is possible to do within a set of political or non-political types of means. It is further connected to how the scientific support for various actions is to be conceived.

With such considerations early in mind in the Swedish COMPLEX group we understood that we first of all had to scan our domain and its history in order to find a reasonable well established conceptual landscape in which to operate. We also needed to create early links to sets of stakeholders – both "official ones" and informal ones. This we considered – and have also continued to develop – best to be done through a sequence of workshops. In parallel we had to start investigating a limited set of issues – and those being connected to the various scalar levels of our case region (regional, county, municipality, and individual).

The design of our investigation strategy thus could be illustrated in terms of the chart in Fig. 1.

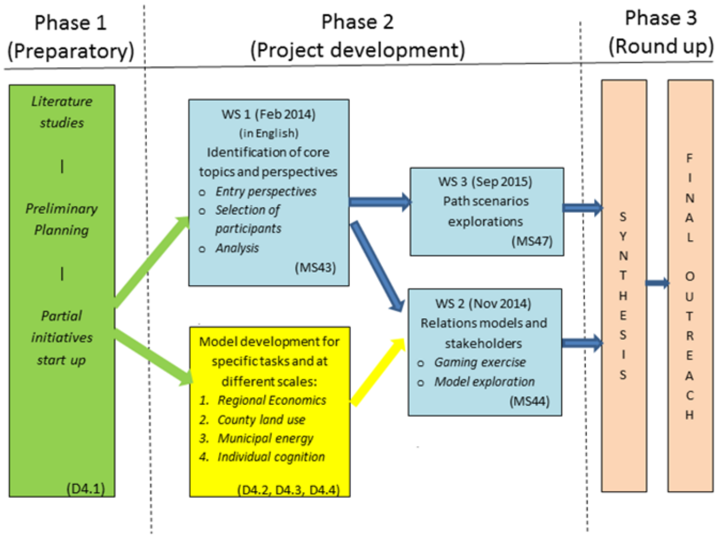


Figure 1. *The main WP4 activities in the three phases of the project. Delivery and milestones reports are given in parenthesis in the various boxes.*

Thus, in parallel to a number of modelling activities, WP4 has arranged a sequence of stakeholder interaction activities. The specific parts, including modeling, reflect different transformational aspects, but also different geographical levels, including:

- Economy (regional level)
- Land use (county level)
- Energy planning (municipal level)
- Cognitive aspects (individual level)

In addition to the continuous and frequent stakeholder interactions, as in the example of the Uppsala Climate Protocol (further described below), several stakeholder workshops were organized in the Swedish Stockholm-Mälar region. The purpose of these workshops has not primarily been to support the modeling in WP4, but to provide understanding of the broader mindsets regarding the regional societal transformation issues. Still, all the stakeholder interactions have contributed, to the modeling activities.

In the following, we will present these elements one by one in a sequence of chapters after a broader investigative, initial overview.

An affluent part of Sigtuna, on a peninsula in Lake Mälaren. Photo: H. Liljenström

II. BACKGROUND SURVEY

Hans Liljenström, Stephan Barthel, Ing-Marie Gren, George Marbuah, Cecilia Sundberg, and Uno Svedin

In this Section, we outline various elements of the state-of-the-art of this type of research, in particular considering conditions in the Stockholm-Mälar region. We are especially interested in the larger context of complex socio-natural systems. The overriding emphasis is on e.g. "green" aspects of economy, bioenergy and land use, but also on societal transformation and behavioral change. This Section reflects our early work on the project issues, and provides a background to the following Sections. For example, stakeholder and policy maker positions discussed here were grounded at a stakeholder workshop held in Sigtuna in spring 2014, which will be presented later in Section III, together with our other workshops and stakeholder engagements. Illustrations in this Section are often drawn from the general literature and when possible being explicitly cited.

Section II consists of the five chapters:

II:1 From EU to the Swedish Regional Case

II:2 Complex Systems, Processes and Challenges

II:3 Towards a Green Economy

II:4 Bioenergy, Land Use and Local Transitions

II:5 Governance, Policy Instruments and Stakeholder Positions

II:1 From EU to the Swedish Regional Case

General Views on the Low Carbon Issue

Based on a variety of scientific evidence (e.g. codified in the IPCC 2007 assessment; this was later consolidated by the IPCC 2013/14 assessment reports) and on the judgments in the United Nations Framework Convention on Climate Change. Our planet is experiencing an unprecedented fast increase of carbon dioxide in the atmosphere. This corresponds to a global temperature increase, which in the next half century could pass 2 degrees, or more. The increase in temperature is accompanied by potentially very harmful effects in terms of extreme weather conditions, such as storms/hurricanes, changed precipitation patterns (including droughts and flooding), change of ecosystems conditions and other types of impacts, as elaborated by the IPCC. Thus, it is highly reasonable to define the target within the next half century of not exceeding the +2 degrees as a global mean, as has already been defined as a policy by the political authorities in the EU. (This was further reinforced by the UN Paris conference, December 2015).

Many countries in Europe (including Sweden) have also adopted this goal as a national target. In order not to transgress this chosen limit there is a strong need to combat the emissions of greenhouse gases (GHG), especially the dominant ones with their origin in the use of fossil fuels, i.e. those connected to the carbon cycle. Thus, the maximum 2 degrees centigrade target can also be seen dominantly as a target concerning the main GHG contributor i.e. the carbon dioxide outlet to the atmosphere.

The goal could thus be expressed in terms of an approach - by deliberate action - to achieve a “low carbon society”. This should be reached at the latest by 2050 in order to match the needs. This low or non-fossil based society thus has to be achieved within a few decades from now. The means to reach this goal is by mobilizing an array of actions, including societal transformations of various kinds. These include not only technical solutions e.g. in the energy sector (e.g. new versions of wind, solar, bio-energy etc., and energy efficiency improvements), but also changes in land use (with relevance for agriculture and forestry practices), infrastructure and transportation system designs as well as changes in production and consumption patterns.

This means that the induced changes span over a wide array of practices, and correspondingly calls for changes in incentive structures and indicator sets. These elements of transformation of society are at the heart of the EU-FP7 project COMPLEX – especially how the relevant support (e.g. in terms of models and process designs) to the connected governance efforts can be designed.

It will be important to find out which paths over the next decades that would be most relevant, in order to reach the low carbon society goal – but also to investigate which conditions are most conducive for favourable paths.

EU Positions

Efforts by the EU are both directed towards the climate policy domain, and towards other policy domains with strong indirect influence on climate outcomes. The suggested mechanisms relate both to mitigation and to adaptation impacts. One important EU policy effort of a general kind was the establishing by the Strategy for "Innovating for Sustainable Growth: A Bioeconomy for Europe" (2012). The Background Documents - but also the connected "Action

Plan for Europe" - provide several elements of importance in order to handle the path towards a low carbon society.

In this strategy document, the importance of the sectors of agriculture and forestry are distinctly highlighted, as well as the connected issue of how land use patterns are developed and managed. It is e.g. stated (p.29) "Over the coming decades Europe will be challenged by dwindling natural resources, the effects of climate change and the need to provide a sustainable, safe and secure food supply for a growing global population". Specifically for agriculture it is said (p.30) that it is "a significant contributor to climate change and is in return dramatically affected by climatic instability." Agriculture and food production is said to represent 40 % of the global industrial energy demand (including emissions embedded in inputs). Global direct agriculture emissions (with carbon losses from land use and land-use change not accounted for) are perceived to make up 10-12 % of the total greenhouse gas emissions (according to the IPCC 2007 assessment). Similarly, forest processes are of great importance for the carbon cycle. Hence, these two sectors could be seen as an important arena for creating potentially encouraging contributions to the paths towards low carbon societies.

With regard to the research and innovation dimensions the EU system has established "Horizon 2020" as the tool for directing the main EU resources in these fields. One important aspect of the "grand challenges" deals with the climate related "low carbon society" concerns – directly or indirectly.

Swedish National Positions

The Swedish government has requested all counties (Länsstyrelser) in Sweden to create regional dialogue events on the issue "how we can reach a society without net emission of climate impacting gases by the year 2050". Examples of topics that have been raised include e.g. societal planning, transport systems, agriculture and vehicles for work, energy supply and use, research and development, and issues related to a climate "smart" lifestyle.

The results of these dialogue events were sent to the Swedish Environment Protection Agency ("Naturvårdsverket") covering ideas and suggestions on how the regional level can contribute in a cost efficient way to the establishment of a zero net emission of GHG by the year 2050. This county based investigation of the path towards 2050 was finalized, and the Swedish EPA did in turn report to the central government at the end of 2012 how "a plan for the path towards 2050" ("Färdplan 2050") might be designed for the Swedish situation. The aim was to provide reflections on how the government's vision could be manifested in practical work – not least at the regional level.

We, already at the beginning of the COMPLEX project, chose to use a Swedish regional case as a test arena for issues that were highlighted in the broader project. The aim was to test some of the instruments that could emerge as results from the research in the project. The choice was the Stockholm-Mälar region, which is related to two NUTS2 regions in the EU system.

The Swedish Regional Case

The Swedish case study did focus on some potential development lines and their associated conditions of this key

Swedish region (see Fig. 2). The lake Mälaren is a fairly large lake, around 150 km wide in the East-West direction - having its main outlet eastwards in the centre of Stockholm City, into the Baltic Sea. Why was this region chosen and how could this choice be perceived to help understanding European societies to select appropriate paths to a low carbon situation by 2050?

The answer is that the chosen case region encompasses the capital of Sweden with its relatively large city conglomerate. It also includes a wide range of smaller cities connected to the capital with an elaborate and efficient network of railways and roads. The regional political aim is to create an even stronger connectivity in the future in this geographical space with its variety of natural, as well as social and cultural features.

A Region of 3 Million Inhabitants – Connected to the Outside World

The Stockholm-Mälar region, as defined here, consists of the five counties ("län") associated to the lake Mälaren: Stockholm, Uppsala, Örebro, Västmanland, and Södermanland. Also Östergötland, has from time to time been included in our considerations, as it is a part of one of the two NUTS2 regions we are studying (See Fig. 2). Thus, our object of study deals with a major region in Sweden, also including its national capital.

The region has approximately 3 million inhabitants, corresponding to roughly 1/3 of the total Swedish population. It is one of the fastest expanding areas in Sweden and one of the major hubs for economic and cultural life. Its position at the Western side of the Baltic Sea makes it, since ages, the natural contact point for relations to Finland, to the three Baltic countries within EU i.e. Estonia, Latvia, and Lithuania, but also to Russia through the close connection to the St. Petersburg area. Seen in that light, the *sub-national* Stockholm-Mälar Region could be regarded as one of the major concentration areas of the Baltic Sea *super-national* region i.e. of Northern Europe.

Figure 2. *The "Stockholm-Mälar Region" in our study is constituted by parts of two NUTS2 regions of Sweden, SE11 and SE12 (left), which combines the five counties around the lake Mälaren: Stockholm, Uppsala, Västmanland, Södermanland, and Örebro (right). In some cases, we also involve Östergötland.*

Railway and highway between Stockholm and Uppsala

The Stockholm-Mälar region has certain characteristics. Its socio-economic features are coloured by the function of a central historical, economic, administrative and cultural national area. It is one of Europe's areas centred around a national capital. It is a strong and economically expanding region with the characteristics of a polycentric region around a central city node (i.e. Stockholm with its major harbour facilities opening up to the trade and other transports to the Baltic Sea region and to the world). Its economic and political centre, Stockholm, is thus networking with a substantial number of other sub-regional urban centres and municipalities, all included in the Swedish study region of the COMPLEX project.

The wider Stockholm-Mälar region has a diverse natural geography characteristic. In the east, it includes the long coast to the Baltic Sea manifesting itself in many places from the north to the south of the region in the form of a vast archipelago with thousands of islands. In the southern part it opens up for the Bråviken part of the Baltic Sea, providing the inlet to the industrial city of Norrköping. Further south inland you find the scholarly and administratively important city of Linköping in the midst of a vast and historically prosperous agricultural area. Moving to the north and east through forest areas up to the lake Mälaren area with cities such as Strängnäs, Eskilstuna, Västerås, Enköping, and Sigtuna – all are situated at this major inland lake, third largest in Sweden. Further north a mixed forest and agricultural land opens up, with Uppsala as the centre of the sub-region in the north-eastern part of our case region.

In summary, the Stockholm-Mälar region thus connects coast and inland areas. It spans from large inland water bodies to major connected areas of agricultural and forestry land - often in mixed settings.

Corresponding to these characteristics the historical economic strongholds in this part of Sweden span from traditional sectors, such as agriculture and forestry, but also with connection to historically related iron mining (nowadays more or less closed down). Today these historical connections have taken new industrial forms, although for example Eskilstuna is still one of the major industrial cities in Sweden, in particular for the steel industry.

The various economic raw material sectors have, during the course of history, thus become connected with high tech forms of use of these natural resources e.g. in terms of paper mill and forestry product oriented activities but also machine manufacture in general and in later days ICT and similar sectors. The match of the natural resource base with the historical industrial development and its later "ultramodern" offspring in various high tech areas is based on high levels of education in the population at large, which is one of the characteristics of this entire region. In addition, major academic institutions such as several universities and institutes for research and higher education exist in the region. The connectivity provided by the transport infrastructure linking the various parts of the region is part of the economic features of the regional setting. Currently, further improvement of the fast train connection systems is heavily discussed and improved upon with the creation of a combined regional economic and social space in mind as a planning strategic goal for the region.

Thus, the Stockholm-Mälar region as our case study provides the possibility to elaborate upon, for example:

- A historically developed region over more than 1000 years - or longer
- An area of more than 3 million people and around 1/3 of the Swedish population, which may rise to 5 million by 2050
- Urban – rural connections
- Considerable agricultural and forestry landscape uses which represent a future basis for reinforced bio-economy activities
- Closeness from urban settings to vast forestry areas but also to the considerable Baltic Sea coast line (included in our region) with strong recreational and touristic values
- A transport connected region under quick and emergent intensification
- Representation of different forms of transport means (not only road traffic and rail national hub but also a large harbour for Baltic Sea trade and passenger connections – and geographically also contacts further on outside the Baltic Sea realm to a wider space of international character, in addition to the international airport of Arlanda – largest in the country), as well as a number of smaller airports of regional character
- A differentiated structure of industry and business activities
- Multi-layered governance structures (including the absorption of EU level directives, connections to the Baltic Sea region of nations and its cooperative mechanisms, national (Swedish) policy level operations, the interplay between the capital of a Northern EU country and its surrounding regional areas

With these and other characteristics we regard our chosen region to be very well suited to express options and problem features for the next half century with regard to the transformation of society into a low carbon situation – formally defined already as a goal for 2050 both at EU and national Swedish levels.

Thus, the framing of this intended change is already settled at EU and national Swedish levels. What is not done is the exploration of what it really means in practice – and what the paths towards this goal could be. However, in these fields of inquiry efforts have already been initiated. In the following sections, we will give a theoretical basis for the complex problems involved in this study, as well as more specific examples from the Stockholm-Mälar Region. In Chapter 2, we start with a reflection on how to approach complex problems in general, and climate change in particular, as individuals and as a society. This section can be skipped for those who are more interested in the concrete examples of our study region. Chapter 3 deals with green economy and governance in general, and in the Stockholm-Mälar Region in particular. Chapter 4 gives an overview of bioenergy, land use and greenhouse gases (GHG) emissions in relation to the transition to a climate neutral society, exemplified by various studies, but with focus on the Swedish case. Finally, in Chapter 5, we look forward and include some regional stakeholders and their initiatives and processes as examples for our further explorative studies in this Swedish case study.

II:2 Complex Systems, Processes and Challenges

The Challenges

The entire EU project is called COMPLEX because it deals with complex socio-natural systems and processes at many different levels. In the Swedish part (i.e. WP 4 covered in this text), we deal with this complexity with a specific case in focus, namely that of socio-economic and land use dynamics in the Stockholm-Mälar region, as described above. In our perspective, it constitutes a "meso-scopic level" case in the EU frame. There are many specific questions that relate to climate change and the regional path to a low carbon society, that we will deal with below. However, first we will outline some initial thoughts on the general issues involved, in particular how complex systems can be dealt with, conceptually, psychologically, as well as socially. A central issue will be how we can change our mind-sets, including our associated behavioural patterns. Is it possible? Which are the means? What are the drivers? Which are our preferences, and priorities today and tomorrow?

In order for us to change our society, i.e. to meet the challenges ahead of us – not least with regard to climate change and associated challenges – we have to understand the human capacity to deal with complexity, e.g. with regard to our capacity to adapt and to innovate. To reformulate this challenge: we need to consider the relation between internal and external complexities i.e. the relation between mind and nature. Thus, the path towards a low carbon society relates both to deep human issues, as well as to a vast array of more practical considerations and actions. In order to understand our situation at large but also to support the decision making at various levels and by different stakeholders we need to improve and design new types of models of various kinds. These could be conceptual as well as formal, such as computational models that can be used for simulations and scenario building for decision support.

Some Basics on Complexity and Complex Systems

What do we mean by complexity? There are several definitions and descriptions of complexity and complex systems, and the word "complex" can have many meanings, depending on context. For example, complexity can be studied and described in terms of structure, dynamics or function/behaviour (Liljenström & Svedin, 2005).

Structural complexity can be seen as the interplay of many elements in a varied fashion due to many variables and structural constrains. In this context, algorithmic complexity refers to the degree of complexity that can be measured in terms of information: "the more information that is needed to describe a system, the more complex it is". Considering complexity features, it is important to distinguish between regularities and randomness.

Yet, there is no obvious or pre-eminent definition of complexity. It is measured by how well we understand causes, expect behaviours and, in praxis, achieve purposes. Hence, large numbers of variables, non-linear relations among them, and the open nature of a system are important only to the degree they present barriers to understanding (Holling, 1986).

Characteristic features of complex systems have to do with the web of (often non-linear) interrelations between variables that may provide thresholds, lags and discontinuities. Feedback and feedforward loops enable amplification, as well as attenuation and control. This often results in unpredictable and non-intuitive behaviours. Complex systems are often self-organizing and adaptive, where spatio-temporal order may emerge out of disorder, and where new qualities may emerge above a certain threshold of complexity. Such systems typically have a high degree of redundancy, which make them less vulnerable to disturbances and malfunctioning parts. Examples of such systems are ecosystems, or combined socio-natural, as well as socio-technical systems (see e.g. Liljenström, 1997).

Micro-Meso-Macro Scale Relationships

Many complex systems are characterized by a hierarchy of subsystems and different levels, both in time and space. In relative terms, these levels can be viewed as *micro, meso* (i.e. "the in between level"), and *macro* levels, often equally applicable to temporal, as well as to spatial scales. In fact, often the temporal and spatial scales are correlated, so that spatially "microscopic" systems and structures are characterized by a "microscopic" time scale, i.e. "the smaller the system, the faster it moves". Similarly, larger systems are typically characterized by longer time scales (slower motions). For example, the characteristic time scale of molecules is at fractions of seconds, whereas the time scales of mesoscopic systems (such as "touchable objects") might be at the time scale of seconds to years, or macroscopic systems (such as planets or galaxies) relate to much larger time scales (Liljenström & Svedin, 2005).

Often, analytical approaches to structural phenomena have either been devoted to the macro level, or to the micro level. The interest in probing the complexity nature of systems calls for an increased attention to the interplay between the levels, including a special focus on the "meso-level", i.e. the level in between the micro and the macro, as that is the domain where bottom-up meets top-down.

Approaching an organization through its micro-meso-macro aspects, applies also to social structures. That approach could be appropriate when discussing the relation between an individual ("microscopic") and the group or population ("mesoscopic"), within which it is a part, and to the entire ecological system ("macroscopic"). In our case, we regard the sub-national regional scale as the meso-scale, in relation to the micro-scale of individuals or households, and to the macro-scales of nations and the world at large. We have alluded to this regional meso scale previously in this report when presenting our regional case, and will return to it again, when discussing specific aspects of that study (including the modelling approaches).

In this context, it may be worth focussing on the connectivity of network structures, whether they are hierarchical or not. Many properties of networks, such as stability, resilience, and flexibility, as well as diffusion of any kind, depend on the strength and types of the network connections. For example, strong connectivity may under certain circumstances lead to increased local resilience. However, such strong connectivity may also, under other conditions, lead to effects of contrary nature, e.g. fragmentation and social/cultural polarization. Also weak connections are of interest, as they may link different parts and levels of a system in new ways, which may provide stabilizing features. Such ideas were raised already forty years ago by Granovetter (1973). Similarly, there seems to be an optimal degree of randomness in social networks, with regard to efficiency in information transmission and social learning, as is described through the concept of "small-world-networks" (Watts, 1999; Porter, 2012). Analogues results have been found for models of neural networks (see e.g. Liljenström, 2003, 2010ab).

As briefly mentioned above, there are also interesting and important relations between *processes* at micro- and macroscopic levels, often describable in terms of "microscopic" and "macroscopic" time scales. Environmental changes occur at several time scales relevant to life, but it is impossible to make any exact separation of these scales matching the different life processes. One attempt is to crudely relate to the average life span of an individual or a generation. This becomes obvious when we discuss the relation between individual choices and those policies taken by the society at large, which recently has started to involve much longer times scales (several generations) than what politics normally has been used to do (Rockström *et al.*, 2009).

In a social system, e.g. dealing with the structure of decisions, the multi-layered structures play more and more important roles (Rolén *et al.*, 1997). This was the basis for the development of sustainability science (Kates *et al.*, 2001). Globalisation phenomena (macro) meet phenomena at a local level (micro). It is very difficult to deduce the effects at one level to those at another. Of course, the ensemble of micro events builds up global tendencies. But what are the mechanisms of shaping coherence on the way up the ladder? And to which extent do globalisation phenomena really frame local events, more than just preconditioning them in certain fairly vague directions? Often, the analyses about such layered interdependencies (O'Riordan *et al.*, 2001) take as a start the observation that no specific actor may claim a full knowledge of the system. Thus, the issue of overview, or the lack of it, holds some of the keys to the understanding of such multi-layered phenomena, including the understanding of interdependencies between levels and the actors operating the interplays.

Social phenomena often express themselves in a frame of a natural environment. In this way, there may be two ladders of micro-macro relations that relate to each other: one of socio-economic-cultural character, and one of natural origin. The specificities in these two realms, and the logic running them, may be very different. However, when combined these two systems connect. Then, the issue of the match between them becomes paramount. One example is the watershed management around a river. The natural system of the water flows has to be managed within a socio-economic and cultural context, which comprises the other part of the joint socio-natural system. Sometimes this issue has been named the issue of "fit" (Folke *et al.*, 2007) .The interplay between the levels – and the specific role of the mesoscale – is here of central importance. For a presentation of the interplay of humans and the environment in a sustainability and democracy context with relevance for our chosen case region, exemplified with the two municipalities of Linköping and Åtvidaberg, see Svedin & Hägerhäll Aniansson (2002). A number of studies have been devoted to regional developments of this kind, exemplified by Lafferty & Eckerberg (1997), Eckerberg & Forsberg (1998) Lafferty (1999), Coenen *et al.* (2000).

Dynamics and Transitions

Features of systems in terms of their development over time are, of course, highly interesting. In particular, this holds true for social systems, including the changes in cultural patterns. In order for individuals and societies to survive in a complex and changing environment, they need to be able to respond and adapt to environmental events and changes at several time scales. In particular, they have to learn from experience. At a general level, learning features in systems provide early warning capacities. The capacity to transform such signals to adaptive changes of the system makes them more robust and increases their resilience.

We usually try to distinguish the evolution of a system under "normal conditions" (which often means slowly varying conditions), from those which are due to unexpected external shocks, such as a meteorite plunging the surface of the earth (or unexpected financial crisis, such as the one in the early 1930s). Examples of how the dynamics of a specific complex system can change due to various intrinsic and extrinsic effects are given in Liljenström (2010b).

When discussing the long-term evolution of complex systems, we sometimes have to deal with catastrophic events, in terms of intrinsic and external influences, respectively (see below). Mostly, catastrophic events (such as a hurricane or a tsunami, mass extinctions of species, or breakdown of a technical or social system), are considered to occur due to external "forces" acting on the system (such as a sudden weather event, an earthquake, the eruption of a volcano or the impact of a meteorite). However, there is a need also to reflect on the intrinsic factors of the system itself, which either enables the impacts of the catastrophic event to be very severe (flooding in a landscape with insufficient preventive measures), or even as the real source of these catastrophic events (long term developments within a financial system of destructive practices). Small fluctuations might inevitably, sooner or later, bring the system across the threshold of instability. This phenomenon is sometimes referred to as "self-organised criticality", and has popularly been illustrated by the growth and collapse of a sand pile (Bak, 1998).

Resilience and Vulnerability

An interesting question in this perspective is when "microscopic fluctuations" can have effects at a macroscopic level, and become shocks to the entire system. Many examples can be given from the physical sciences, but different types of systems in the socioeconomic domain express similar features. It is generally considered that the coordinated action of a large number of stock holders can avalanche into a stock market crash.

An important feature of a combined social and ecological system is its *resilience*, as expressed by Folke *et al.* (2002a,b) and in Gunderson & Pritchard (2002). When such a system loses resilience it becomes vulnerable to change that previously could be absorbed (Kasperson & Kasperson, 2001). Many of these features have to be understood in terms of multiscale interplays. A closely connected issue deals with the role of diversity - including the layered structure connecting different roles of organisms and their functions. In the societal management of such combined bio-social systems also multi-layered governance systems have to be designed and mobilized in which the stratification of the appropriate roles at the various levels and their interplay should be outlined. This often happens as a social nested process within which political will is only one of the components in the causal chain leading to a specific setting (Svedin *et al.*, 2001).

Are there general features of resilient systems which can recover smoothly after shock treatments? What is required by a system to be resilient? It is very difficult to provide a list of such general features, but some properties that make systems less vulnerable to shocks include the following: network structure, redundancy, large numbers of secondary safeguards, a high interconnectivity with multiple connections to and from essential parts, heterogeneity, self-organised regulatory mechanisms (negative feedback), and elasticity.

The reduction of resilience creates an increased vulnerability to societies. For example fresh water systems may have their vulnerability increased with regard to flood events, but also to toxic algal blooms, which originates from intensified fertilizer use, higher densities of animals and poor other agricultural practices (Carpenter *et al.*, 1998; discussed in Folke *et al.*, 2002a,b).

At a very general level Hägerstrand (1985) trace**s** some of the dangers to the combined natural and social systems, which make up our planetary predicament, to the split of what is going on in "the external world" and what is mapped as "projects" inside the human mind. "It is as if our well-developed capacity to store and hold together systems of ideas makes us unable intuitively to feel the limitations of the external world to accommodate our projects". Indeed, this is an expression of a severe vulnerability at a profound level in our civilization.

Cognitive Aspects on Spatio-temporal Complexity

When dealing with complex systems from the point of view of an individual, which in the end is the basic element of our societies, we have to consider his/her cognitive functions, notably perception, learning, anticipation, decision making, and intention/action. In particular, action is necessary for change in our external environment, but it is based on change of perception in our internal environment. We explore our world in a perception-action cycle (Freeman, 2000). This cycle is at the heart of human mind, where cognition transforms the primary aspects of consciousness, attention and intention, into perception and action (Liljenström, 2011).

The development of our cognitive and conscious abilities depends on an appropriate interaction with the complex and changing environment, in which we are embedded. Our perceptions and actions develop and are refined to effectively deal with our external (and internal) world. This also means that all human understanding is shaped by the interaction between these "worlds". In particular, our cognitive processes are related to the spatial and temporal aspects of our environment, and thus have to be understood in this context (Freksa, 1997; Burr & Morrone, 2006). The sense of agency is also based on these spatio-temporal relations, specifically on cause-effect relations and correspondence between goals and actions in space and time (Balconi & Crivelli, 2009). An understanding of these relations is important when we discuss e.g. agent based models below.

We will here briefly discuss problem perception, realisation of crisis, perception of perturbation and change, awareness of uncertainties and risks, as well as decision making under the condition of uncertainty. In this context, we will also consider perception of spatio-temporal scales, causative chains, perceived capacity to adapt/respond to changes/crisis, eventually expressed as the dual action of adaptation and mitigation. It also includes information as a potential structure (instruction) for organization of phenomena (action), where information in some sense is only in our minds, while action, preceded by intention, is in interaction with our external environment. Connected to this is the possibility through the education system to inject new ideas and carry on established knowledge to the next generation. This holds also true for the systemic knowledge related to sustainability ideas and practices (Melville, 2010).

The processes by which information is generated are what we usually call perception and cognition, and they are heavily influenced by our individual and collective histories and cultures flows of information that create and maintain shared meaning, understanding and expectations. Van der Leeuw & Aschan-Leygonie, (2005) discusses our cognitive functions as part of a dynamic interplay between internal and external environments, also at the level of a society. They mean that a*t any moment,* all levels of a society are involved in making *choices between basins of attraction,* and the *intervals* at which a system changes trajectory are determined by the effectiveness of the society's interface with the environment. As soon as that effectiveness decreases, pressure builds up to improve the group's adaptive mechanisms.

In their view, the *resilience* of a socio-natural system is dependent on the degree of adequacy of human interaction with the environment, as the resilience of a system depends on adequate and timely adaptation to changing circumstances. The other important condition for a system's survival is that the system's *spatial* structure is more or less adapted to its new mode of functioning. Another requirement is that the system is adaptable to the new mode within a reasonable *temporal* delay connected to the growing integration of economic activities on a planetary scale. If the autonomy of local or regional systems is decreased significantly, they are made more vulnerable to perturbations. Unfortunately - on the whole - many of the inherited spatial structures hinder the contemporary adaptation process (van der Leeuw & Aschan-Leygonie, 2005).

Different actors' difficulties in coming to grips with the changes in the system's underlying dynamics are a threat to the system's survival. This is to a large extent due to a dis-equilibrium between e.g. the spatial organisation and the modernisation of agriculture. This in turn is the result of differences in the rhythms by which the subsystems change the inherited spatial structure. The concomitant interactions may influence a system's resilience in different ways. It might happen either by facilitating adaptation to the conditions introduced by the perturbations, or by impeding the necessary re-adjustments. It is thus very difficult to draw any conclusions when it comes to the link between inherited structure and a system's dynamics.

On the one hand, the spatial structure and the interactions within it do affect the capacity of a system to be resilient in a significant way. On the other hand, the complexity of the system, inherent in its many different temporalities and its internal diversification is also a fundamental feature of system dynamics affected by a perturbation.

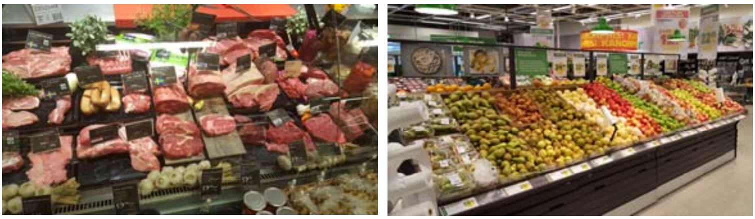
Van der Leeuw & Aschan-Leygonie (2005) conclude that "most of our present-day 'environmental' problems are due to the arbitrary separation in our minds between the 'natural' and the 'cultural'". They call for the development of "a conceptual toolkit which enables us to conceive of such mixed socio-natural systems as dynamic, complex 'flow structure' systems, both in qualitative and in quantitative terms". They also suggest testing this toolkit on a number of case-studies. In particular, there is a need for a better understanding of the interface between people and their environment, including the dynamics of the perceptual/conceptual domain. But, the authors propose, "We should also look at the nature of human impact on the environment, and the unintended consequences that it entails. Such research should, moreover, link the roles of individuals to those of groups of various kinds, from the family up to the whole society, and must thus conceive of information processing as being in part distributed, in part localized".

What are the consequences of all this for our approach to climate change? How can we go from cognition and understanding to policy and action? In the literature, perception and action is often in focus, but intention is generally neglected. There is a need to link perception to action, and this should include intention, our conscious will to change. Information is not enough, but intention needs to be transformed into (appropriate) action (Liljenström, 2011).

Central to the problem is to understand public perception of climate change, which defines the local and global socio-political contexts for policy makers. In an interesting study by Crona *et al.* (2013), where the authors conducted a cross-cultural analysis from six different countries on why and how people understand and interpret climate change and associated risks, there is evidence of a shared cultural model of climate change, irrespective of context and geographical location. Instead, experiential factors, such as affect, imagery and values seem to be more important for public perception and response to climate change (Leiserowitz, 2006).

Cognitive and Behavioural Challenges

It is interesting to note that people in different social contexts perceive the climate change crisis differently, e.g. there are national and regional differences in responses, but also differences of other nature, e.g. socio-cultural differences between different groups in society, sometimes depending on the level of formal education, sometimes depending on particular functions (types of work), or on general world views by connection to specific cultural, religious and political groups.



The choice of food has a major effect on climate and is a challenge for both production and consumption patterns. Photo: H. Liljenström.

There are interesting relationships between information and concern, and information and action. In particular, there is a study by Bostrom and co-workers (1994) showing that Americans, in general are not well informed and have a different "mental model" of the climate change situation than many others in the developed world. In general, many Americans seem to believe that climate change may be serious at a global level, but not a threat to themselves (Norgaard, 2009).

Stanford social psychologist Jon Krosnic has studied various aspects of the relationship between efficacy, concern and willingness to take action. In some work on public perceptions of climate change, Krosnic *et al.* (2006) observe that people stopped paying attention to global climate change when they realize that there is no easy solution for it. Instead the authors note that many people judge problems as serious only if they think action can be taken in these specific cases. This has been shown also in communities in developing countries, where e.g. the individual's belief in their own abilities to manage water stress play a crucial role in driving intentions to adapt (Kuruppu & Liverman, 2011). Myers *et al.* (2012) noted that there is also an affective dimension of climate change engagement, and among US residents a public health focus was the most likely reason for supporting climate change mitigation and adaptation.

Why has the public (not only in America) failed to respond to climate change? There may be several answers, but they include 1) people don't know enough to realize the danger, 2) people don't care enough to take action, 3) there is hierarchy of needs - and climate change is not an immediate need, 4) people have trust that the government will fix the problem.

So what are the cognitive and behavioural limitations - or barriers - that the public is facing in responding to climate change? These may be placed in three categories:

1) psychological/conceptual barriers,

2) social and cultural barriers and

3) structural (political economy).

Barriers to effective engagement in response to climate change exist on all scales from the individual to the institutional, and these dimensions clearly interact. Hence, many well informed individuals feel unable to make change in a world where the fossil fuel industry has so much power (Norgaard, 2009).

Another issue along these lines concerns the human capacity to adapt. Although our policies for climate change, in particular in the COMPLEX project, is focused on mitigation, it is also important to keep in mind that adaptation is probably necessary, as well. Mitigation alone can probably not prevent the climate from changing (dramatically) within the next decades, so adaptation will be necessary to dampen on a more immediate time scale the impacts of climate change on human and natural systems (Grothmann & Patt, 2003; 2005). The human *adaptive capacity*, as described by IPCC, is "the potential or ability of a system, region, or community to adapt to the effects or impacts of climate change" (Smit & Pilifosova, 2001).

Grothmann & Patt (2003, 2005) at the Potsdam Institute for Climate Impact Research object that this view is too limited, and does not take human cognition into sufficient account. They regard adaptation as a socio-cognitive-behavioural process and have developed a socio-cognitive Model of Private Proactive Adaptation to Climate Change (MPPACC), focusing on risk perception and perceived adaptive capacity. The authors point at the importance of the *subjective* adaptive capacity, which may be different from the objective capacity, and relates to what an actor thinks he/she *can* do. Another major psychological determinant of adaptation is *motivation*, which relates to what an actor *wants* to do. This links back to the basic perception-action cycle of our neuro-cognitive system, with its roots in the two aspects of consciousness, attention and intention (Liljenström, 2011). To understand how these processes are related and how our actions result from a complex decision making process, where much is unconsciously determined, is a key to our readiness to behave rationally, also with respect to the anthropogenic climatic changes (Norgaard, 2009; Vietta, 2013).

However, it is now commonly understood, partly due to the fundamental studies on intuitive assessments and judgements by Daniel Kahneman and co-workers, that human decisions are often more irrational than we like to believe, in particular when acting under uncertainty (Tversky & Kahneman, 1974; Kahneman, 2011). Even if this view has been challenged (e.g. Gigerenzer, 1991), there is a need for further studies on the processes and drivers that determine our decisions and behaviours (Simon, 1992; Lawrence & Nohria, 2002).

Taking both mitigation and adaptation into account and in light of the fundamental response options to climate change, three major decision contexts can be distinguished:

1. Specification of long-term targets for the *mitigation* of global climate change.
2. Identification of particularly vulnerable regions and/or groups in society to prioritize *resource allocation* for research and for adaptation (both internationally and nationally).
3. Recommendation of *adaptation* measures for specific regions and sectors.

As discussed above (e.g. by Leiserowitz, 2006; Norgaard, 2009), the concern for global and local impacts of climate change is to a large extent dependent on personal experience. For example, in a survey with Californian farmers the perceived changes in water availability had a significant effect on their intention to adopt mitigation and adaptation practices and strategies, both at a local and global scale (Haden *et al.*, 2012). The study suggests that mitigation is largely motivated by psychologically distant concerns and beliefs about climate change, whereas adaptation is driven by psychologically proximate concerns for local impacts. This relates also to the more general discussion on the relation between local and global concerns in the context of time-geography (see e.g. Hägerstrand, 1992).

Formalized Descriptions and Models

So, what kind of perception-action relations can be at work with regard to climate change and environmental or socio-natural crises? Can our understanding of our cognitive capacities and limitations aid us in dealing with these global issues? How can we understand the potential processes that will bring us to a relevant and creative landscape of solutions with regard to a low carbon society? Which paths seem possible for us to reach such a goal in four decades? How should the transformation be orchestrated – not least with regard to the needed change of mind set about how we will be able to conduct our lives and make it desirable also for future generations?

These complex questions need to be addressed with combined efforts from various fields of science, such as psychology, cognitive science and behavioural economics, but also neuroscience and computer and system sciences. All scientific approaches depend on various types of models, from conceptual to more formal, mathematical and computational models, but the complexity involved here is immense and calls for advanced integrative models that can capture different types of nonlinearities, thresholds, avalanches, hysteresis etc.

Given the enormous complexity of the socio-natural interactions involved when addressing climate change, it is reasonable to ask if our understanding of the problems is sufficient and if our conceptual models can be transferred to more formalized, mathematical models and computer simulations. If so, what are the modelling tools required to address these issues? Which kind of models can be useful for this demanding task?

Several types of modelling techniques and approaches have been applied to aid our understanding of socio-natural systems and processes related to climate change, in particular with regard to mitigation and adaptation. Some general principles for modelling sustainability are given in Todorov & Marinova (2010). Many models are based on System Dynamics (SD), Discrete Event (DE), or Cellular Automata (CA) modelling (see e.g. Borshchev & Filippov, 2004; Hjorth & Bagheri, 2006; Mendoza & Prabhu, 2006). They can all be seen as historically related to the more elaborate and practical Agent Based Models (ABM), as described below and in Sec. 4.6 for applications to land use modelling.

Computational models of mitigation and adaptation to climate change can aid our understanding of how several interacting factors influence the sensitivities and consequences of various driving forces. An excellent survey of adaptation models for climate change is given by Thea Dickinson (2007), where different categories and types of (adaptation) models are distinguished, notably Integrative Assessment Models (IAM) and ABM, with the related Multi-Agent Based Simulations (MAS). A recent example of IAMs for climate change, related to uncertainty analysis, is given by Cooke (2013), and an interesting example of MAS modelling with cognitive aspects is found in Frank *et al.* (2001). A good introduction to ABMs is given in Goldstone & Janssen (2005) and in Janssen & Ostrom (2006). Balbi & Giupponi (2009) provide a comprehensive review of ABM of socio-ecosystems with special focus on climate change. Applications of this kind of modelling to land use and land cover change (LUCC), which is of particular interest for the current project, will be discussed later on in this chapter.

There is also some early work on cognitive models of geographical space, where geographical information science is seen as a result of the merging of cognitive science, behavioural geography and cartography that emerged in the 1980s. Computational models of geographical or spatial cognition could be seen as the foundation for GIS – geographical information systems. Indeed, cognitive geography and geographical cognition are fields that also include the neurophysiological and neuropsychological basis for human spatial cognition and behaviour. (For a review of this work, see Mark *et al.*, 1999). Another kind of approach is based on various types of networks, notably Bayesian networks (e.g. Cinar & Kayakutlu, 2010; Yunyuan *et al.*, 2010).

In the research within COMPLEX, we have explored different modelling approaches and also developed a neurocognitive model of decision making, applied to choice of travel, which will be discussed in more detail in Chapter IV:5, page 197. In the following sections we will pursue different tracks of more particular approaches to some of the more overriding concerns addressed above. These will be devoted to our specific regional case – the paths towards a low carbon society in the Stockholm-Mälar region until 2050, with special focus on land use dynamics.

II:3 Towards a Green Economy

The concept of a "Green Economy" or "Carbon free economy" has intensely attracted the attention of policy-makers, economists, environmental activists and the academia in recent years. Following from the Stern Review in 2006, which among other things showed "that the cost of inaction exceeds the cost of early investment in low carbon technologies", the need for some sort of economic transformation necessary to enhance economic growth while safeguarding the future of our environment has become apparently inevitable (Stern, 2006). In view of this, the concept of "green economy" is viewed by proponents as a coherent and comprehensive way of economic transformation with the natural environment central to its success. While some opponents claim that a "green economy" may hinder their development towards higher income and wealth, proponents hold the view that sustainable use of natural capital resources is necessary to advance economic and social goals. The concerns being raised for bold steps towards a global green economy is that in the absence of action, CO_2 emissions would reach path with dangerous implication for global warming, increasing threat to biodiversity, high levels of air pollution in many cities and expanding desertification among other rising extreme climatic conditions.

The Commission on the Future of Sweden (2013) concerns how Sweden can develop into a green economy, and acknowledges the environmental and climatic challenges accompanying actions such as international trade, emissions, natural resources and ecosystems depletion, and biodiversity loss. The natural question that arises from these genuine concerns is, how can Sweden, which is a small open economy much dependent on international actions, and the different regions develop sustainably while minimizing the deleterious effect of economic growth and development on the environment? What are the key actionable steps capable of delivering a green economy in Sweden in the future? Which of these policy instruments are optimal in ensuring environmental sustainability and hence deliver green growth? How are the policy instruments designed and implemented within a hierarchical governance setting?

These pertinent issues is the motivation for the present study which seeks to identify the key lessons to be drawn from a comprehensive literature review on how to achieve the green economy target in the Stockholm-Mälar region of Sweden by 2050. It also seeks to bring to the fore a pool of policy instruments set within a multi-governance setting to deliver the 2050 agenda in the region. The main question here is thus, what can we learn from the literature with respect to which instruments are best for achieving a green economy in the Stockholm-Mälar region by 2050? The rest of this section is organized as follows: a brief discussion of the concept of a green economy and delegation/ decentralisation is undertaken, followed by a brief description of the Stockholm-Mälar region regarding its geography, economy, environmental potential and challenges towards reaching a carbon-free society in the future. A review of the literature on environmental multi-level governance, policy options towards a green economy, a brief discussion of key findings and conclusion follow, respectively.

Green Economy and Environmental Governance

Any design of policy instruments requires relatively well defined targets, and it is therefore necessary to investigate how green or carbon free economy can be expressed in operational terms. Being a region within a country with multilevel jurisdictions, it is also important to have a good understanding of what we mean by delegation and/or decentralisation of discretion among jurisdictions for making decisions on targets, policies, implementation and enforcement. We therefor discuss the targets in terms of green economy, and present current understandings in economics of delegation and decentralisation in this section.

A hybrid (diesel) electric bus running between the SLU campus and downtown Uppsala. Photo: H. Liljenström

Green Economy as a Concept

The concept of green economy has been interpreted and defined in many ways. According to Eklund (2012), "green economy says that we need to produce and consume goods and services which do not endanger the environment of our planet". The Commission on the Future of Sweden of the Swedish Government defined green economy at a September 2012 workshop as "one that is low-carbon, resources efficient, and maintaining sustainable ecosystem productivity".

At the political level, the UN and its agencies have come up with some other definitions, including the following. The UN Secretary-General's report emanating from the High-level Panel on Global Sustainability in 2012 recognized the significance of inclusiveness as an important ingredient of its long-term vision. The report further defines green growth as "to eradicate poverty, reduce inequality and make growth inclusive, and production and consumption more sustainable, while combating climate change and respecting a range of other planetary boundaries". At the visionary level, the United Nations Environment Programme (UNEP, 2011), defines green economy as: "An economy that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities". At the operational level, the green economy is seen as one whose growth in income and employment is driven by investments that reduce carbon emissions and pollution; enhance energy and resource efficiency and prevent the loss of biodiversity and ecosystem services (United Nations Environment Management Group - UNEMG, 2011). The United Nations Development Programme (UNDP, 2012) gives a more elaborate definition of green economy as "The Green Economy is one in which the vital linkages among the economy, society, and environment are taken into account and in which the transformation of production processes, and consumption patterns, while contributing to a reduced waste, pollution, and the efficient use of resources, materials, and energy, will revitalize and diversify economies, create decent employment opportunities, promote sustainable trade, reduce poverty, and improve equity and income distribution. With regard to labour and what constitutes employment in the green economy, UNEP (2008) defined it as: "Green jobs are those that contribute appreciably to maintaining or restoring environmental quality and avoiding future damage to the Earth's ecosystems."

The OECD however takes a narrower approach to the green economy/growth concept. They define green growth as "Green growth means fostering economic growth and development, while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies. To do this, it must catalyse investment and innovation which will underpin sustained growth and give rise to new economic opportunities" (OECD, 2011). More importantly, the OECD identifies four main areas to capture the main characteristics of green growth: environmental and resource productivity; economic and environmental assets; environmental quality of life; and economic opportunities and policy responses.

The foregoing review clearly shows the lack of consensus on an internationally agreed definition of green economy and the related concept, green growth. A glean through the literature reveals multiple definitions and interpretations of the concept, a summary of which can be found in Appendix A of this report.

Environmental Governance in Hierarchical Settings/Environments

The term governance is defined variously depending on the context and discipline (see also Chapter II:5). Governance has multi-perspectives and interpretations and often implied to focus on systems of governing and means for "authoritatively allocating resources and exercising control and coordination in which state actors are not necessarily the only or most significant participants" (Rhodes, 1996; Bulkeley, 2005). Environmental governance refers to interventions aimed at changes in environment-related incentives, knowledge, institutions, decision-making and behaviours. Specifically, environmental governance refers to a set of regulatory processes and organizations through which political actors influence environmental actions and outcomes (Lemos & Agrawal, 2006; Ostrom, 2001, Jagers & Stripple, 2003; Agrawal, 2005). Various forms through which environmental governance takes place include inter alia international accords, national policies and legislation, local decision-making structures, transnational institutions, and environmental NGOs (Lemos & Agrawal, 2006).

Multi-level or hierarchical governance has been defined variously in the literature. It traces its roots to international relations theory as a modernization of earlier regime concept (Hasenclever *et al.*, 1997) and as a comparative European public policy analysis (Peterson & Bomberg, 1999; Rhodes & Mazey, 1995). In international relations, Krasner (1983) defines multi-level governance as "a set of implicit or explicit principles, norms, rules, and decision-making procedures around which actors' expectations converge in a given area of international relations". Van Kersbergen & Van Waarden (2004) distinctively defines 'governance' as "...it refers both to the power relations resulting from such rules, as well as the substance of policies" while 'multi-level' "refers to different government levels (e.g. European, national, subnational), but also to the involvement of both public and private actors at these levels". In this study, we will mainly consider hierarchical governance by the public bodies.

The Stockholm-Mälar Region– Some Facts and Figures

As was noted in the introduction, the population of the Stockholm-Mälar region amounts to approximately 3.6 million, which constitutes about 1/3 of the total population in Sweden. It is divided among 6 different counties and involving 77 municipalities. One of the main characteristics of the region is the location of the capital of Sweden, Stockholm, which has a population of approximately 1 million. Although there are many interesting aspects with the region, such as cultural and social, this very brief background description will focus on three main issues; economic, environmental (mainly carbon), and environmental governance.

Macro-economic Performance

The Stockholm-Mälar region accounts for a relatively large share, 44%, of the total economic activities of Sweden, as measured by its contribution to gross domestic product (GDP). However, the allocation of GDP contributions, which total to 1470 billion of SEK for the Stockholm-Mälar region in 2010, is unevenly distributed among the six counties, where Stockholm county accounts for 70%, see Fig. 3.

The five counties besides Stockholm have almost equal share of total GRP, which is also the case for the development of GRP/capita over the period 1993-2010, see Fig. 4.

The gap between Stockholm County and the other counties with respect to GRP/capita increased from 129 thousand SEK/capita in 1993 to 201 thousand SEK/capita in 2010. Although the absolute difference has increased the share of difference of the lowest GRP/capita is relatively stable, 69% in 1993 and 71% in 2010.

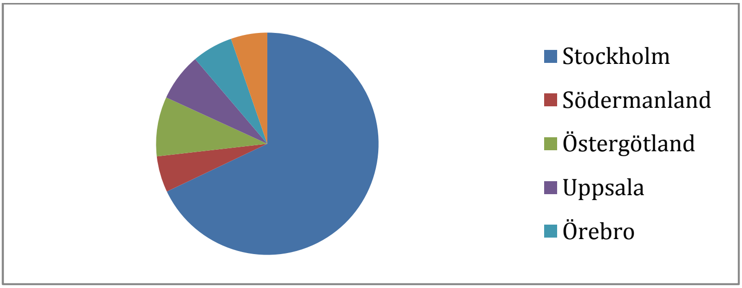


Figure. 3. *Allocation of total gross regional product among counties in 2010. (Sources: SCB, 2013a, Table 1)*

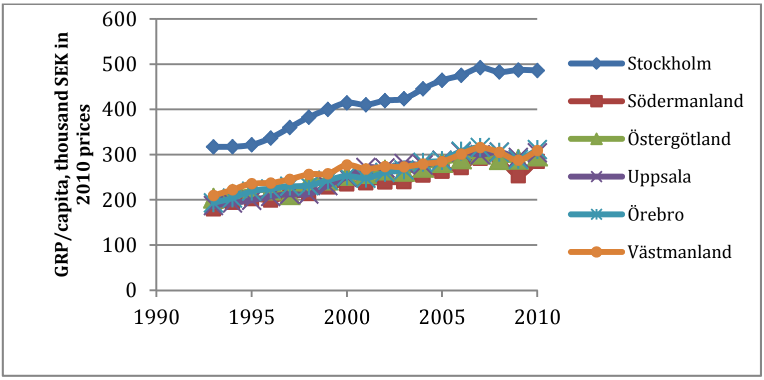


Figure. 4. *Gross regional product (GRP) per capita in the Stockholm-Mälar counties during 1992-2010 (Sources: SCB, 2013a, Table 3)*

Environmental Aspects

Data on carbon dioxide emissions from the different counties are not readily available for several years and we therefore calculated these based on data on use of different classes of fossil fuel (coal, gas, and oil products). These uses were then converted to carbon dioxide emissions. The calculated results for the period 1990 to 2008 show that total emissions are highest in Stockholm County, see Fig. 5.

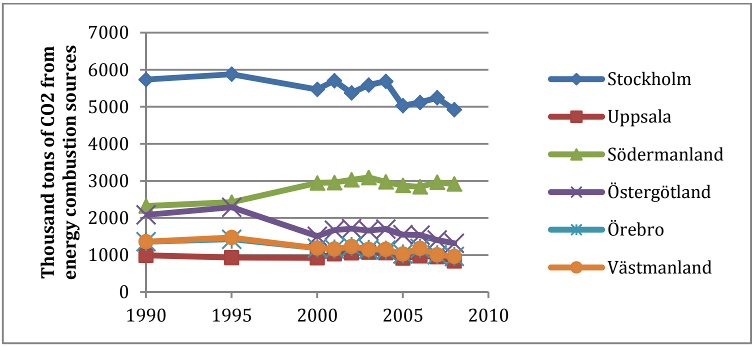


Figure 5. *Emissions of CO_2 from fossil fuels. (Source: Calculations based on uses of fossil fuels in SCB, 2013b)*

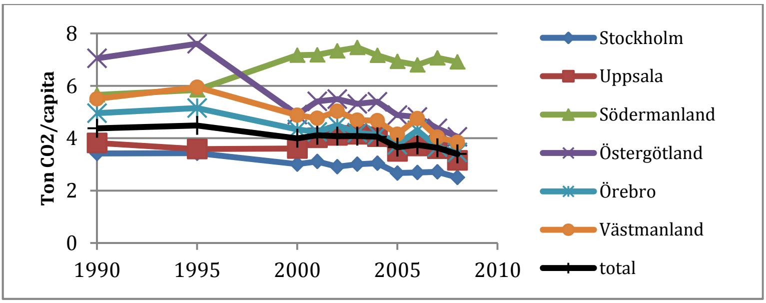


Figure 6. *CO_2 emission from fossil fuel per capita (Sources: SCB, 2013a. and data in Fig 5)*

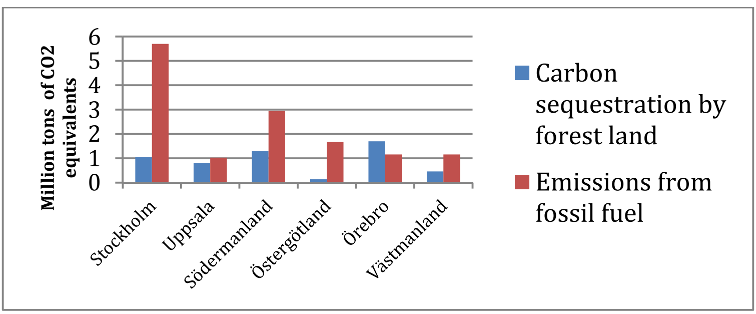


Figure 7. *Carbon sequestration from forests and emission from fossil fuels in 2000 (Sources: Gren and Isacs (2009) and data in Figure 5).*

Interestingly, all counties but Södermanland show relatively unchanged or declining total CO_2 over the period. This pattern is reinforced when investigating CO_2 emissions/capita, see Fig. 6.

Stockholm County shows the lowest CO_2 emission per capita during the entire period. It has decreased from 3.2 tons of CO_2 in 1990 to 2.5 in 2008. Östergötland County accounts for the largest decrease, from 7.1 tons in 1990 to 4 tons in 2008. On the other hand, Södermanland has increased its emissions from 5.6 tons to 6.9 tons.

However, carbon is removed from the atmosphere by the uptake of growing biomass, so-called carbon sequestration, which takes place in all counties, in particular by forests. On the other hand, some land use practices, in particular drained peatland and agricultural practices contribute to emission of CO_2 equivalents in the atmosphere. All these processes have not been calculated for the Stockholm-Mälar region. Partial estimates are made by Isacs (2007) who calculated carbon sequestration by forests for the year 2000. It is then interesting to compare emissions in this year with these calculations of carbon sequestration, see Fig. 7.

The relation between emission and sequestration differs considerably between the counties; emissions being at least five times higher than sequestration in Stockholm and Östergötland but close to or higher than emissions in the Uppsala and Örebro counties. Thus, if only these emissions and sequestrations were considered, Örebro County is already carbon neutral. This is not the case for the entire Stockholm-Mälar region, for which the carbon sequestration of 5.5 Mtons of CO_2 equivalents corresponds to 40% of total emissions.

Carbon sequestration is one of several ecosystem services provided in the Stockholm-Mälar region. Other regulatory services are nutrient sequestration by wetlands, and cultural services are supplied by the recreational opportunities in several ecosystems. The values of some of these services are calculated in Gren & Isacs (2009) using the green accounting framework where both consumption and investment values of the services are included. The consumption values refer to the value of the flow of the services, and investment is the current and future values of supply of ecosystem services caused by changes in the ecosystem, which can be positive or negative. For examples, decreases/increases in area of forest land and wetlands imply less service from the deleted areas that would have been provided now and in the future. The total calculated value of these value components from carbon sequestration in forests, and recreational values of forests, wetlands, and agricultural land corresponds to 88 billion SEK. It is however unevenly allocated among the counties, see Fig. 8.

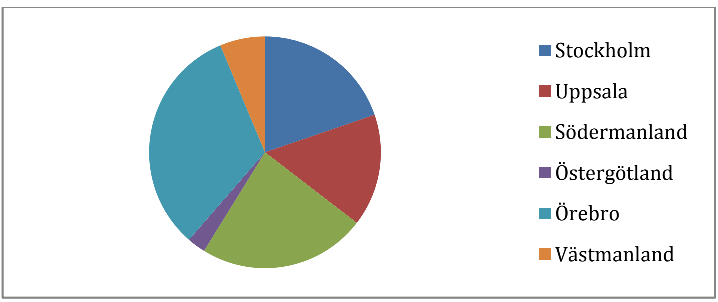


Figure 8. *Allocation of total value of ecosystem services (carbon sequestration of forests, and recreational values from forests, wetlands and agricultural land). Source: Gren and Isacs (2009).*

The main part of the total value of the ecosystem services is provided by carbon sequestration in forests. This is the reason for the large share of Örebro County, which together with Östergötland county accounts for more than 50% of the total value. It can also be interesting to compare the value of the ecosystem services with the green GRP (gross regional product) in each county, see Fig. 9.

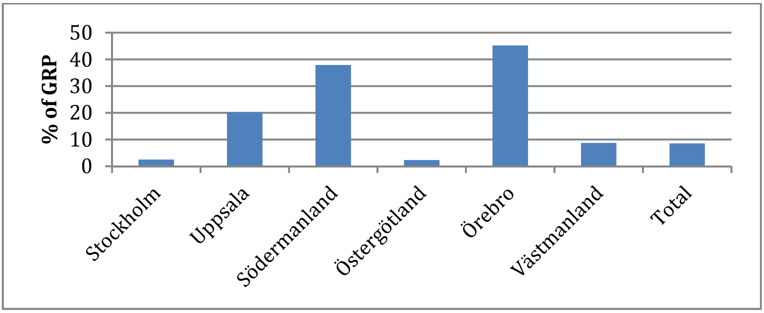


Figure 9. Calculated value of carbon sequestration from forests and recreational values from forest, wetlands, and agricultural landscape in % of GRP in the Stockholm-Mälar region counties. (Source: Gren and Isacs, 2009).

The results presented in Fig. 9 reveal interesting differences among the counties. Whereas the included ecosystem services would increase GRP in Örebro County by 45% and in Södermanland by 39%, the contribution is only a few percent in Stockholm and Östergötland.

In sum, this brief presentation of the Stockholm-Mälar region with respect to economic and some environmental factors indicate significant difference among the counties. Stockholm is the richest as measured by convention GRP and does also show the lowest CO_2/capita. On the other hand, other counties, in particular Örebro, bring the largest shares of values from ecosystem services into the region.

Furthermore, this county may have already reached the carbon free society if this is defined as the net of carbon emissions and sequestrations.

Environmental Governance

Allocation of discretion with respect to environmental governance (including decisions on environmental targets, policy choice, and enforcement) among different jurisdictions and authorities is adapted to the Swedish system for general governance. This means that the region consists of three different public bodies; County Administrative Boards which are the branches of the central government, and the elected County Councils and Municipality Assemblies. The municipalities have strong fiscal power and responsibilities for a large number of tasks within the general welfare systems such as child care, primary and secondary education school, roads and water management. In addition, the veto allows a municipality to inhibit investments within its jurisdictional borders. On the other hand, the County Councils have responsibility mainly for healthcare.

With respect to environmental governance, the central government is responsible for decision on national environmental targets, and is the only body equipped with the right to implement economic instruments, such as carbon dioxide and energy charges on fossil fuels. The central government also sets the national environmental targets to be achieved, currently divided among 16 different targets. Several of these targets are implemented by means of command and control instruments, where firms are obliged to follow certain requirements. Examples are minimum cleaning of water in waste water plants, bans on certain pesticides, and firms' reporting and application for operation activities creating environmental harm. The Swedish Environmental Protection Agency has the overall responsibility for the implementation of these regulations, but has delegated the operational responsibility to the County Administrative Boards and municipalities.

Policy Instruments toward a Carbon Neutral Economy

Neglecting different jurisdictional scales, the choice of policy instrument has been on the environmental economics agenda since early 2000th century when Pigou suggested taxing of negative externalities created by production of goods traded in markets (Pigou, 1932). Pigou used detrimental health outcomes from building factories in congested areas as example of a negative externality. Forty years later, Coase presented an alternative view, where instead of taxing negative externalities, involved partners should bargain, which would result in an efficient outcome (Coase, 1960). Since then, a large number of developments have been carried out, reviewed by Oates & Crooper (1992 & Helfand *et al.* (2003), but the basic difference in approaches to environmental regulation is still valid; reliance on i) enforcement power for implementation of a policy and ii) voluntary (non-governmental) mechanisms. Today, one could relate the choice between the two approaches as dependent on beliefs in enforcement power of a governmental body, or, as in this paper, several linked governmental bodies. With strong enough enforcement power it is possible to implement policy instruments such as charges, command and control or subsidies. When this is not possible, environmental improvements are obtained only through voluntary actions which can be community based or carried out by single firms or individuals. The reasons for differences in enforcement power for a given task, such as promoting environmental development, can be due to differences in discretion set by constitutions or development of institutions. A notable application has been on transboundary pollutants or global commons where there exists no enforcement power at the international scale.

However, irrespective of implementation by public authority or voluntary actions, different mechanisms for affecting peoples' behaviour act in a similar way, and we will therefore give a very brief review on these before entering the main part of this section; to assess theoretical lessons learned from implementing policies in hierarchical governance systems. One, old such lesson, is that of delegated and non-delegated policies with respect to actions to be taken. In general, command and controls system is a non-delegated system since the authority tells the firm what to do. In the other end of the delegation chain we find economic instruments, such as carbon emission charges, where the authority has no command over which actions the firms take but only on the level of the charge.

In addition to certain concrete policies there are also information and education activities which can be exercised by all irrespective of enforcement and delegation systems. Command and control constitutes the most prominent example of a policy where the public body has strong enforcement power and the firms little discretion of action. Enforcement power is also required for the implementation of economic instruments, but now the firms choose which action to take. With little or no enforcement power the public body has to rely on voluntary actions, either by setting requirement of public procurement, or by promoting voluntary actions by giving compensation payment to firms. In these cases, the public body has control over the firms' actions. The delegated case is instead characterized by reliance on firms' initiative and enforcement of environmental friendly actions, such as environmental labelling.

However, irrespective of placement in the enforcement-delegation boxes, the policy instruments have their pros and cons. There is therefore a need for defining which criteria to use for assessing the instruments. Common criteria used for policy analyses are:

- cost-effectiveness and technological development, which means that the instruments should generate determined target(s) at minimum cost in the short and long run by stimulating technological development,
- equity and fairness, implying that agreements should result in equal relative cost burdens among the partners and adopt the polluter pay principle,
- precision and flexibility, the instrument should result in actions as close to the target as possible, but at the same time be flexible enough to give the opportunity of changing targets if found necessary in an environmental perspective, i.e. adaptive management,
- enforcement and transaction costs should be as low as possible, which include, among others, costs of administrating the instrument and enforcing compliance.

Enforcement Power

The vast majority of studies have been analysing and comparing policy instruments under assumption of complete enforcement by the public body. The question posed is then if there is any instrument that is best with respect to all the criteria of comparison? Unfortunately not, but there are candidates that perform relatively well with respect to several of the criteria. The choice is then in principle between four types of policies: command and control, economic instruments, markets for trading, and information.

The command and control policy usually generates a certain target at relatively high costs since it gives no room for cost adjustment at the firm level. On the other hand, given that all firms comply with the regulation, the precision is high. Economic instruments create incentives either to reduce alien spreading activities, such as energy charges, or to make it beneficial to adopt cleaning activities, such as subsidies for bio energy. Charge instruments rely on the polluter pay principle, and are also cost-effective since firms have the possibility to adjust their activities according to their prevention or control costs. Furthermore, since it is costly to contribute to the carbon dioxide emissions, incentives exist for finding new prevention, control or damage reduction technologies. However, the precision is relatively low since it is difficult to predict the final outcome from firms' adjustments to the instrument. On the other hand, there is a great degree of flexibility since it is in principle relatively easy to change the charge level, increasing it if the final spreads are too high and vice versa. A disadvantage is that firms' relatively high control costs create incentives for evading charge payments, which in turn implies higher transaction costs than for other instruments.

The third option – trading market – is a combination of command and control policy and economic instruments, where a maximum level of total carbon dioxide emissions is set for a specific region and quotas are distributed to all affected countries or firms. The European emission trading system is the largest markets in the world. The difference compared with a command and control policy is that these quotas, or permits, can be traded between the firms. This means that firms with high control costs purchase permits and low costs firms sell if the offered price exceeds the corresponding control cost. Thus, cost-effectiveness is achieved through the allocation of control towards low costs firms. In principle then, the trading market has all the relative advantages attributed to both the command and control and economic instrument systems.

The fourth possibility, dissemination of information, on, for example, the risk of damages from climate change, appeals to people's concern for the environment. As such, transaction costs are likely to be low. Another type of information is on methods for, for example, producing bioenergy, which may promote technological development. A disadvantage is that the instrument is likely not to result in sufficient mitigation activities in cases where large efforts with high costs are required.

Little or no Enforcement Power

Studies on instruments available for authorities or organizations with little enforcement power are much more recent and emerge from the recognition of transboundary pollution and the need for international cooperation that must be based on voluntary agreement since there is no international super state that can enforce policies among sovereign states (e.g. Segerson & Li, 1999). Although at different scales, this translates also to local jurisdictions where the scope and scale of limited enforcement power is instead given by national constitutions.

The importance of economic incentives and other motives for peoples' voluntary contributions to public good has been tested in a large number of studies resting on game theoretical foundations (e.g. Gächter & Herrmann, 2009). The results are mixed; both economic incentives and other factors, such as perceived fairness in allocation of outcomes, affect behaviour. However, regardless of the motives for voluntary actions a main disadvantage is the difficulty of predicting environmental outcome. An important advantage is the likelihood of high level of commitment and compliance.

Delegation Design

In principle, the issue of delegation arises from the existence of asymmetric information, i.e. that different actors have different pieces of information of relevance for the environmental task. Delegation can then be made part of or all of the steps in the decision chain: 1) choice of target, 2) policy, and/or 3) enforcement and supervision. Most of literature is devoted to the first two steps, and there is now a plethora of studies on the merits and demerits of environmental policy design and implementation within a multi-level governance structure. The case for centralized and/or decentralized (environmental/fiscal federalism) environmental governance continues to stimulate discussion in the literature. Decentralization is seen as a way of dealing effectively with a large number of objectives, increasing flexibility in policy-making and permitting the use of a broader range of policy instruments (Dalmazzone, 2006).

Those who front for environmental federalism hold the view that the responsibility of decision-making over a particular environmental issue should be the responsibility of the smallest jurisdiction that spatially encompasses all the benefits and costs associated with it (Oates & Schwab, 1988; Oates, 2002; Dalmazzone, 2006;). They believe that making lower-level officials responsible for the provision of a wide variety of goods and services should result in more efficient and participatory government and that unlike national-level agencies, the argument goes, local politicians and officials will design more appropriate policies because they are more familiar with their environments and users' needs (Food and Agriculture Organization, 1999). For example, there are views inter-jurisdictional competition compels public agents to make efficient decisions in the sense that competition among jurisdictions is seen as a powerful constraint on the undesirable expansionary tendencies of the public sector (Brennan and Buchanan, 1980; Oates and Schwab, 1988). Another strand of literature contends that inter-jurisdictional competition is a source of distortion in public choices in the sense that state and local officials in their pursuit of their objectives may hold down taxes and other sources of costs to households and particularly to business enterprise to such an extent that public outputs will be provided at sub-optimal levels (Oates, 1972; Ostrom, 1990).

Other proponents of decentralized environmental governance have emphasized that the capacity of communities and small-scale social entities to manage resources have provided the intellectual grounds for a shift toward co-management, community-based natural resource management, and environmental policy decentralizations (Peluso, 1992; Ostrom, 1990; Wade, 1994). It did so by demonstrating that forms of effective environmental governance are not exhausted by terms such as state and free market institutions, and that users of resources are often able to self-organize and govern them. The success of a decentralized governance of natural resources effects changes in the political relationships through which human beings relate to resources (Agrawal, 2001). The first change is observed in the way decision-makers at the lower level in a territorial-administrative hierarchy relate to those at higher levels (Andersson, 2004). Another significant change relates to the ways local decision-makers relate to their constituents with respect to environmental resources and services. The final aspect of decentralized governance has received very little attention and relates to alterations of the subjective relationships of people with each other and with the environment as part of changing relationships of power and governance (Agrawal, 2005).

Interaction between measures and delegations was considered by Elofsson (2011) who used a two-stage game to investigate strategic abatement decisions with respect to nitrogen fertilizer reductions, waste water treatment, plant phosphorus reductions and wetlands. The key assumption in the paper is that wetland decision can be decentralized. Key among the findings is that under some particular instances, strategic consideration may imply central governments reach more socially optimal abatement actions than a decentralized entity. Thus decentralization of wetland decisions only benefits the local government if its wetland technology is significantly more efficient than that of the central government.

In analysing the role of the national government in developing local environmental policies and institutions in Norway, Hovik & Reitan (2004) argue that the strategy has changed during the period of study (from the late 1980s), shifting from a strong emphasis on the development of local institutions to an emphasis on the delegation of responsibilities from central government to local governing bodies. The authors further argue that this approach, motivated by national, macroeconomic objectives and the role of local government in service production, is inconsistent with the government's ambitions of a more important role for local government in environmental policy. They concluded that the nature of environmental challenges, which often cut across political and administrative borders and characterized by conflicts between different levels of government, suggests that local institutions are crucially important within the environmental policy domain.

Lundqvist (2004) analysed proposals for a new multi-level governance of Swedish water resources to implement the EU Water Framework Directive. At the core of the analysis is an administrative 'trilemma' encountered in designing ecologically effective and democratically acceptable multi-level governance. Within the tenets of good governance, the trilemma is characterised by tensions between effectiveness, participation and legitimacy. The assessment of the Swedish proposal addresses issues of integrating such 'super-local' and local alternatives within the larger web of multi-level water resource governance. In the end, the proposed combination of formal government and informal governance is found wanting in terms of effectiveness as well as participation and legitimacy and failed to escape the 'trilemma'.

Another dimension of delegation is provided by Bulkeley (2005) who sought to develop an account of the geographies of environmental governance to current conceptions which tend to take space and scale for granted as pre-given, contained, natural entities. The paper argues that through a more careful deployment of concepts of hierarchy and territory, common ground between scalar and network geographies can be forged, and can inform our understanding of environmental governance. In making this case, the paper provides an overview of contemporary configurations of global environmental governance and illustrates it by referencing to one trans-national municipal network, the Cities for Climate Protection programme, how governing the environment involves both political processes of scaling and rescaling the objects and agents of governance, as well as attempts to create new, networked, arenas of governance. The paper concludes that recognition of new spatial grammars is necessary for understanding emerging hybrid forms of environmental governance and their political and ecological implications.

Some Summarising Remarks on the Regional Green Economy

The main purpose of this section was to try to answer the question on what can be learned from the literature on economics for the governance of the Stockholm-Mälar region towards a carbon neutral society. This question involves the choice of policies as such, and the choice of decentralization/delegation of discretion among the jurisdictional levels in the region. The different policies, being compulsory or voluntary have their pros and cons, and the choice depends on which criteria are important. Cost effectiveness is one important criterion often met by economic instruments, which, on the other hand, may give rise to low precision reaching targets and undesired income distribution effects.

A particular challenge for the Stockholm-Mälar region is the heterogeneity among counties with respect to economic prosperity and environmental performance. This may be perceived as an argument for delegation of decision rights on policy choice and implementation from central to local jurisdiction. One important justification is the gains obtained from local knowledge on economic and environmental performances and formation of local communities pursuing sustainable use of resources. However, the literature points at potential costs, the neglect of impacts on other jurisdictions and the risk resource exhausting competition among jurisdiction. The main task and challenge in reaching a carbon neutral Stockholm-Mälar region is then to identify, quantify, and balance advantages and disadvantages of different policy instruments and jurisdictional delegation levels. A specific consideration is then the current lack of a strong jurisdiction in between the national state and local municipalities.

II:4 Bioenergy, Land Use and Local Transitions

The aim of this section is to describe the current situation regarding a potential future transition to a climate-neutral society, with a focus on the role of bioenergy in the transition in Sweden. Methods, models and concepts are described. The state of international research on interactions and links between technology, the environment, agricultural land use, models, policy, and scales in time and space are explored, in order to widen the perspectives and prepare the scene for future research.

Land-use changes due to biofuel production can have impacts locally, regionally or even globally and affect a variety of socio-economic and environmental aspects. The effects can occur instantaneously or emerge slowly during a long period of time. Moreover, land-use changes are affected by policies and stakeholder decisions on local, regional and global levels.

Roadmaps to a Climate Neutral Society in Sweden

In response to the major challenge of radically reducing GHG emissions to 2050, the EC has developed a roadmap to 2050 for the whole union (EC, 2011). At the national level in the member states, development of road maps is ongoing. In Sweden, a number of government authorities, coordinated by the EPA, developed a "Background report for a roadmap to climate-neutral society" in 2011-2012 (Naturvårdsverket, 2012). Two scenarios are outlined, one with full reduction in Sweden, and one with less reduction complemented with compensatory activities in other countries. In Sweden, contrary to many other European countries, the power and heating sectors do not require much change to become fossil-free, as power is mainly based on hydropower and nuclear energy (and the current policy does not prioritize nuclear demolition over climate policy) and the heating sector is mainly based on bioenergy and electricity. So the remaining sectors with large GHG emissions are transportation and industry.

For the transportation sector, the roadmap sets up a four-step hierarchy: (i) Reduced demand for transport; (ii) Change to less energy-intensive transportation; (iii) More energy efficient vehicles and (iv) Change to renewable fuels. Consequently, changing urban and regional planning to develop a less transport-intensive society comes high on the agenda. This requires changes in planning policy. In addition to the roadmap, the government has set up a commission for fossil-fuel-independent vehicle fleet, which will go more into detail on transition in the road transport sector. Intermediate reports are being published on the commission website (http://www.sou.gov.se/sb/d/17384).

At the local level, Stockholm has developed a municipal roadmap to 2050 (Miljöförvaltningen, 2013). It is focused on the transport sector, but also includes a major investment in a renewable heat and power plant to replace an existing coal-fired plant. The transport sector plan calls for major investments in public transport, as well as more compact urban development in order to promote pedestrian and bicycle transport. The limited availability of bioenergy is identified as a major risk for the realization of the roadmap, as bioenergy is seen as an important energy source for all sectors – heat, power and transport.

In Uppsala, a project was performed in 2013-15 to develop a roadmap to a climate-neutral society, funded by the Swedish

Energy Agency. The project was initiated by the municipality and had a participatory approach. It included a large number of stakeholders, which were already cooperating in the Uppsala climate protocol, where organizations (business, the major energy utility company, the public sector including public housing companies and the hospital, and the two universities in the city) in their work to reduce their greenhouse gas emissions. The work built on previous modelling of the current and future energy system in Uppsala performed by energy system engineering students at SLU. It is further described in Chapters III:1 and IV:4.

Bioenergy in the Swedish Energy System

Bioenergy is a major energy source in Sweden, supplying about 30% of the total energy. Most of this is forest residues and wood industry residues going into district heating and CHP plants. Bioenergy also has a substantial share of single house heating, as pellets or wood logs. The share of biofuels in the transportation sector has increased to about 5% in the last few years. This goes mainly as blend-in into petrol and diesel, but also to dedicated vehicles using ethanol or upgraded biogas. There is long experience of using willow in short rotation forestry in Sweden, but the production has not reached the large scale that was previously anticipated (Helby *et al.*, 2006) There is a large potential for growing more energy crops on agricultural land, which is related to the fact that there is large agricultural lands that is not intensively used for food production due to lack of profitability (Andersson, 2007). Bioenergy used in Sweden is a mix of local and imported biomass. In the national roadmap to climate-neutrality, an increased use of bioenergy is anticipated (Naturvårdsverket, 2012). General policy measures such as a tax on CO_2 and the EU-ETS system are central to the Swedish climate policy. However, for introduction of new technologies, more specialized policies are needed. One area where this will be decisive is for the introduction of lignocellulosic biofuels (Ericsson *et al.,* 2011). Since bioenergy has such large potential environmental effects related to land use, it is anticipated that there will have to be a continuous development of policies to avoid negative effects of bioenergy (Khan *et al.*, 2011).

Bioenergy, Land Use and GHG Emissions

Bioenergy is used since it is a renewable fuel, and to reduce greenhouse gas emissions by replacing fossil fuels. Bioenergy is of particular interest during the transition from a fossil-based energy system because it is technically similar to fossil fuels, and thus possible to use in existing energy infrastructure, directly or with minor modifications. Biomass comes from a wide range of source (agriculture, forestry, wastes) and can be transformed into a multitude of solid, liquid and gaseous forms.

In recent years there has been a major debate internationally as to whether, and how much, different biofuels reduce greenhouse gas emissions, and this has lead research and new policy on the topic. LCA is by far the most widely used tool for estimating GHG emission from biofuels. Its strength lies in that it sums all emissions in the life cycle of production and use of biofuels, and related this to the function of the fuel, i.e. describing greenhouse gas emission as kg CO_2/ MJ fuel or CO_2-eq/ km driven. Standardisation of the methodology is ongoing and there is consensus on many parts of the methodology (Cherubini & Stromman, 2011). However, some issues are still under heavy debate and research effort. One such issue is how to account for the greenhouse gas emissions caused by land use and land use change, another is how to account for temporary emissions of CO_2 when forests are cut down and regrow (Helin *et al.*, 2012). A key reason why bioenergy is questioned, is that it uses large amounts of land, land that could be used to produce food, or for natural or managed forests. Cutting down forests to produce biofuels releases CO_2 to atmosphere, and is therefore not necessarily beneficial to the greenhouse gas balance, especially in a short time perspective. This has large implications for the role of biomass in the future energy system, as it is clear that biofuels can only supply a minor share of the energy need on a global level. Large research efforts are needed to guide bioenergy development towards sustainable solutions, and policy development in close cooperation with the research community is necessary to achieve that (di Lucia *et al.*, 2012). In the EU, sustainability criteria that require detailed life cycle greenhouse gas emissions calculations for liquid biofuels were implemented in 2011 to ensure that expected greenhouse gas emission reductions are achieved (Ahlgren *et al.*, 2012). Further EU policy to steer development from biofuels produced from food crops towards biofuels based on waste and forest biomass is under implementation. In Sweden, such policy is already in place, for example favouring production of biogas from manure and food waste, as well as development of technology for production of liquid biofuels from forest residues. The Swedish Energy Agency funds large research programmes as well as knowledge synthesis projects on how to avoid negative environmental impacts of bioenergy (Höglund *et al.,* 2013; Egnell *et al.,* 2013).

Key sources for emissions of greenhouse gases from the life cycle of bioenergy is use of fossil fuels to produce fertilizer, run machinery in agriculture or forestry, as well as transport and conversion of biomass to fuels; emissions of nitrous oxide from mineral nitrogen fertilizer production and use, and reduction of the carbon stock in soils or vegetation. Increased carbon stock in vegetation and soils is a potential negative emission, i.e. reduction of greenhouse gas emissions.

The EU has introduced a requirement that life-cycle based greenhouse gas emission are quantified for each fuel, and are shown to give at least 35% reduction in GHGs compared to a fossil fuel reference (Directive 2009/30/EG). The requirement will be sharpened to 60% by 2017 or earlier. The methodology specified is based on LCA, but does not consider the uncertainties in GHG estimations (Ahlgren *et al.*, 2012) and are not quite consistent with LCA standards.

LCA, which relates emissions to the products and services produced, uses a different way of allocating greenhouse gas emissions than the geographically based inventories used at EU, national and local level. These are all based on the sectorial method of allocating GHG emissions defined by the UNFCCC and the IPCC methodological report (IPCC, 2006). Direct emissions are accounted in the sectors where these occur, such as power and transport. Some emissions related to land use, such as carbon stock changes, are attributed to the sector "land use, land use change and forestry", LULUCF. For bioenergy, this means that emissions related to production of biofuels are split between different sectors, including agriculture, transport and industry. The life-cycle and geographic-sectorial perspectives are both relevant for understanding the role of bioenergy for current and future greenhouse gas emissions, but they are not fully compatible.

Land-use changes due to biofuel production can have impacts locally, regionally or even globally and affect a variety of socio-economic and environmental aspects. The effects can occur instantaneously or emerge slowly during a long period of time. Moreover, land-use changes are affected by policies and stakeholder decisions on local, regional and global levels.

Wherever biomass is produced, i.e. on land in Sweden or elsewhere in the world, the production is affected by local and distant factors and has local and distant effects. The actual land use affects future production capacity on that land. The production affects the local environment (biodiversity, water and soils) and local economy, and the local context in turn affects production. Production also affects the climate and world market, and is affected by them. Distant effects can be both direct (i.e., green-house gas emissions from land use) and indirect (i.e., affects land use in other countries in addition to food prices).

Future Biomass Demand and Supply in Europe

The future availability of biomass for bioenergy is an issue of large debate, and it is dependent on many factors such as food demand (especially meat) energy prices, assumptions about biomass productivity and conversion technology development, energy policy and agricultural policy. Bentsen & Felby (2012) reviewed assessments of bioenergy potential in Europe focusing on the time period until 2020. The found a large potential in lignocellulosic energy crops. They also identified energy purposes as a potential major future demand on forest biomass in addition to traditional timber and fibre products. Based on the national renewable energy projections reported to the EU, an increase in bioenergy demand from 3.8 EJ in 2005 and 5.7 EJ in 2010 to 10.0 EJ in 2020, was estimated, as well as a further increase in demand after that. Heat and power would still be the main part of the demand, but transport demand would increase from 5 to 20% of the biomass demand. They cite other authors that have found that demand for meat is a major competition for land availability for energy. In a recent paper, Jansson & Wilhelmson (2103) estimated the effect on European agriculture and land use if the goals for first generation liquid biofuels according the national energy projections are met. This would lead to a large increase in vegetable oil demand for biodiesel, and a large increase in vegetable oil prices and imports. The total amount of agricultural land would change by less than 1%, but there would be large regional changes in crops grown and amount of agricultural land.

Transition Management

Policy for achieving climate goals was described in Section 3. Another perspective on policy for societal change to achieve sustainability targets is transition management towards sustainable development has been described by Kemp *et al.* (2007). Transition management uses both bottom-up and top-down approaches and is highly adaptive. It is described as co-evolution between different subsystems in society, which influence but do not control each other. Transition management is seen as inclusive, and new institutions, arenas, where many actors can meet, are one key aspect. Setting of long-term goals is another important aspect, and a third aspect is innovation, experimentation and learning from experiences. Transition management is exemplified with the development of the Dutch waste management sector from the 1970s to the 2000s, which is described as co-evolution of the waste management system and societal values and beliefs. Three levels are described:

- strategic, including new ways of thinking, especially the waste hierarchy (ordered from the top: prevention, re-use, recycling, energy recovery, landfilling)
- tactic, including a new institution, a national network organization, the waste management council; and producer responsibility policy
- operational, which includes closing of polluting landfills and incinerators, and replacing them with fewer, larger, better ones, as well as source-separation and recycling.

The development of roadmaps to fossil free society is a type of back-casting. Participatory back-casting is a method for system innovation and socio-technical transition with involvement of stakeholders, which includes defining first steps and roadmaps towards an envisaged system change. Quist *et al.* (2011) analysed the 5-10 year impact of back-casting experiments performed in Netherlands. These were research projects with stakeholder engagement through workshops and other activities. Three key areas for success were identified:

1. That one clear vision, with orientation (where to go) and guidance (how to get there) is formulated.
2. That networks are formed, that continue beyond the project; networks with different stakeholders in four domains: research, business, government and society, and that there are resources and activities in the networks.

3. That the networks, visions and actions are institutionalized, and that there is not too much institutional resistance to the vision.

Models on Energy Systems, Land Use and Transitions

Energy Systems

Energy system modelling is an important of analysis of pathways to fossil-free society. There are numerous energy models available, developed for different type of energy systems analysis. A full review of energy system modelling is beyond the scope of this report. The scoping report D5.1 of COMPLEX WP5 also reviews modelling strategies for renewable energy systems. Thirty-seven models of relevance for integration of renewable energy into energy systems were reviewed by Connolly *et al.* (2012) including a short description of each model, and aiming to guide users to the best model for their specific application. No models that are specialized on bioenergy or that include land use were included in the review. Models were categorized based on number of users, and whether they can be used of simulation, optimization, scenario-building, if it is an economic equilibrium model among other factors. Moreover, the time frame, time-step and geographical area differed between models, as well as the energy sectors considered. Most models covered the electricity and heat system, and some also included the transport systems.

For the roadmap to a climate neutral and fossil-free Uppsala (Section 4.1), the Long range Energy Alternatives Planning System, the LEAP model (www.energycommunity.org) developed by the Stockholm Environment Institute (SEI) was selected, based on its appropriate one-year time step and flexibility regarding scope and detail (Lantto, 2014).

Land Use Dynamics

Several approaches for modelling land use have been proposed in recent years. These can be divided roughly into those originating from economics and those originating from geography (Vliet *et al.*, 2011). Economists have mainly been using models that compute an equilibrium situation, in which resulting land use or population density is depending on the distance to an urban center, sometimes in combination with other factors (for an overview, see Anas *et al.*, 1998).

While these models may be useful in the context of land pricing and urbanization, they have a few drawbacks that make them less suitable for the study of land-use dynamics. For example, *time* is not treated explicitly, and therefore developments over time cannot be studied. Moreover, *space* is considered only as the distance to the urban center, ignoring features that are not homogeneous over space such as elevation, transport networks, or rivers.

In Europe as a whole, about 10% of the GHG originates from agriculture, and in Sweden this percentage is 13 (SEPA, 2012). Most of the land in the Stockholm-Mälar region is agricultural, and the EU Common Agricultural Policy (CAP, EC2005) is highly relevant for this region. An integrated modelling tool, the LUMOCAP PSS (Dynamic Land Use Change Modelling for CAP Policy Support System), has been developed for assessing how different policy scenarios will impact the land use and landscape at different levels in the EU, including at the NUTS2 regional level (van Delden *et al.*, 2010). In particular, this system is used to investigate the relation between EU policies, agricultural economics, land suitability and land use dynamics using dynamic simulation. At the regional level the system uses Metronamica, which allocates the area demands for different land use categories, and simulates the competition for space between land use categories, in order to obtain the most preferential locations (See Fig. 11).

While CA based models are simple and data friendly, they cannot capture the richness and diversity in land uses one observes in reality, for example mixed land use at one location. Also, individual actors and decisions are not considered in CA models. Hence, more complex models have been developed, where several types of decision-making actors, or agents, can be modelled, in addition to spatial locations. This type of agent based models (ABM) or multi-agent systems (MAS) was discussed in a previous section.

As with CA, ABM and MAS include time explicitly, allowing for feedback mechanisms over time, but the agents in ABM/MAS are actors that can act and move independently over space. The advantage of these models is that they can represent the behaviour of agents in a very straightforward way, since agents can interact directly with each other and with the environment. More precisely, these local interactions between agents and differences among them generate the patterns observed on a global scale.

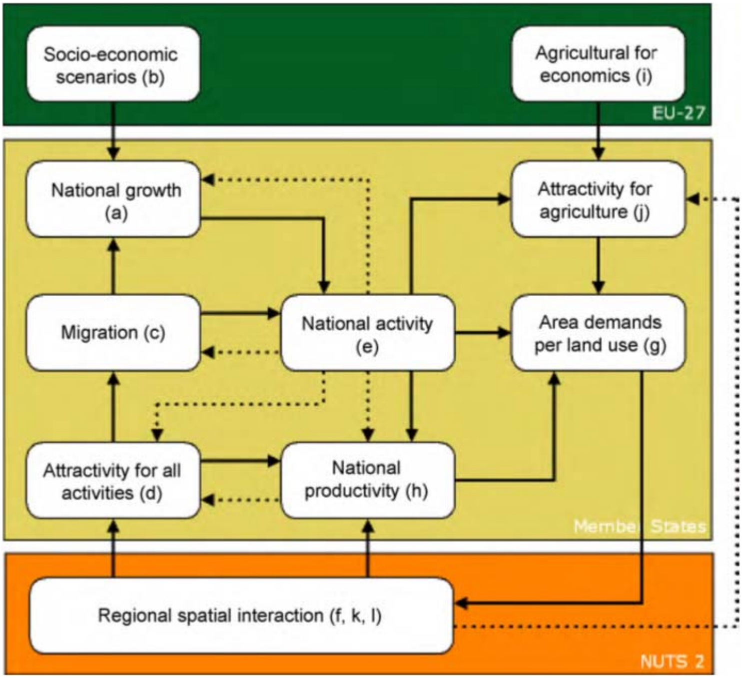


Figure 11. *System diagram of the national (and regional) spatial interaction and distribution model. The arrows show the flows of information; black arrows represent current values and dashed arrows lagged values (values from the previous time step). (Adopted from van Delden et al., 2010)*

Case Studies on Bioenergy and Land Use in Energy System Transition

Some recent cases studies have been published, mainly in Europe, which relate transition to renewable energy and land use, with bioenergy in a key role. Climate change and food production are included to variable extent.

Schmidt *et al.* (2012) analysed the potential for a region of 20 000 inhabitants in Austria to supply its own heat and power in 2020. They used a coupled model of energy demand, energy technology, economy and spatially explicit land use to optimize the energy system based on cost, under different constraints. The energy system was modelled for two seasons, i.e. not in any temporal detail. Current energy use includes a large share of fossil oil in the heating system. As biomass was the most competitive source of local heat, it was the main source of local energy. Forest, SRC, biogas from crops and oil crops were included, and SRC was most competitive. In scenarios with local heat and power, a large share of the arable land was used for SRC plantation. For the scenario with only heat, land use change was less and the increase in cost was very small. The results were very sensitive to oil price – with slight increases in oil price (compared to baseline \$80 bbl^{-1}) self-supply with biomass would become profitable. GHG emission reduction was not central to the analysis, and reductions were not reported.

Trade-offs between renewable energy (bioenergy, wind and solar power), food, feed and wood production at the local level in England was analysed by Burgess *et al.* (2012). A per capita approach was used to illustrate the local potential to produce food, wood and bioenergy needed for a growing population in a town doubling its population from 25 000 to 50 000 . A GIS with 17 land use categories was used. The report discusses the benefit of producing and presenting data in formats that are useful for stakeholders, and use the unit kWh d^{-1} p^{-1}, which they think eases understanding and comparison. The model and framework presented is intended for future expansion to include greenhouse gas emissions and economic aspects. In another publication form the same project, Howard *et al.* (2013) define “energyscape” as “the complex spatial and temporal combination of the supply, demand and infrastructure for energy within a landscape”.

The paper is centred around the energyscape concepts and its potential for communication and decision-making on energy in the landscape, especially concerning environmental aspects, identified and classified as ecosystem services. A key aspect is the geographical aspect, with renewable energy being explicitly localized in the landscape. The potential for communication with stakeholders is discussed, showing that "the local energy landscape" may be a better term for introducing the concept.

Conversion to fossil-free agriculture using biomass has been analysed in a number of projects at SLU, Sweden. The land use and the life-cycle greenhouse gas emissions for supplying current or future biofuels to tractors, and for producing mineral fertilizers from biomass have been estimated (Ahlgren *et al.*, 2008ab, Fredriksson *et al.*, 2006). More recently, it has been shown that the agricultural residues available on an organic arable farm are sufficient to supply all energy needed for running the farm, using energy conversion technologies that are technically but not commercially available (Kimming *et al.*, 2011).

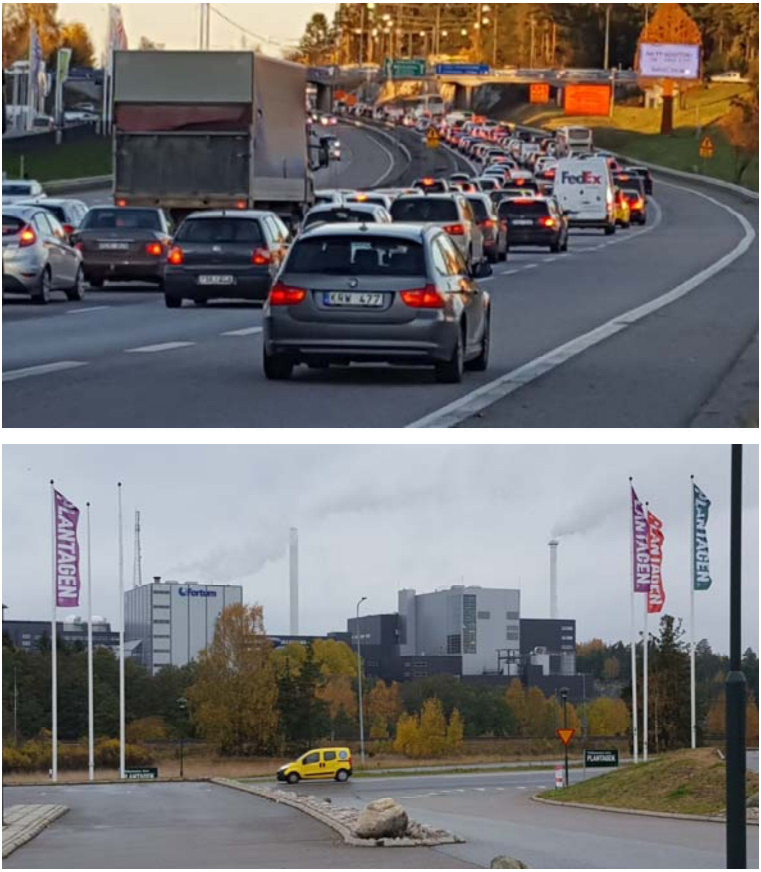
An interesting example of an integrated modelling approach including the spatial distribution of agricultural production, life cycle greenhouse gas emissions, net energy and economic profitability was described by Bryan *et al* (2010) , who modelled agriculture for food (wheat, legumes, sheep) and biofuels (wheat and canola) under different climate change and carbon subsidy scenarios In South Australia. The agricultural production model used a daily time step for 115 years and could thus account for production effects of different scenarios for future climate. The spatial variation was 14 soil types and 16 climate zones modelled in a GIS. Land use decisions was assumed to be made based on profitability, which were affected by the level of subsidy based on greenhouse gas emission abatement by biofuels. The result of the model was that a modest subsidy would lead to a major conversion of about half the agricultural land to biofuels, which would give a substantial reduction in GHG emissions, but also in food production.

In addition to these local case studies, modelling has also been done at the global level. Reilly *et al* (2012) used linked economic, atmospheric and terrestrial ecosystem models to analyse the effect of different policies on land use and climate in 2100. Dynamic models were used – with climate change affecting productivity of land, which affects the economy. This type of modelling cannot be scaled down directly, as food prices are not set by local productivity but need to be included as externally determined parameters in local land use models.

Some Summarizing Remarks on Bioenergy

The concepts of transition management and co-evolution of different societal and socio-technical systems seem suitable for a higher-level description of the long-term processes and changes that drive climate change mitigation. Participatory back-casting, and more precisely roadmaps to climate-neutrality by 2050 is a current tool being applied at EU, national and regional levels to guide long-term decisions towards reduced greenhouse gas emissions. In Sweden, bioenergy is a key energy source in the transition to fossil-free society. However, bioenergy production causes greenhouse gas emissions, and there is a trade-off with food and fibre production, even though agricultural and forest residues can be valuable bioenergy resources. Evaluation of the role of bioenergy in the future energy system and the reduction of

GHGs requires integrated modelling, and there are many opportunities for new integrations in future research.



The intense traffic on E4 Stockholm-Uppsala at rush hour (top) and the bio- and waste-fired power plant Bristaverket in Sigtuna (bottom). Photo: H. Liljenström

II:5 Governance, Policy Instruments and Stakeholder Positions

A Multi-Level and Multi-Actor Approach

Among the central perspectives that need to be considered when dealing with paths to a low carbon society is how the governance systems – in particular the decision making structures – perceive dilemmas and are operating in this regard. As our focus is a regional one, our attention is mainly devoted to that governance layer. However, we are concerned with a multi-layered structure from the very local and "upwards", often in nested combinations. Many of the challenges depend on how such a multi-layered structure – and multi-type of actor space might be able to adapt to the new circumstances and tasks (see e.g. Bressers & Rosenbaum, 2003).

Thus, in this "perspective on policy making" the wide variety of stakeholder positions is of great importance as it "frames" how problems, dilemmas and options could be understood. Indeed an analysis around what is perceived (in all its plurality) and done in various political and planning communities (including industry and related actors) and within the open discussions in society will also indicate the variation within which the system tends to operate. Key to this is how the underlying "framings" (or mind-sets) provide the conceptual landscape as a basis for positions taken around these issues. Indeed sometimes such an analysis may also indicate venues not yet sufficiently actualized and which in the future may rise in importance. This is especially relevant when contemplating how the decision support system should be designed in order to fit the challenges. Further steps will involve relevant decision advice in a broad sense, including suggestions for widening the current framings in the public debate.

The Level of the Stockholm-Mälar Region

By means of interviews and listening to presentations at a number of occasions from a wide range of politicians and employees in municipalities, counties, regional bodies (e.g. *Mälardalsrådet*) as well as from representatives of industry, including agriculture and forestry, NGOs in the region, and from civil society in general, our own understanding of positions and framings have been built up. This learning process has been further complimented by participatory observation in seminars and in our own focus group workshop with stakeholder participation in Sigtuna. Contacts have also been taken referring to the national and international/EU levels on these matters. As a condensed version of some of our key findings - so far - we present the following insights below.

Key Political Issues Shared

There is a strong focus in the political and planning communities in the region (but also among industrial actors) on transport and physical mobility in combination with issues around workplaces and housing. It is not surprising that an indicator system is given high weight in regional policy that is focused on commuting times to the Arlanda International Airport from different spots in the region. In the current discussions these concerns are slowly also being broadened to include the entire energy-climate-water-food nexus. This nexus is closely connected to the spatial bio-geographical concerns that relate to climate change impacts on the biomass production (i.e. the future of agriculture and forestry issue). It also relates to matters concerning carbon sinks and, in general terms, the competition of land use. Here, the concept of ecosystem services has been articulated as an important and emerging indicator to be included in transition models. This means that other types of indicators, as those for mobility have only rudimentary been developed (although there are signs of other interests in e.g. ecosystem services approaches).

Culturally oriented drivers for change and the topic of what could in the future constitute "social status" is something that is under emerging concern. This connects to how the GDP measure is used as indicator of progress, and what it reflects (and not). Another concern for further elaboration is the need to innovate novel policies in ways that are informed by cultural perspectives. Given the cognitive landscape of expressed types of interests, a number of policy-oriented concerns are rising, as well as the need for reformed indicators of change. The consumption issue is articulated as a very important topic related to this.

New indicators, measuring the progress of the transformation to a low carbon society, could perhaps include some new measures on social wellbeing, and at the same time include environmentally oriented goals. In a broader picture, there is a concern for the future needs to enhance the protection of ecosystem services as a central part of the overriding challenges. An interesting issue is also how to care for central values in our society, e.g. with regard to democracy and human rights in the midst of the transformation turmoil towards a low carbon society. Ideologies behind both projections and solutions in the transition work need to be explicitly and publically discussed also in the future.

Exploring Policy Options

Urban decentralization in spatio-political terms is emerging as an important topic. The meaning of that for this region is to steer urban growth also to smaller cities, not solely to Stockholm. A regional low carbon society might need to be based on a multi-node urban structure - linked to strong investments in public transports and accessibility capacities by means of e.g. improved "walkability". Here the importance for the future of a careful design and planning of multiple cosmopolitan urban hubs in the region, including effective public transports between and within those hubs. This relates to interests in a development of smaller towns in the wider region that would counter the trend of the current "just commuting into Stockholm" tendency. With focus on local solutions in a decentralized urban structure of the region the following ingredients are highlighted: a decentralized mode for energy production and consumption, a need to support small scale enterprises, industries and employment possibilities, a reduced overriding transport need, and increased local food production. In the ongoing discussions in the Swedish society it seems to be of strong importance to support local initiatives, ranging from energy production to 're-localization' of food production. The food issue has also opened up for concerns of eating habits, including aspects around meat eating in connection to the carbon cycle. In this way the broader concern about the impact of consumption and on consumption patterns in general has gradually come more into the picture. This in turn connects closely to the topic of "life style" which seems to be of increasing importance.

The industry sector in the region is diverging in terms of strategies and perceived responsibilities related e.g. to when and how certain technologies may be introduced in market terms. In some segments of industry, investments for phasing out fossil fuels are not seen to be easy before 2040 due e.g. to perceived potential losses of market shares. It thus seems that early industrial leads of a transition towards a low carbon society will perhaps come from some sectors rather than from others. Some industry sectors, such as forestry, already are seen to take initial steps in phasing out fossil fuels as it already now is seen by them to give a competitive advantage. As evidenced by the state investigation finished late 2013 the vehicle and connected fuel support industry already have their eyes set for considerable changes already for the period leading up until 2030 (including e.g. renewables and electricity solutions). All these potential changes are conditional to what might be developed as patterns of public incentives into often cut-throat-competitive markets (or at least dependent on over time strongly reduced direct or indirect subsidies to fossil fuel solutions). Here the instruments from the public policy side (e.g. with regard to state regulations and incentives) related to potentially new directions of industrial solutions are important – not least with regard to novel (and maybe not yet even manifested or existent) innovations. The entire field of innovation policy is of high importance.

Another line of policy options is dealing with the need to consider the time sequence of efforts in transition work. For instance energy efficiency improvements are initially seen as a "low hanging fruit". However there are indications that this measure alone most probably will not be enough to reach the goals by 2050. Political bodies in the region have discussed other types of policy instruments that could support and guide a transition e.g. a possible law on civil society community service, tax reform which includes a reduction of the tax on labor simultaneously as an increased tax on fossil fuel consumption, and government support to promising initiatives (see Fig. 12). The State investigation on vehicles and their fuels provided several didactical examples of new ways of thinking about multiple benefits solutions. It also provided a broad set of both private and public actors that need to – and already are starting – to collaborate.

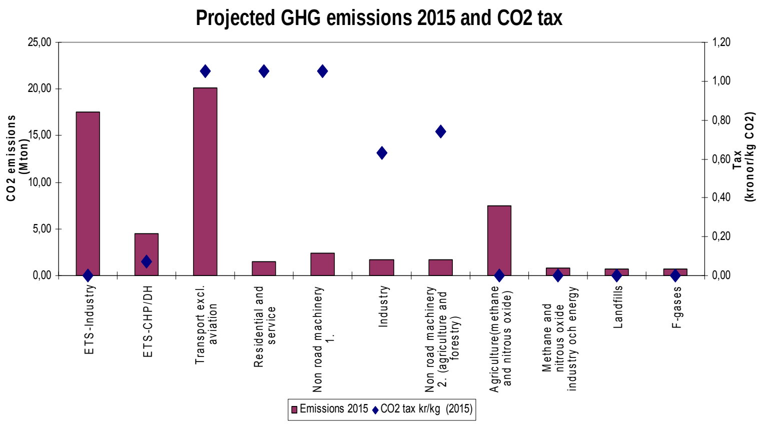


Figure 12. *GHG emissions and CO_2 tax predicted for Sweden in 2015 (Swedish report for assessment of projected progress in accordance with article 3.2 of Council decision No 280/2004/EC on a mechanism for monitoring Community GHG emissions and for implementing the Kyoto Protocol).*

Another related issue under debate is how to connect government politics (in its function to create a basis for a low carbon society) with market based processes in order to find a creative balance between both market and non-market mechanisms in the region. In order to enable such a development it seems that bottom-up initiatives would have to meet state support of various kinds (i.e. top-down approaches), e.g. with regard to renewable energy production policy initiatives (and other similar supports to innovations and demonstrations). There is a need to link to ongoing activities also outside the region and thus for the top-down policy interventions and support that is required for this. The combination between bottom-up processes and processes more of top-down character is thus seen to be essential, as illustrated in Fig. 13. Early examples of these types of policy solutions are already visible and should definitely be further encouraged as pilots. There are a number of initiatives already in place in this direction that need to be given distinct visibility. In order for such solutions to take-off there is a distinct need of financial support and governmental intervention e.g. by a creation of a "sustainability fund" (or similar financial mechanisms).

In the discussions related to the interplay between the national level at the top of Fig. 13, and the municipal, or cross municipal, at the bottom in the figure, the following pattern is seen. Here we see some of the basic elements that are involved in a pathway to transition. The interplay between the levels is indicated by the arrows on the left and the right hand side:

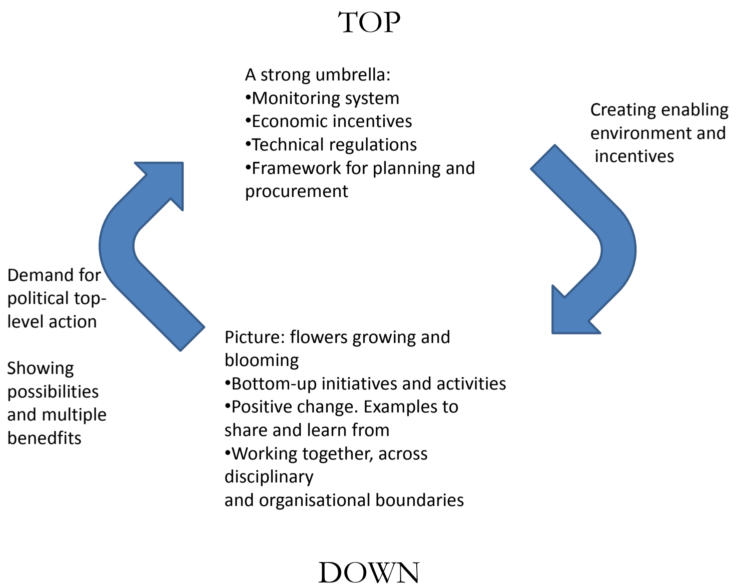


Figure 13. *Illustration of combination of bottom-up and top-down mechanisms*

Barriers in a Transition to a Low Carbon Society

Many of the discussed directions and solution elements may have difficulties to materialize. Thus it is important to analyze hindrances, blockages and also tensions around many of such suggested policy oriented concerns and action lines. One explicit barrier on the governance structure is problems with overlapping spatio-governance regimes not adjusted to the new goals of a low carbon society. This may create emerging system contradictions in policy making between different actors (and between sections within organizations) and operating bodies at the regional level due to unclear needs for changed system boundaries related to roles and mandates. Accordingly "obstructing actors and institutions"

– often actors and institutions that are heavily embedded in old solutions and resist to change to low carbon futures due to earlier large scale investments-are expected to resist a transition. Related is the need to better understand policy instruments that can deal with "cognitive lock-in" situations and issues of "cognitive dissonance" raised in relation to a transition to a low carbon society in this region. The key for an understanding of the transition out of 'cognitive lock-ins' are increasingly seen as also to be related to people's choices of life-styles and to the professional production of preferences. These aspects relate to a number of issues, for instance to issues of design of local spatial solutions that go in line with a low carbon society, of social learning, as well as to issues related to social equity and inclusion in spatial planning.

The Policy Context of the Swedish National Level

What has been said above, related to the regional level, has to be viewed also in the broader context of the Swedish national policy (including how it encompasses also EU/international levels of operation). Many of the conditions – but not all - within which regional developments are made possible have their source at a national policy level. Thus considerations about future options for regional transformations until 2050 always have to be spelled out in this broader national frame – including issues about blockages and solutions to blockages. Below, we just touch on some very recent national level examples to indicate the type of considerations – with reference to the topic of low carbon society developments – that currently are discussed in Swedish governmental circles. This list is by no means exhausting all current activities on these matters. It is just a small set drawn from different institutional platforms within a very particular field, i.e. the development towards a fossil free vehicle fleet.

The emission goals have been dwelt upon in several settings in the public sphere, including the Parliament, the Government and its ministries, and among national agencies. It is interesting to note that with regard to the Swedish government, major future challenges close to the ones we are dealing with in the COMPLEX project, were addressed in the Commission on the Future of Sweden that delivered its results in 2013 (Johansson, 2013).

The Commission on the Future of Sweden was concerned with – among other issues - how Sweden can develop into a green economy. (Several questions related to this were already addressed in Sec. 3, within the specific perspective of "A green economy in the Stockholm-Mälar region".) The Commission acknowledges the environmental and climatic challenges that are connected to actions, such as those in international trade, emissions profiles, natural resources and ecosystems depletion, and biodiversity loss. However, the Commission is eager to stress that Sweden has already made significant progress by meeting key milestones in transforming to a green economy. Sweden's C02 emissions per capita are among the lowest compared to most countries. This is due to fossil-free electricity generation using hydro, biomass and nuclear technologies. In addition clean air and fresh water policies and actions are among others measures that indicate that Sweden is on a sustainable development path. Despite these achievements, a lot more remains to be done in reaching the long term European Union's emission targets for 2050.

At the national agency level, the Swedish Environment Protection Agency has had an overriding responsibility to coordinate what is called *The Road-map For a Sweden Without Greenhouse Gas Emissions in 2050* (Swedish Environmental Protection Agency, 2012). A wide representation of Swedish actors has been involved in this process including counties and municipalities. The Road-map 2050 points at the way to reach a carbon neutral Sweden by 2050 with the aim of having no *net* emissions from Sweden. In order to reach these goals it is important to address which policy instruments need to be changed – how, and to make it cost effective. The county boards conducted stakeholder dialogues and reported about the outcomes to the Swedish EPA. These were intense dialogue processes with focus on policy change instruments.

The development of scenarios of the emissions inside the Swedish territory is important (but they do not include the embodied energy from imported products). In this regard it has been seen to be important to develop back casting techniques aimed at answering e.g. the question "how near zero can we reach". Different industrial sectors have varying strategic approaches to the needs and to the operational steps that are needed – and when. The forest sector is indicated to be an example of delivering early positive moves in terms of changed perceptions and actions. It seems that these sector actors already have started their transition. There are also other examples from industry having taken creative strategic steps.

One particular – and highly relevant and illuminating – sector case has been handled by the specially appointed Commissioner for the Official Report to the Swedish government

Thomas B. Johansson (including his staff and an elaborate consulting structure) on fossil free vehicles (Johansson, 2013).

The background to the commission work is the acknowledgement that today´s international energy systems need to be drastically changed as 80 % of energy use comes from fossil fuels. The changes needed relate e.g. to energy services, universal access, affordability, health and environmental concerns, as well as the concern to connect to planetary boundary issues (and in particular the climate issue), and issues about global peace (risk of oil wars and security). Some of these issues are strongly related to regional realities, but others are not in reach of regional policies (but such policies may support goals in need of being pursued at higher system levels). New possibilities are emerging. Drastic fossil reductions can be made possible e.g. with regard to changes in the sector of fuels. This both holds true for energy efficiency gains but also for strong shifts towards renewables and electricity based solutions for vehicle fuels.

"Multiple benefits" is a concept that the Commission has highlighted as a suggested benchmark tool that may help the needed transitions, by moving attention away from focus just on specific costs. Instead there is a need to develop methods where multiple benefits of a societal transition are highlighted, e.g. in terms of jobs, growth, security, health, improving local environments etc. In relation to such benefit assessments social science studies are needed to illuminate which segments of society are gaining and which are losing. Among the energy system changes that need to be addressed for the future you find those related to the transport system, or in general terms the possible energy efficiency improvements (which are seen to provide the most close by immediate action lines for the near future). The overriding goal is clear: Fossil fuels must be phased out. The Commissions position is that it might definitely be possible in its field of investigation i.e. a fossil free vehicle fleet – already until 2030 – given that sufficient support is given and surrounding conditions are met (Ibid.).

III. STAKEHOLDER INVOLVEMENT

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A sequence of stakeholder interaction events and processes, including development of partial models covering specific transformation aspects have been carried out.

In addition to the continuous and frequent stakeholder interactions, as in the example of the Uppsala Climate Protocol (further described below), several stakeholder workshops were organized in the Swedish Stockholm-Mälar region. The purpose of these workshops has not primarily been to support the modelling work, but to provide understanding of the broader mind-sets, regarding the regional societal transformation issues. Still, all the stakeholder interactions have contributed to the modelling activities.

Section III consists of the three chapters:

III:1 Stakeholder Workshops

III:2 Stakeholder Participation Using Model Support

III:3 What Stakeholders Really Think About Models

III:1 Stakeholder Workshops

Participants at the four workshops included representatives of stakeholders of different types at different levels, according to Table 1. (Numbers in the boxes correspond to the different workshop numbers). As seen from the Table 1, most categories of stakeholder were represented, often with several participants for each category. For example, National/Public stakeholders included representatives from the Ministry of Environment, Swedish Environmental Protection Agency (Naturvårdsverket), the Swedish Transport Administration (Trafikverket); Regional/Public included Mälardalsrådet and representatives of various county authorities; Local/Public - a considerable number of municipality representatives; Regional/Enterprise included large companies and consultancies; Local/Enterprise included businesses dealing with solar panels, etc.; Civil society included transitional movement, and a large environmental NGO and their regional or local representations. According to the workshop design a number of the stakeholder representatives (about 1/3) were invited to be present at all three workshops, in order to provide a degree of continuity.

Table 1. *The representation of various types of stakeholders acting at different levels, with numbers referring to the corresponding workshops conducted. (In all workshops researchers were involved, either through the core organizer group or as invited scholars).*

Level/Type	Public	Enterprise	Civil society
Local	1,2,3,4	1,2	1,2
Regional	1,2,3,4	1,2	1,2,3,4
National	1,2,3,4	1,2,4	1,2,4
International	1	2	

Workshop 1

The investigation of dominant understandings in the region showed that there are a lot of activities aimed at reaching a low carbon society. Parallel strains of planning/development approaches seem to coexist, both more "conventional" lines of thought and policy, as well as "new", and still only to a limited degree articulated, and even less manifested perspectives. This can be seen as a simultaneously ongoing "double-think" i.e. a multi layered framing situation with a plethora of different thought patterns.

Regarding the first category, the strong focus in the political and planning communities (but also among industrial actors) on transport and physical mobility was evident, also in combination with concerns over the locations of workplaces and housing. In the discussions these topics broadened to the entire energy-climate-water-food nexus. This is closely connected to the spatial bio-geographical concerns related to climate change impacts on biomass production– but also to matters concerning carbon sinks and land use competition. Here the concept of ecosystem services was articulated as an important indicator to include in transition models.

The food issue led to discussions about eating habits and local food production. The connection between meat consumption and the carbon cycle was explored. In this way the broader concern about the impact of consumption and consumption patterns in general, was highlighted. This in turn connected to the topic of "life style", which was considered to be of increasing importance and which came back over and over again in different combinations in the context of transformation of society towards a low carbon goal. In discussions on possible future culturally oriented drivers for change the topic of "social status" and what it could be in the future was mentioned as a possible and maybe promising pivotal point to induce transformation by way of novel policies informed by the cultural perspective.

A final remark was that current policymaking seems mostly to be oriented to handle one thing at a time – sector divided. A relevant example of this is the emphasis on cost efficiency in climate policy at national level, which tends to close the door to implementation of a broader "policy for dynamic change". This is closely related to the choice of (environmental) indicators. Such indicators used at the political level are concerned with emissions and environmental states in the current situation i.e. in relation to the time sequence from the past to the present. However, dealing with future goals requires indicators that can cover future emissions.

The importance of placing this and the following workshops within the context of other stakeholder events in the overall sequence of WP4 activities was clearly demonstrated. (A more thorough description of the workshop and its outcome is found in the COMPLEX report MS43).

Workshop 2

The second workshop, "Stakeholder involvement in gaming and model reflection - on decision support capacities using an experimental framework", was also held in Sigtuna, in November 2014. The objective for players in the game was to act as the government of Sweden, and to reduce the CO_2 emissions in the Stockholm-Mälar region. The Stockholm-Mälar Region model was based on commercial software (DEMOCRACY 3) and was created in a series of preparatory smaller meetings with regional experts and policy makers. In these meetings, the model, which DEMOCRACY 3 is based on, was presented, and the participants were asked to reflect on how the model could be adapted to better reflect the Stockholm Mälar regional context. These changes were incorporated into the model.

This time the goal was to explore the positions held by a specific set of selected professional planners and decision makers in the region, and to reflect on causalities and how to represent them. The participants did not bring models of their own, but displayed experience with handling and setting up of models within their own organizations and activities.

Around 25 persons participated in the workshop representing a diversity of institutional experiences and competence backgrounds. A general plenum discussion focused on the relationship between decision making and modelling. More information on this exercise is given in Chapters III:2 and 3.

In addition to the gaming exercises in Workshop 2, ongoing WP4 modelling work (regional economy, municipality climate planning and cognitive modelling) was presented and discussed. Again, the central issue was the approach to modelling in relationship to decision-making - rather than the models themselves.

Conceptual models of various kinds were discussed, concerning for example the relationship between choice of living places in the region and options for travel from home to work. One of the main learning outcomes was an understanding on causality and its codification in relation to decision-making (e.g. uncertainty, biases, trade-offs etc.). The overall recommendation was the same: exercises like these should be positioned with the context of other stakeholder activities within a project.

Figure 14. *A picture from the gaming exercise of WS2*

Workshop 3

A third workshop, on "Paths towards a fossil free society in the Stockholm-Mälar Region", was organized in September 2015. The aim was to explore the positions held by a range of stakeholders in the region, and their understanding of the particulars of *alternative pathways* to a low carbon society, and how these could be considered together.

The stakeholders were chosen to represent a wide array of different stakeholders at different levels and with different backgrounds. Around 20 persons participated (see Table 1, and examples given above).

No particular models were used, but a general set up of dominant factors to be considered was used as input to the discussions. The choices of factors were based on the accumulated understanding of the issues based on the continuous interaction with stakeholders throughout the WP4 research process.

Conceptual models of various kinds were exposed in the different discussions originating from the participants backgrounds and experiences. The learning outcome was a deepened understanding about which the key alternatives are regarding an appropriate path to a low carbon society. For example it became quite clear that the regional development in the Stockholm-Mälar setting in a planning perspective seems to be very dependent not only on the development of the physical infrastructure (e.g. of the transport system with all its investment, technical and managerial aspects), but also on how the drivers of the demand of mobility come about in terms of future citizens preferences. The outcomes will be very different depending on whether they choose to concentrate their living space to Stockholm and vicinities - or to use a more commuting style of life for parts of a family or with regard to certain parts of a personal life career (e.g. relationship to study opportunities or connections to future job markets). This in turn is highly dependent on life style changes and choices. The main lesson was about the diversity of positions and what it means for the societal choices of decisions, and how different conditions could be regarded.

As an overriding outcome of the reflections around the scenarios the position is that some would be very much easier to implement than the others. Especially paths under harsh economic conditions may need stronger efforts and policy interventions in order to reach the goal. However also within these more problematic scenario conditions, paths may well be found although the time distribution for the solution activities within the change process might be shifted forward in time, i.e. later arrivals of solution impacts of sufficient strengths. (More details about this workshop are reported in the COMPLEX report of MS47).

Workshop 4

As a final round up of the work we arranged a workshop for around 30 specially invited participants. This workshop was labelled "Strategic Choices to Reach a Fossil Free Society in Sweden – the Regional Dimension", and was held at the Sigtuna Foundation on 20 September 2016. The basis has been a combination of the issues high on the list of the Swedish case project and issues of high concern in the Swedish political and organizational system with regard to the fossil-free society challenges. Thus the meeting could be seen as a contribution to the national and regional work in Sweden in a situation when the implementation of the UN meeting in Paris in December 2015 is high on the political agenda – including the wider Agenda 2030 work related to the Sustainable Development Goal (SDG) agenda also consolidated at the international level during 2015.

The presentations and discussions had a distinct Swedish national profile, but with interest and concerns about the regional dimension as well, not least with regard to our case domain i.e. the Stockholm-Mälar region. Much of the implementation and innovation efforts within the next few decades will have to be performed at that level.

The workshop design contained three consecutive thematic areas

1. The Swedish national challenges in the work to implement a fossil-free society
2. The regional dimension
3. The role of science in the societal transformation process to a fossil-free society

The workshop participants were welcomed by the leader of the Swedish part of the EU-COMPLEX process (WP4) Professor Hans Liljenström, SLU, by the local host of the event at the Sigtuna Foundation premises in Sigtuna, Sweden Dr. Director Alf Linderman and given an introduction to the workshop by Professor Uno Svedin, leader of the Stockholm University part of the project. Below, a few glimpses from the workshop are given.

The National Level

The first part on the national policy level was introduced by two key notes about "the Swedish challenges".

At first, *Anders Wijkman* (chair of the Swedish All Party Committee on Environmental Objectives "Miljömålsberedningen" i.e. the commission on the choice of environmental national goals to ensure broad political consensus on environmental issues) gave a broad description on the situation in addressing these issues in the Swedish parliamentary realm and in society at large. The time perspective for a climate neutral situation in Sweden was in the All Party Committee recommendations set to 2045, but with aims for partial solutions much before that date. There is a unanimous support across the entire party structure that this should be aimed at. An important interim target should be reached by the year 2030. There are distinct partial areas of importance e.g. changes in the transport system (not least handling of the carbon issue in air transportation), increase in the role for agriculture to serve as carbon sink in Sweden, and consumer related issues as the meet consumption challenge. Many of these changes will have to be framed within a new "circular economy" where data shows that currently only 5% of materials are renewed after the first cycle. This has implications for resources, climate, energy etc. The mobilization of technical innovations is high on the list (e.g. in the bio-, nano- and ICT- fields). There is a need for parallel actions and experimentation. The needed investments should be quickly explored and relevant life style changes be promoted but also exploring and understanding new behaviors that the sharing economy and Internet of Things are creating. He also underlined the importance of holistic approaches, while society today still is working in silos. He closed by noting that "there is incredibly much to do – and possible to do – in a limited time".

The second keynote was presented by *Maria Wetterstrand*, former spokesperson and co-party leader for the Green party in the Parliament (MP), now chairing various commissions and committees, e.g. the Environmental Objectives

Council "Miljömålsrådet" (a platform for the heads of government agencies that are strategically important to achieving the environmental objectives). She is also serving as an "independent" commentator about national policy issues). She started by taking a historical perspective over Swedish political developments over the last decade. Also she discussed the timeframe indicating targets both for 2050 and zooming in on 2030. She especially reflected on the character of the development of the national political discussions, providing personal reflections on the process over time and the challenge of agenda setting for environmental issues. According to her, this is not a theme that creates political tension, nor attention. Thus, concrete solutions for green transformation needs to be included in greater societal perspectives in the political debate, rather that discussing narrow technical solutions in isolation. Maria Wetterstrand especially reflected on how visions and paths should be framed under different political conditions. She noted, in particular, the importance of the development of the service sector in the transformation process. She also addressed the way how the political party system has to improve the capacity to involve also persons outside the strict party organizations, especially in issues like the large transformation to a fossil-free society. Also she addressed issues about consumption preferences including life style changes as meat consumption. The role of the finance sector in the transformation was reflected upon including green procurement.

In the lively discussion that followed issues about the role of science, the processes in the government offices and among national agencies, and infrastructure and urban issues were given as examples of concerns. Also the needed tempo of change and the level of ambitions were discussed. Regions were identified as possible fore-runners that can push the development forward through concrete solutions and collaborative platforms.

Regional Aspects

Here, *Ida Texell* provided a strong message about the importance of a new type of leadership needed at different levels - not only at national and regional ones, but also at municipal and individual levels. She highlighted the importance of the value basis for actions – also with a long term planning perspective. Tendencies to consolidate traditionalistic hegemonies of values are important to reflect upon – and to provide platforms for open discussions about such issues. She also stressed the importance of reforms of social organization. There is a challenge for leaders to constantly have in mind the question: "What am I really doing in having an impact in reality". According to her future leaders need to inspire people to be responsible for their behaviors and be part of the change, speak about values, understand context, complexity and the society as well as promote lifelong learning.

After these reflections, some glimpses from the planning landscape in the Stockholm-Mälar region were given by *Johan Hjelm*, especially with regard to the political collaborative platform of Mälardalsrådet. In addition, *Mats Helander*, from Region Östergötland presented his reflections on the experience of introducing the OECD Better Life Index at the regional level rather than BNI Index (what gets measured, gets done).

The Role of Science in the Societal Transformation Process to a Non-fossil Society

The initial reflections were delivered by Professor *Karin Markides* (former President of Chalmers University of Technology and currently chair of the Government Committee for Science in support of Sustainable Development, ("Vetenskapliga Rådet för Hållbar utveckling", VRHU). She started by connecting to the session before i.e. on the role of regions – especially that those regions are different in set up and in operations. She indicated with an analogy that "there are both islands and deep valleys" indicating separate situations among regions. She indicated the importance of different roles for many different types of stakeholders. This is an important fact when considering planning for a large societal transformation. The responsibility to address these issues is large and rests on the shoulders of all sorts of decision makers (e.g. ministries, academic institutions and society at large). This should also be seen in the wider context of the EU. Thus also in the institutions of the EU we have to be present and to take action in order to promote a sustainable development oriented policy. Here the role of science - and research in general - is very important. Especially the long term issues must be highlighted. But you have to operate both in long term and in short term. These two domains of tasks cannot be put in a competitive relation in terms of responsibility. They are both needed.

The initial reflections were followed by comments. First, Professor *Bengt Gustafsson* (Uppsala University) stressed the essence of the scientific endeavor: i.e. to scrutinize initial assumptions, to really "dig in" analyzing "how things really are", and to be transparent enough in one's scientific activities that it is possible for others to return to the issue and check again. The choice of perspectives is also a key element. These aspects have a special character when the object is society at large and its dynamic changes. Here investigations about risk are of importance. In order to handle such societal challenges the leadership – also in Academia – is of central importance.

In the second comment *Anders Turesson* - the office of the government and the head secretary of the Science body VRHU (see above the body Karin Markides is the chair of) – stressed the role of science in transforming society. The time perspective up to 2050 has to be used well, e.g. investment in research about sustainable development. He also stressed the role of IPCC (The Intergovernmental Panel on Climate Change) and its investigations in the broad field of climate change. He stressed the development of practical solutions and the formulation of a holistic, interdisciplinary effort and strong needs for synthesis work. We face large global challenges and these have to be matched also in the process of creation of relevant knowledge.

In the follow up discussion gradually moving towards more cross-going topics concerning the totality of the workshop challenges – the following types of issues were mentioned:

- Values
- Ways of tracing the development in economy and society (the GDP issue and green versions of it that could also mirror environmental destruction costs) i.e. "the metric".
- Not only addressing technical solutions, but also solutions of other kinds (societal, institutional etc.)
- Cognitive approaches to behavior and individual decisions in everyday life
- A stronger presence of researchers in the societal debate. But scientists should not be regarded as one of several pressure groups in society.

- Interdisciplinary efforts, including research from the social sciences and the humanities
- Addressing the urban issues more fully in a situation where most people in the world start to live in urban situations
- The educational aspects in order to prepare the next generation
- Supports for the strategic transitions (investments, intellectual input, organization of public debate etc.)
- Securing the spirit of dialogue

The workshop 4 has also been documented in the form of an edited video presentation (Svedin & Potter, 2016), which is available at the WP4 homepage, www.slu.se/complexwp4.

III:2 Stakeholder Participation Using Model Support

Our stakeholder workshops have had a wide range of tasks. There are specific cases where the formal modelling work has been of high interest in a stakeholder dialogue context. This has been done in addition to the general feedbacks to stakeholder groupings about the modelling activities.

Here, we highlight two examples with close connections between stakeholder involvements and modelling:

A. The modelling of municipality planning of climate paths (The "Uppsala Climate Protocol") of the city of Uppsala

B. The investigation of interactions between decision makers and large-scale decision support models of cross cutting nature (as discussed in connection to Workshop 2 on page 101).

A. **The Uppsala Case**

An intense and fruitful collaboration between WP4 researchers and various types of stakeholders has been carried out within the so-called Uppsala Climate Protocol (UCP), which has run throughout the whole period of the COMPLEX project (Sundberg & Byfors, 2015).

***Figure 15**. The Stockholm-Mälar region, Sweden, with Stockholm and Uppsala marked specifically (modified after the Swedish National Atlas)*

With over 200 000 inhabitants, Uppsala is the fourth most populated municipality in Sweden and the central area is the fourth largest city. The public sector is the largest employer, including two universities, the municipality and the county council, occupying over 30 000 people. High technology dominates the industry, primarily within information technology and biomedicine, closely linked to the research at the universities.

In 2010, the municipality of Uppsala initiated the Uppsala Climate Protocol (UCP) with the purpose to involve local and regional stakeholders and decision makers in a joint effort to reach the local energy and climate goals. The 25-30 private and public organizations, including Uppsala´s two universities, participate in energy and climate efficiency actions that are accessed through collaboration (http://klimatprotokollet.uppsala.se/). The UCP members commit to systematically reducing climate impact within its own operations, implementing and declaring climate mitigation measures, contributing with knowledge and collaborating with other members to reach their own as well as the municipality's climate targets. Short-term targets for climate impact reduction are set every three years and the progress is reported at advisory round table meetings that are held at least once annually with top executives and environmental managers. Cooperative projects take place in working groups in areas such as solar energy, waste management, sustainable transports, communication and energy management, which are open also to organizations outside the UCP. The UCP is managed by a project management group and a group of environmental managers.

The Uppsala roadmap project was initiated in 2013 within the framework of the UCP, aiming to analyse potential pathways and measures to reach the municipality's long-term climate objective. It was funded by the Swedish Energy Agency and COMPLEX. As a central piece of the project, the Uppsala roadmap model was developed with the intention to provide an overview of the current energy system and indicate possible trajectories towards the realization of a low-carbon society. The roadmap contains a number of future scenarios where emissions and energy demand are simulated. An inclusive process was initiated, bringing together members of the climate protocol and adopting a 'whole system' approach, including technical requirements, social learning and adaption, policy and legislation. The stakeholders involved include universities, the municipality, local energy companies, politicians, non-profit associations, local residential corporations, academic building corporations and municipal companies including waste and water management. Workshops were organized to identify possible measures for local future scenarios, focusing on issues such as electricity generation, smart grids, bioenergy production and district heating generation. Results from the workshops fed into the scenario building and modelling of future energy systems, which was performed by the researchers in the project.

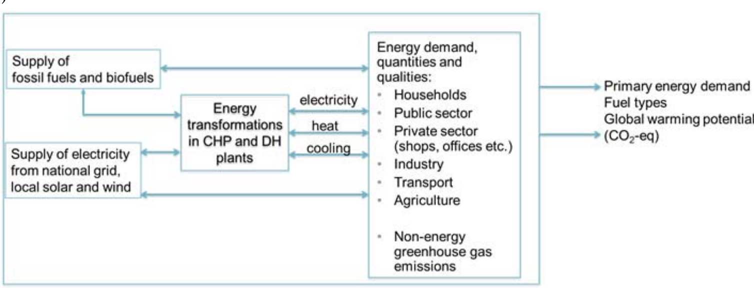

***Figure 16**. The structure of the Uppsala LEAP model*

The Uppsala energy system and GHG-emissions in each scenario were modelled using the Long range Energy Alternative Planning system (LEAP). LEAP is an integrated modelling tool for long term forecasting using an annual time step (www.energycommunity.org). The concept is an end-use driven scenario analysis with a "business as usual" scenario and one or more alternative scenarios. It simulates "what if" energy futures along with environmental emissions under a range of user-defined assumption. On the demand side of the framework, LEAP supports bottom-up accounting and provides a wide range of accounting methods for modelling energy generation, distribution and capacity expansion planning on the supply side. All sectors within an economy or energy system can be included in the model as well as external pollutants. Modelling is based on a comprehensive accounting of how energy is consumed, converted and produced under assumptions given regarding energy demand, population, technology etc. (Fig. 16)

The project group developing the roadmap and the model included researchers, senior advisers at the Uppsala municipality, a representative from Vattenfall and a project manager from the Mälardalen Regional Energy Agency. Throughout the project, many stakeholders from the UCP have been included in the process of developing scenarios and collecting data. The researchers had a central role as modellers and data managers, as well as technology experts for certain technologies in the energy systems. The main researcher has also been deeply involved in project management. Communication with various stakeholders has been part of daily work, also between project meetings. A number of students' projects have been performed associated with the roadmap project. The collaboration that preceded the roadmap project was actually initiated as an educational collaboration between the Swedish University of Agricultural Sciences and Uppsala municipality in 2009. This collaboration may be viewed as an example of the emerging mission of universities to be co-creators of sustainable development (Trencher *et al*, 2014). A flow chart of the scenario building process of the Uppsala Roadmap is given in Fig. 17. (Further details on this modelling work are given in Chapter IV:4 on page 179).

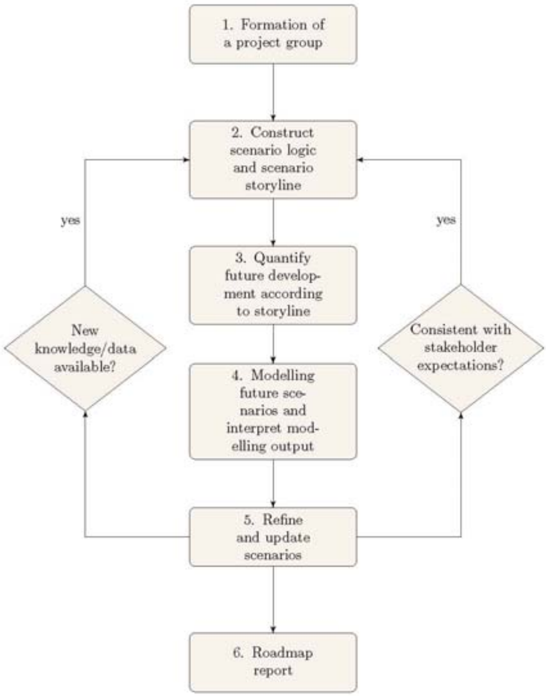

Figure 17. *Iterative scenario development in the Uppsala roadmap project*

B. Gaming Approaches

With regard to our second example, the gaming exercise, this was also discussed in conjunction with Workshop 2, above.

The task here was not the same as in the Uppsala example (which was involved an operational modelling tool for use at a municipal level). Instead, the task was rather to focus on a general level process to explore HOW decision makers in a practical case could make use of a very large decision support model with regard to path decisions of overriding political nature in order to move towards a low carbon society. A report on this work has been published as an invited paper to a large international conference on gaming in Tokyo (Raghothama & Meijer, 2015).

Some of the findings around this experiment with the stakeholder-model interaction (with regard to our target of fossil-free societal path decisions) are:

- The interplay with the model world could be used to support reflections about conditions to political choice (as a follow up in a sequence of successive briefing sessions). Thus it is not primarily the predictive power (which may be limited under the complicated and unsettled circumstances at hand) that is at the centre for this kind of exercise, but the capacity of the specific experimental gaming environment to be used as a didactic reflective tool. One example of the meta-topics that introduced itself for discussion through the process was a debate over "the nature of political action" (with regard to the low carbon policy issues).
- The systems aspects were strongly highlighted. This was less due to the specificities of the large model, but more through the initiation of reflections about the limitations that the model world exposed, e.g. causality related issues, not least connected to risk assessment and handling of uncertainties of different kinds. Also the experience of the limitations of the model to pro-

vide a reasonable representation of certain sectorial issues (as the role of agriculture policy in this context) was also of considerable interest.

- The use of the software model interaction experiences with regard e.g. to the importance of time sequencing of policy and in general the role of "timing" in application of policy action are examples of issues emerging in the discussions. Specifically attention arose towards an improved understanding of subtle aspects of what could be meant by "political capital" (which under certain circumstances could be lost very quickly, whereas under other circumstances such losses could be avoided or limited - or the time development of this "capital" may be different). This was also a feature that was encoded in the software (with a limited formal repertoire of expressions). However, the discussion about what was uncovered in that realm of experience had deeper didactic flavour than what came out of the formalism of the model itself. The model served as an introducer to the topic and provider of a "playground" for reflection, but less as a predictive tool.

Another realm of experience dealt with how the particular focus on the path to low carbon society is embedded in a broader political frame (e.g. more general environmental policy concerns, foreign and national policy general considerations, economic and financial policies and styles under which these are exercised – and with regard also to an understanding about which policy features may not be so central or having limited impact under certain conditions for the low carbon policy arena). Further presentation of this model oriented activity is given in the next chapter.

III:3 What Stakeholders Really Think About Models

In the report covering the gaming exercise with stakeholders, we present background work on the issues inherent in models, especially when used to inform a decision-making processes. Following that, we present a game-based approach through which this context is examined. Following the game session, the players (all of whom are policy makers at different counties within the Stockholm-Mälar region) are asked to reflect on the model and the use of the model for planning. Given that the model was designed to be only approximately correct, this provoked a discussion on the appropriate use of such models and methods in a planning process.

Modelling in Complex Systems

Despite the vast improvements in computational power, and the methods by which we process information, there is little evidence of the benefit of (computational) tools in situations where policy makers are faced with problems in complex systems. Focusing on simulations and models, this could be due to a dissonance between the requirements of a decision making process, and the perspectives through which these models are built. Reviewing studies on simulations and models for policy analysis shows that most such models are designed from the modellers' perspective (van der Leeuw, 2004; Weinstein *et al.*, 2001).

A central feature in such simulations is that they inform decision making by providing insights on "good" choices within the system, or create representations to allow for realistic explorations of the dynamics of systems. The manner in which simulations can inform decision-making processes depends in turn on their validation and evaluation. In complex systems it is practically impossible to adequately represent or make predictions about such systems, primarily because of their complex nature, the implausibility of simulating open worlds in a (necessarily) closed simulation and the lack of availability of comprehensive datasets that describe such systems (Batty, 2012; Petersen, 2012).

Under such circumstances, it is hard for a modeller to design and build a model without understanding exactly how the model is going to be used. Situating a model in its proper context of use within long and complicated decision-making processes will bridge this dissonance and will be crucial for the model to deliver scientifically valid relevant insights into decision making. This can be achieved by first gathering data and insights from decision makers on how computational models can serve them best.

In the following sections, the authors present a modification of the popular game DEMOCRACY 3 (D3) which was used to provoke a discussion on the use of models in decision-making. The systems dynamics model in D3 was modified to suit the context of the Stockholm-Mälar region. Decision makers from the counties in the region played the game, and the debriefing session provided valuable insights on how best to use such methods and tools.

DEMOCRACY 3

DEMOCRACY 3 (D3) is the latest version of the popular entertainment game, DEMOCRACY (Harris). D3 is a political strategy game and simulates the desires, motivations and loyalties of people in a country. The people are voters in the country, simulated through a neural network model and forming social groups, such as capitalists, socialists, environmentalists and so on. The player takes on the role of a politically elected government, and has to implement or change policies and keep the voters happy. Policies have Effects, which are parameters that denote how the country is performing on various aspects. For example, increasing Education Subsidies will improve Education as an effect. All policies are implemented by turning them on, or by increasing their level in a slider. Policies and Effects also influence how the voter groups feel about the government.

Fig. 18 shows a screenshot of the user interface for D3. The blue icons are Effects, white icons are policies which can be changed, and social groups are shown in a rectangular block in the centre. Green arrows indicate a positive influence, red arrows a negative influence. By modifying the model in D3, it is possible to create games for specific countries, such as UK, USA and so on.

The game for the Stockholm-Mälar region was played in Workshop 2, as described in Chapter III:1, page 101. The objective for players in the game is to act as the government of Sweden, and reduce the CO_2 emissions in the region. The Stockholm model was created in a series of preparation workshops with policy makers from the region. In these workshops, the model as developed in D3 was presented, and policy makers were asked to reflect on how the model can be changed to suit the local context. These changes were incorporated into the model to create the Stockholm mod.

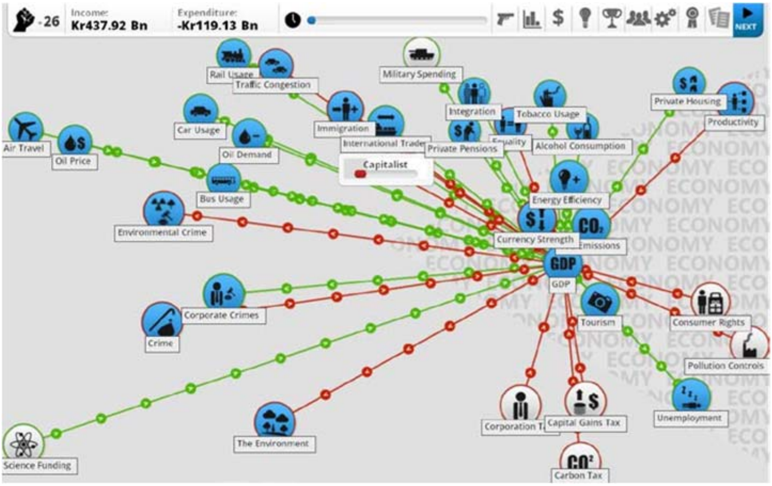

***Figure 18**. Screenshot of the User Interface for Democracy 3*

D3 is designed to be modified. The core model of the game is available in the form of comma separated value (.csv) files. Modifications are meant to be achieved by adding files in a different folder with the same names. Mod files are meant to add policies and effects to the core model, ensuring that the core model remains untouched and available for future modifications. However, this mechanism of creating mods for the Stockholm region was insufficient, since the changes to the core model were too many. As such all the changes were incorporated into the core model of the game. The Stockholm mod was created first by changing the core Policies, Effects and Voter Groups files to reflect the context of the region, and by adding data such as GDP, Population to the mod. The Policies, Effects and VoterGroups files are all linked, and relationships are created by using simple formulae. Error checking was performed by implementing a custom parser for the csv files, which checked for inconsistencies in the files, and by continuously play testing the mod over several turns in the game, to ensure that the game would not crash.

In contrast to the effort taken to have a complete (approximately, based on feedback) model, effort to validate the Stockholm mod was not undertaken, because the game was meant to provoke the policy makers into completing the model themselves, and to reflect on how such tools can be used effectively. This is based on the assumption that instruments such as interviews or focus groups would not be as effective in explicating the same issues as an interactive, fun and exploratory game would be.

The Stockholm mod was played with 18 policy makers, who played the game in groups of two. They all played the game simultaneously, on different machines. The setup for all the groups was identical. The game was played twice in two sessions over the course of a single day, once in the morning and once in the after- noon. The game play in both sessions lasted for approximately 45 minutes. A de-brief was conducted immediately after both sessions. Both the game play and debriefs were recorded on video cameras, and conducted in in Swedish, while the game and game interface were in English.

After each session, the players were asked to fill a form explicating the different entities (policies, effects, groups or others) in the mod they found missing, or correct existing variables. In debrief they were asked to reflect on the conceptual nature of the model and the game play. The videos of debrief, and the forms were transcribed and translated into English.

In the following sections we present an analysis of the policy makers comments, mainly focusing on the debrief comments.

Discussion

Following the transcription and translation of the debrief comments, the data was treated as qualitative in nature and analysed accordingly. The data was analysed for major themes that emerge. The authors tagged all comments made with key- words from the professional simulation vocabulary, and then grouped them in themes that link to the discussion on the use of models as presented above. The themes are presented below, in no particular order.

There were over 60 comments commented over the 2 rounds of game play.

Systems Unrepresented in the Model

The analysis demonstrates that the policy makers prefer the model system to be complete. They notice important systems or sub systems that are not included in the model. The following comments were made:

You could adjust the number of policy instruments so that it roughly reflects the proportion of emissions in each sector. The agricultural sector for example, is difficult to find and it still gives quite a lot of carbon emissions. Environmentally aware consumption/production is missing.

Heating options etc. are missing.

The analysis shows a preference not just to have a complete model with all aspect systems included, but to have a complete model that is contextually relevant.

Policy makers also prefer the model to include and if possible, present the model from different perspectives. Perspectives such as ethnicity, gender, political perspectives and so on need to be included in the model:

It is still the politicians' prime objective function and the politicians in charge. Sometimes you lose that perspective in the discussions. For me it is perhaps one of the most *interesting parts…Could be interesting to add a general gender perspective throughout the game. What questions/answers would be directly affected?*

Are there gender or ethnicity perspectives related to attitudes?

These perspectives or attitudes can be linked to the voter groups. Policy makers were very interested in being able to observe how these perspectives, or attitudes change over time, especially in relation to changes in policy:

The voters always have the same attitude to anything before and after a decision. It would be interesting to see that now it's like this now but once it got started, it may be changed. It is incredibly difficult because it is so difficult to predict how people will behave afterwards. It depends on many things.

Legislation becomes the norm and internalized gradually and it usually takes 20 years in a societal perspective. It is 20 years since the paper collection started at this time, it is a great educational projects. Today, you become outcast if you do not sort your garbage and then surely you defend yourself. There are those changes.

You can influence attitudes through campaigns, information and knowledge, and with this dimension too you can be able to do actions that change and influence behaviour and moreover create acceptance in order to get re-elected again. It would be a further dimension to this with attitude and changed behaviour.

Relating this theme to the earlier theme of aspect systems, policy makers preferred to have complete models of the technical components (such as water, electricity, heating etc.), and then understand how changes in those components affect attitudes and perceptions. This is because of their expertise in their respective domains, the predictability of technical components, the intractability of social perceptions, and the impossibility of predicting human reactions:

These factors as what it will cost, what it will lead to efficiency, it is very predictable factors. You have this in your analysis in your daily work. How does this affect attitudes, how does that affect perceptions of things is something you do not normally have in their calculations. This is where you feel that if you have to have a decision support that will give another dimension, it is the attitude pieces and that is where I think you could have an added value.

Should be more adapted to Swedish conditions. E.g. free school lunches, cannabis is not legalised etc. Consider removing items that are not relevant to Swedish conditions and translate operational language to Swedish.

Perspectives

Policy makers also prefer the model to include and if possible, present the model from different perspectives. Perspectives such as ethnicity, gender, political perspectives and so on need to be included in the model. Here are their comments:

It is still the politicians' prime objective function and the politicians in charge. Sometimes you lose that perspective in the discussions. For me it is perhaps one of the most interesting parts. Could be interesting to add a general gender perspective throughout the game. What questions/answers would be directly affected?

Is there also a gender or ethnicity perspective to attitudes?

These perspectives or attitudes can be linked to the voter groups. Policy makers were very interested in being able to observe how these perspectives, or attitudes change over time, especially in relation to changes in policy.

The voters always have the same attitude to anything before and after a decision. It would be interesting to see that now it's like this now but once it got started, it may be changed. It is incredibly difficult because it is so difficult to predict how people will behave afterwards. It depends on many things.

Legislation becomes the norm and internalized gradually and it usually takes 20 years in a societal perspective. It is 20 years since the paper collection started at this time, it is a great educational projects. Today, you become outcast if you do not sort your garbage and then surely you defend yourself. There are those changes.

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The other factors are more traditional financial planning or technical developments which are much more predictable what it will lead to but not this social aspect.

System Dynamics

Related to the previous theme, the decision makers are also very interested in observing changes over time. This can be seen as a need to observe trends over time and to have possibilities to intervene at the right time in the system. These interventions can be considered as different scenarios, and they prefer to observe how different scenarios change the system over time and relating it to the earlier themes, they would prefer to observe how attitudes change over time in reactions to policy changes:

When it comes to the need for a tool to create policies, then it might have an influence in what order you do things. How can you handle that in the game? It can have a major impact on the result. Regarding history, can you go back and see what you have done? We worked for some quick points, little in between and the slower ones. It would be of interest to be able to start with a base to work within a couple of years and then you can "sweeten" with additional measures.

Being able to look back and see which policy initiative being launched and for the years to come. You might want to try these variables and the next time you want to test other, to make it just like in politics and the democracy.

Governance and Agency

Another important theme is agency within the model. The parameters in the model should be related to the governance level that has agency to change that parameter, and as far as possible, all major governance levels should be included in the model, linking this to aspect systems:

I think of what we keeps coming back to, there is a dilemma in that virtually all the actions we are doing here is related to the state. And in reality we want everyone to be *on a regional or local level, and that is where you really need to think about. Where is the dilemma? It is not that you need to think about or it is not that local democracy.*

From an energy and environmental perspective, the EU is an important actor.

Model Flexibility, Openness, Exploration and Game Play

The four inter-related themes of model flexibility, openness, exploration and game play also emerge. Policy makers prefer to make changes to the model themselves, to have a tool that enables them to include aspect systems and perspectives that are important to them in the model:

It is built so that you in some cases want to be able to pull down an empty ball and be able to enter things that have been missing, for example, transport, train or boat traffic. And by yourself link some of the balls to each other and as a result of the game see what was added.

This implies that models should be built according to the perspectives of the decision maker, and the inflexibility of the model is a hindrance to decision support:

The only thing you could do was to raise agricultural subsidies and you cannot freely do it with the logic they have now, then you had to do in a different way, and those choices did not exist. There is a lot that could be done. We have free school lunches and this comes from an area where you do not have it that way, it's like a completely different starting point.

There is a point in the general if you want to use it as one of those tools. There are a lot of things that we lack and if we add them there are other things we miss so it is itself the solution to the game.

The notion of flexibility contradicts to a certain extent the notion of complete- ness. A complete model will be complex and make it hard to change very easily:

There is an option to make the model more complex and instead make it possible to change some parameters.

A related notion is that of openness, where policy makers are sensitive to hid- den parameters, the assumptions behind the model and the data and literature that substantiate the model. This could be because of the general incomprehensibility of models, especially by policy makers. Making decisions based on models that policy makers do not understand can be hard, especially in complex systems:

I would like to have as a supplement here, it is that there was some little box where you could gather and find the scientific literature. Why is it calculated this way? Provide links to information of scientific or other data that has been used. What is the underlying principle for weighting costs?

If you're going to use it as decision support you must be able to discern the data by which the game is based on. If you could tap into your own data, I think you could use it. You have to have full control of data to be able to use it.

Another related notion is that of exploration, which emerges strongly from multiple comments, many of which have already been described earlier. Policy makers want to explore the model, and as mentioned earlier change the model to suit their needs and to try different options and scenarios. There seem to be multiple reasons for this, some of which are derived from the themes described previously. They prefer to test the assumptions in the model, explore it from different perspectives, watch how the model evolves over time and compare different scenarios and starting points for the model. This could be because of the intractable nature of complex systems, and policy makers prefer an understanding and exploration of the dynamics and processes in the system over predictions of future states (Lee, 1994; Petersen, 2012). They "like to play with" and "like to play in" the model and do not perceive the two as different:

One would like to see the change in game plan according to your previous actions. Connections between things would have to be changed. Bicycle and things like that, I think is such a thing. You get used to different things, you get used to drive a car, and you get used to ride a bicycle. Your preferences depend on how it looks in the community.

You see it more as a framework when you read the facts and then you start the game under those conditions. It would be interesting to see if we could have scenarios, i.e. several parallel games going on at the same time where you run a scenario where you *invested on one thing, and so running a scenario where you do in a different way and to be able to compare the different scenario developments. It is of course very difficult to grasp the "real life" in this but you can still see the one or the other and how they turn against each other, which will quickest lead to results and which will influence attitudes, etc.*

One of the most important things about this is that it is fun. As a politician you are confronted with thick stacks of paper, and it is not that uncommon for politicians and city councillors and others, have not read the paper yet before a meeting. When you walk into this (game) so if you read the small text and ingests some information, it is a pretty important part and you become curious about the things that do not match one's perceptions and that was why I started thinking that maybe if you press the button, there would be a reference to where it all comes from and that it can spark an interest to actually look at the research.

You want as substitute your own judgement with some kind of science. You want as well as clear some of the things out and then have it as a light-app to test these things in which you pinpoint a side track. Because it takes time to get to know something. I had a thought also of the external factors that can change over time and also scenarios. The development may be this or that or some other way. Being able to put this game against a number, maybe four different future scenarios and play it in the different environments.

Conclusions

Modellers and simulators are inclined to believe that their products are powerful tools for the description of complex systems, and that these tools can be used to inform decision making and lead to better decisions. Modelling as an activity is done from a scientific perspective, or at least from a modelling perspective, which is at constant odds with its context of use within a decision making process. It is important to note that decision makers frequently have different problems and different requirements from models.

Decision makers prefer models and tools that are open, flexible and complete, which enable them to explore different perspectives and tools and understand the dynamics of the system under study. This can be perceived as a call for highly elaborate models, but this will on the other hand close down the inherent flexibility.

Models should reflect the nature of the system under study. Achieving open- ness in a model will prove difficult, since by its very nature, building a model within a computing system means that the model boundaries should be closed at some point. Conceptualizing an open, flexible model that is at once complete and scientifically valid is a challenge.

Models should also facilitate exploration, which in conjunction with the open- ness and flexibility means that models should allow its users to change relation- ships and parameters within the model. Facilitating the exploration of the bi-directional relationships between technical components (energy, water, etc.) and social perspectives (attitudes, perceptions in society, etc.) is key. Also important is to be able to explore these relationships over time. As before, allowing exploration in an open, flexible and complete model while maintaining scientific validity will prove an enormous challenge.

Other important aspects are that of agency and realism. The model should account for agency within a governance structure. The model should simulate, or provide structures to link parameters to governance. The model should also be realistic within the local context, by including various aspect systems specific to the area or domain under study, and relate these aspect systems to the governance levels present in that local context.

Models and simulations have come under increasing scrutiny and criticism of late. Among the many criticisms is that models have increasingly failed to deliver on their promise of realistic complex simulation and valid predictive ability.

From the data gathered through the Stockholm version of Democracy 3, it appears that this can be addressed to a certain extent by building many models of the same system or phenomenon from different perspectives, in the pluralistic sense. It can also be addressed by aiming to provide frameworks for valid model building from different perspectives rather than trying to simulate complex phenomenon at high levels of realism and validity.

Given that this is almost impossible in complex systems, perhaps models should look to satisfy other requirements, and engage actual users in the form of decision makers to deliver those requirements.

A new era for gaming simulation might begin!

IV. SPECIFIC MODELS AT VARIOUS SCALES

In this Section, we describe to some detail the specific models developed and applied by different members of the WP4 team for use in the COMPLEX project and beyond. The different modelling approaches address issues at various scales, from the regional, to county and municipal, down to the individual level. Most of the models have been presented and discussed at the workshops organized and described in Section III. The gaming model used in one of the workshops (2) is a commercial product, and discussed in the previous Section.

Section IV consists of five chapters, discussing modelling that reflects different transformational aspects, but also different geographical levels:

IV:1 Cost-Effective Policy and Incomplete Information on Policy Implementation (*Regional level*)

IV:2 The Value of Carbon Sequestration and Nutrient Recycling in Forests (*Regional level*)

IV:3 Climate Impact of Using Locally Produced Willow to Supply a Biomass-Fired CHP Plant in Uppsala (*County level*)

IV:4 Future Scenario Modelling: An Insider's View on Uppsala (*Municipal level*)

IV:5 A Neuro-Cognitive Model for Decision Making in Travelling (*Individual level*)

IV:1 Cost-Effective Policy and Incomplete Information on Policy Implementation

Ing-Marie Gren, George Marbuah, Wondmagegn Tirkaso

There is a general consensus worldwide on the need to reach a low carbon economy to mitigate damages from climate change. The increasing concern for damages from climate change has called for development strategies reducing use and dependence on fossil fuel. This approach thus associates the concept of a low carbon economy with reductions in fossil fuel while maintaining sufficient economic development, which calls for cost-effective solutions. This, in turn, has been met by strategies suggesting technological development, and energy decarbonisation. However, irrespective of number of options, the achievement of cost-effective solutions can be hindered by the existence of incomplete and uncertain enforcement of the suggested measures. Reasons for incomplete enforcement can be that targets on carbon reductions are filtered at different implementation levels such as national, county and municipality levels. Another reason is the existence of non-compliance with the regulations supporting the low carbon emission path. The degree of incomplete implementation of enforcement depends on type of policy instrument (economic, command and control, information etc.) and on the institutional capability (e.g. Sandmo, 2002). The existence of incomplete implementation cannot be disputed; in Sweden the compliance rate with the Environmental Code varies between 3% and 99% of all regulated firms in different Swedish municipalities (Gren & Chung-Zhong, 2011). The actual implementation can thus be regarded as uncertain. It depends on the compliance rate, which, in turn, is affected by a number of different community characteristics such as wealth, environmental attitudes and norms (see Gray & Shimshack, 2011 for a review).

The purpose of this study is to identify cost-effective strategies with incomplete and uncertain local implementation of carbon abatement in the Stockholm-Mälar region in Sweden. To this end we construct a dynamic optimization model with probabilistic constraints on the achievement of carbon reduction targets. Decision makers are then assumed to apply a "safety-first decision rule" where they assign a minimum probability for achieving the carbon target. This approach is particularly useful when decision makers hold relatively strong aversion against deviations from a target or threshold. Variations of the safety-first criterion have a long tradition in economics for dealing with urgent targets, such as minimum food supply (e.g., Tesler, 1955-56; Pyle & Turnovsky, 1970; Bigman, 1995). Our study applies the safety–first criterion originally suggested by Tesler, (1955) which allows for the adoption of relatively easy and accepted decision rules, minimization of costs under emission constraints, where the emission constraint is formulated in probabilistic terms.

In order to calculate cost-effective paths to a low carbon economy it is not enough with a concept, but it has to be operationalized. Among the first to do this was Prime Minister Tony Blair who suggested a 60% cut in British CO_2 emission from the 1990 level to be reached at the latest 2050 (DTI, 2003). In our study we use the EU commission suggestion of a reduction by 80% compared with emissions in 1990 (European Commission 2011). Calculations of minimum costs for reaching this target have been carried out in several earlier studies at the national, regional (EU), and global scales (see Capros *et al.*, 2014 for a review). These studies include technological development for energy decarbonisation, energy efficiency, and cleaning technologies such as CCS, but they do not consider incomplete or uncertain enforcement.

In our view, the main contribution of this study is the consideration of uncertainty in implementation of abatement measures. A few caveats are in order. Although we include in total 12 different abatement measures, measures such as hydropower, wave power, and CCS are not included. The reason is the difficulty of finding data on costs and effects of these measures. Another limitation is the use of a partial equilibrium approach where demand for energy is exogenous. A justification is that endogenous energy demand would require a general equilibrium modelling framework, which accounts for the dispersal of effects and interactions among different sectors through the price mechanisms. For a very open system like the Stockholm-Mälar region, such modelling is less useful since prices are determined outside the region. Further, all abatement measures have other environmental impacts than just the one for carbon emissions. For example, reductions in the use of fossil fuel also create health improvement (by decreases in particulates). These side effects are not included in the study because of difficulties in quantifying these effects. We also take the "production approach" on the region which means that only carbon emissions originating from production in the region are included. Emission created elsewhere because of imported goods and services are not considered. Reasons for our choice are that this is the conventional approach in international negotiations and agreements, the difficulty of implementing policies and abatement measures outside the jurisdiction, and the insufficient access to data.

The study is structured as follows. First, we present the numerical model, which is dynamic and accounts for uncertainty. Next, data retrieval is described, followed by the presentation of results. The study ends with conclusions and discussions of main findings.

Conceptual Approach

The ultimate question posed by the numerical model developed in this study is if and how to achieve an 80% GHG reduction from the 1990 level in 2050 in a cost-effective way. Cost-effectiveness is then defined as the allocation of abatement measures over time and at different locations which reaches predetermined targets in a specific time at minimum costs. In principle, two classes of measures can be used for reducing the emission of carbon; reductions of CO_2e emissions from fossil fuel and investment in renewable energy. Investment in renewable energy is subject to depreciation over time because of reduced functioning, which requires reinvestment. However, due to implementation leakage abatement from both classes is obtained only under

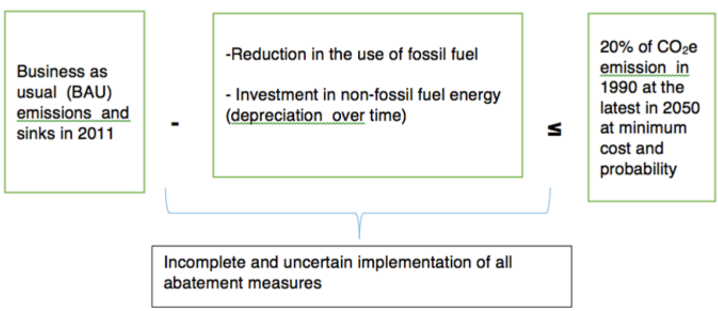


***Figure 19**. Basic structure of the Stockholm-Mälar Carbon Cost Model*

conditions of uncertainty. The basic structure of the model is illustrated in Fig. 19.

In each time period *t*, the business as usual (BAU) emission of CO_2e is determined by the emission of sources, X^{mBAU} where *m = 1,.., n* municipalities. These emissions can be reduced by decreases in the pollution at the emission sources, A_t^{mf} where *f = 1,..,l* are the different types of sources such as energy production, agriculture, and transports Annual reductions in CO_2e are also obtained by replacement with renewable technologies, A_t^{mr}, where *r = 1,..,q* technologies. These are obtained from investments, I_t^{mr}, which have a maximum technological life time, and are then regarded as capital investments subject to depreciation according to

$$A_t^{mr} = \sum_{\tau} (1-\delta^r)^{t-\tau} I_{\tau}^{mr} \qquad (1)$$

where $0 < \delta^r < 1$ is the annual depreciation rate of technology *r*. Abatement by means of a renewable technology *r* in time *t* is thus determined by the accumulated investments prior to *t*, and investment in period *t*.

However, total abatement in practice is lower because of implementation leakage, and uncertain because of uncertain implementation and enforcement, which is specific for each municipality. Total abatement in each municipality is then written as

$$A_t^m = b^m (\sum_f A_t^{mf} + \sum_r A_t^{mr}) + \varepsilon_t^m \qquad (2)$$

where $0 \leq b^m \leq 1$ is the share of abatement that is implemented and ε_t^m is the stochastic parameter which is assumed to be normally distributed.

Total emissions, $X_t = \sum_m X^{mBAU} - A_t^m$, is subject to an emission target in period, $\overline{T}_t$. The introduction of a safe-first decision rule implies that the decision maker chooses a minimum probability, α, at which this emission target should achieved. The probabilistic constraint is then written as

$$prob(X_t \leq \overline{T}_t) \geq \alpha \qquad (3)$$

This can be expressed in terms of mean emissions or leaching, risk aversion, and variance in loads as (e.g. Taha 1974)

$$\mu_t + \varphi^\alpha (\sigma_t)^{1/2} \leq \overline{T}_t \qquad (4)$$

where $\mu_t = E[X_t]$ with *E* as expectation operator; ϕ^α shows the choice of α as the acceptable deviation of the load from the mean, and σ_t is the total variance. The left hand side of equation (4) thus shows that reliability in achieving the target is obtained at a cost, which increases with reliability concern or the probability of achieving the target, *i.e.*, in ϕ^α, and in the total variance in abatement, σ_t.

The exercise of each abatement measure is subject to a cost, which is described by the cost functions, $C^{mf}(A_t^{mf})$ and $C^{mr}(I_t^{mr})$ which are assumed to be increasing and convex in their arguments, i.e., costs are increasing at a higher rate in the use of the measure.

Additional assumptions are that abatement in each period is subject to restrictions where only part, k^f, of the BAU emissions can be reduced, part of total emissions from fossil fuel use can be replaced by a specific technology energy, k^r, in each period. The reasons for these restrictions are that drastic reductions in emissions and land use are difficult to implement in a very short time period. The capacity restrictions are then written as

$$A_t^{mf} \leq k^f X^{mfBAU} \tag{5}$$

$$I_t^{mr} \leq k^r \sum_f X^{mfBAU} \tag{6}$$

Given equations (1)–(6), the decision maker is then assumed to choose among available options, A_t^{mf} ,and I_t^{mr} in order to minimize total cost in present terms for achieving the carbon emission and nutrient leaching targets, which is written as

$$Min \quad C = \sum_t \sum_m \left(\sum_f C^{mf}(A_t^{mf}) + \sum_r C_t^{mr}(A_t^{mr})\right)\rho_t \tag{7}$$

s.t. equations (1)–(6)

where $\rho^t = \dfrac{1}{(1+i)^t}$ with i as the discount rate.

The impact of incomplete and uncertain enforcement is found by solving for the decision problem in equation (7), which is made by formulating the Lagrange expression, L, according to

$$L = C + \lambda(\overline{T}_t - \mu_t - \varphi^{\alpha}\sigma_t^{1/2}) + \sum_f \gamma_t^{mf}(b^f X^{mfBAU} - A_t^{mf}) + \sum_r \gamma^{mr}\left(\sum_r b^r X^{mfBAU} - I_t^{mr}\right)$$
(8)

where $\lambda \leq 0$ is the Lagrange multiplier for the target, and $\gamma_t^{mf} \leq 0$ and $\gamma_t^{mr} \leq 0$ are those for the different capacity constraints on abatement measures. The Lagrange multipliers have an interesting interpretation; they provide information on the change in total discounted minimum cost for a relaxation of the constraint. For example, a relaxation of the carbon emission target in 2050 by one unit will decrease the cost corresponding to λ.

We derive the conditions for a positive value from the first-order condition of a cost-effective solution, i.e., the marginal abatement cost for obtaining a unit reduction shall be equal for all measures and correspond to λ. For ease of exposition but without loss of generality, we assume interior solutions where the capacity constraints are not binding. The first-order conditions for the cost- effective solution are then written as

$$\rho_t \frac{\partial C^{mf}}{\partial A_t^{mf}} = \lambda b^m (1 - \frac{\varphi^\alpha}{2\sigma_t^{1/2}} \frac{\partial \sigma_t}{\partial A_t^{mf}}) \tag{9}$$

$$\rho_t \frac{\partial C^{mr}}{\partial I_t^{mr}} = \lambda b^m \sum_t (1 - \frac{\varphi^\alpha}{2\sigma_t^{1/2}} \frac{\partial \sigma_t}{\partial I_t^{mr}})(1-\delta^r)^{T-t} \tag{10}$$

Both conditions state that the marginal abatement cost in the present value, i.e., the discount factor times the marginal abatement cost, on the left hand side shall equal the weighted marginal impact on the target at the right hand side. The lower the discount rate, and, hence, higher discount factor the more expensive is the marginal abatement cost in period *t*. High discount rate thus favours late abatement.

The marginal impact includes two effects, one is the decrease in average emissions and the other is the change in uncertainty. The effect is then reduced for low b^m, i.e. when the implementation leakage is large. When $\frac{\partial \sigma_t}{\partial A_t^{mf}} > 0$ the impact is reduced compared to when there is no effect on uncertainty. On the other hand, when uncertainty is decreasing in abatement, $\frac{\partial \sigma_t}{\partial A_t^{mf}} < 0$ the abatement measure contributes to decreases in overall uncertainty and thus has a cost advantage. The main drivers for cost effective solutions from the model are:

- Implementation leakage increases costs because of the need for larger emission reduction in order to reach the target.
- Uncertainty in implementation of abatement measures increases overall abatement costs because of the need for a larger abatement in order to reach the target with a minimum probability
- Abatement measures with small increases on uncertainty have a cost advantage
- Abatement is allocated towards municipalities with relatively low implementation leakage and uncertainty in enforcement
- Renewable energy has a cost advantage over reduction in fossil fuel since the impact acts over several time periods. Overall costs are higher for a large depreciation rate since some of the abatement effect is lost over time due to the depreciation

BAU Emissions, Abatement Measures and Costs

As shown in Section Conceptual Approach, the data needs can be classified into three categories; Business as usual (BAU) emissions of greenhouse gases (GHG), costs and impacts of different abatement measures, and implementation leakage and uncertainty. These data are briefly presented in the following, and unless otherwise stated refer to year 2011, which is the latest year for which all necessary data are available. All data is obtained from Gren *et al.* (2014), which we refer to for further details.

The Stockholm-Mälar region we consider here covers an area of approximately 34 000 km^2 which is divided into 5 counties and 65 municipalities. The region inhabits approximately 1/3 of the total Swedish population of 9.1 million in 2011. The share of economic activity as measured by gross regional product is larger and amounts to 44% of total gross domestic product (GDP). In total, emission of CO_2e amounts to 14.6 million tonnes in the Stockholm-Mälar region, which corresponds to approximately 25% of total Swedish emissions.

However, the calculated emissions vary considerably among municipalities, see (Fig. 20), depending on population size and economic production structure.

A sharp increase in emissions is observed around the 60th municipality. Six municipalities (Stockholm Oxelösund, Örebro, Västerås, Uppsala, and Köping) together account for half of the total fossil fuel emissions. The highest emissions are found in Oxelösund which hosts a large firm in the iron and steel industry. The next largest source is Stockholm municipality where the largest share of the population lives.

It can also be observed that the EU 2050 target is achieved by the accumulated emissions of 50 municipalities.

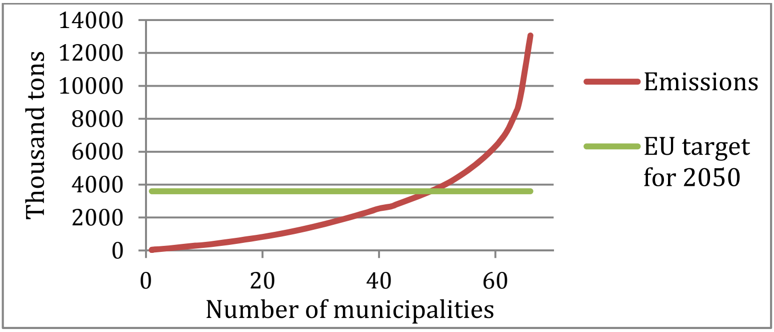


Figure 20. *Accumulated emission of CO_2e from municipalities in the Stockholm-Mälar region, and the EU 2050 target line Source: Gren et al. (2014) Table A1*

The numerical model includes reductions in coal, gas, diesel, gasoline, and heating oil, and investment in wind, solar power, and bioenergy for heat and power production. Options for reducing emissions from the transport sector increases in the number of electric cars, and change in fuel to ethanol and biodiesel. Costs for reducing the use of fossil fuels as inputs in production are calculated as associated decreases in profits. These are obtained from revealed demand function for the fossil fuel products, which show the increase in profits from a unit increase in the use of the fossil fuel product in a competitive market. Similarly, costs of increasing supply of renewable resources are calculated as associated increases in production costs. These production costs are obtained from the output supply functions, which measure the minimum price required for raising the production of the energy in question by one unit. Costs of electric cars are calculated by engineering methods since sufficient data on demand are not yet available. Limitations are imposed on the introduction of electric cars where it is assumed that maximum 1/10 of the existing fossil fuel driven car fleet can be replaced each year.

With respect to the choice of depreciation of electric cars and renewable energy we assume levels related to the economic life length of approximately 10 years for cars and 20 for renewable energy. Finally, we need to choose the level of probability in reaching the target and the discount rate. To the best of our knowledge, explicit consideration of certainty requirement has been made only for Canada (Kim & McCarl, 2009), where the chosen probability was 0.8. There are no reasons to believe that it should be the same for the Stockholm-Mälar region. Because of lack of similar information for the region, we choose 0.8 in the reference case. There is a large body of literature on the appropriate level of the social discount rate, which is determined by pure time preferences, growth in consumption opportunities, and utility of consumption (see e.g. Weitzman, 2001). The level of the discount rate may differ between the counties due to differences in consumption preferences and economic growth. It is generally also suggested to use a hyperbolic discount rate, i.e. a time-declining rate, for long term projects exceeding 50-100 years. A simplification is made in this paper by assigning a uniform discount rate for all municipalities, counties and time periods. Following recommendations made for discounting future streams of net benefits, calculations of cost-effective solutions are made for a relatively low level of 0.02 (Newell & Pizer, 2003).

Incomplete and Uncertain Enforcement

In this study, incomplete and uncertain enforcement is quantified by means of data from compliance with environmental regulations in Sweden (Holstein, 2010; Gren & Chung-Zhong 2011; Holstein & Gren, 2013). In these data source regulated firms are classified into four different categories, A, B, C and U, where firms in category A have the largest environmental impact and firms in category U the smallest. Firms in categories A and B require an operating license. Examples of category A firms are nuclear power plants and firms operating in the steel, paper and pulp industries. Large farms and food producers are examples of category B firms. The category C firms, such as medium-sized farms, have to report their activities. Firms in category U, such as petrol stations and laundries, do not need a license and do not have to report their activities, but are under observation for re-classification into any other category.

The total number of regulated firms in the Stockholm-Mälar region amounts to approximately 17000 firms, of which 75% are U-classified firms, 18% C-classified firms, 4.7% B and 0.3% A-classified firms (Gren & Li, 2010). Violations are reported when the supervision authority issues any injunctions and prohibitions necessary in individual cases. There is a considerable variation in the violation rate among the municipalities, which range between 0.01 and 0.72. The enforcement rate, which constitutes our measurement of the *b* parameter in the Section Conceptual Approach, then varies between 0.28 and 0.99. Uncertainty in enforcement is measured by the standard deviation for each municipality, which is calculated by assuming a normal probability distribution, a range of +- 10% around the average, and that the outcomes are within the range with a probability of 0.95 for each municipality.

We use the GAMS code with the Conopt2 solver for all numerical analysis (Rosenthal, 2008).

Results

The EU target sets a maximum emission of 3.6 million ton CO_2e in 2050. This implies a reduction by 75% from the emission level in 2011 which amounts to 14.6 million ton. In order to evaluate the isolated effects of incomplete and uncertain implementation of abatement, we calculate costs under four different scenarios, with and without complete and certain enforcement, see Table 2.

Table 2. *Minimum costs for reaching 80% emission reduction under different combinations of certain and incomplete enforcement, discounted billion SEK*

	Complete enforcement	**Incomplete enforcement**
Certain enforcement	316	444
Uncertain enforcement	564	927

The cost of 316 billion SEK for the 80% reduction in the reference case with complete and certain enforcement corresponds to 1.4% of the discounted cumulative GRP (gross regional product) of the Stockholm-Mälar region. This is somewhat larger than that estimated for the entire EU, which amounts to 1% of total accumulated GDP (Capros *et al.*, 2014). One reason for the difference is that the results presented above do not consider any economic growth, which would reduce that share of total abatement costs. When considering both uncertain and incomplete enforcement, the total cost increases almost threefold, from 316 billion SEK to 927 billion SEK. The isolated effect on the cost in the complete and certain enforcement is largest for uncertainty. However, the incomplete enforcement requires more abatement which reinforces the uncertainty effect on costs.

In 2011 the total CO_2e emissions have been reduced by 17% from the 1990 emission level. This means that reductions up to this level are obtained at no cost in all four cases. The emission reduction is therefore reduced by this amount for each year. It increases over time because of the advantage to delay abatement because of the discount rate and depreciation of investment. Cost effective paths of the two polar cases with and without complete and uncertain enforcement show such patterns, but the decrease in emissions is more rapid with uncertain and incomplete enforcement, see Fig. 21.

The development of the paths is similar up to 25 years. Reductions in emissions are then higher under uncertain and incomplete enforcement because of the large abatement requirements. This is also shown by the marginal abatement costs in each period of time, which is higher with uncertain and incomplete enforcement and has a more rapid increase over time, see Fig. 22.

At each level of the marginal abatement costs in Figure 4 the condition for a cost effective allocation of abatement among measures and municipalities are met as shown by eq. (7) in Section Conceptual Approach. We can therefore interpret these as the necessary charges on emissions in each period of time in order to reach the cost effective solutions. As shown by eq. (10) the charge imposed on the emission source depends on the implementation leakage in the municipality and the effect on uncertainty. Charges are higher in municipalities with low implementation leakage and for measures with low increase in uncertainty.

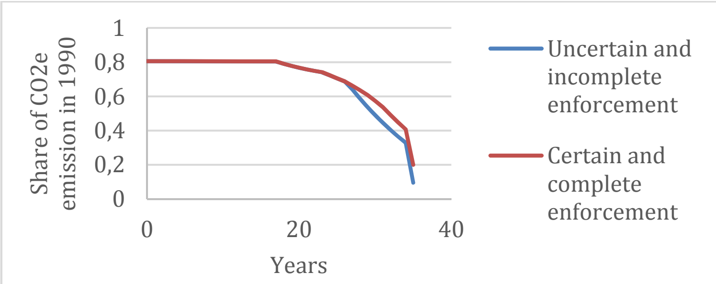


Figure 21. *Cost-effective share of emission of BAU emissions over the time period with and without certain and incomplete enforcement.*

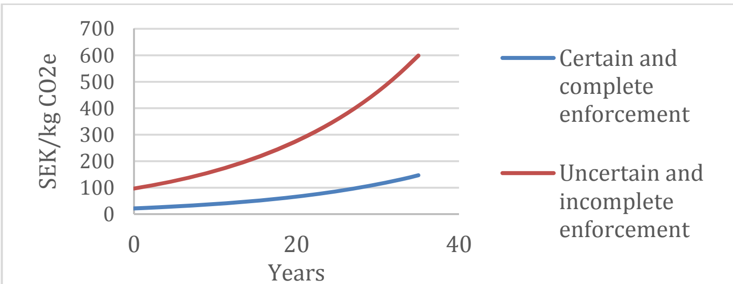


Figure 22. *Cost effective marginal abatement cost over the time period with and without certain and incomplete enforcement.*

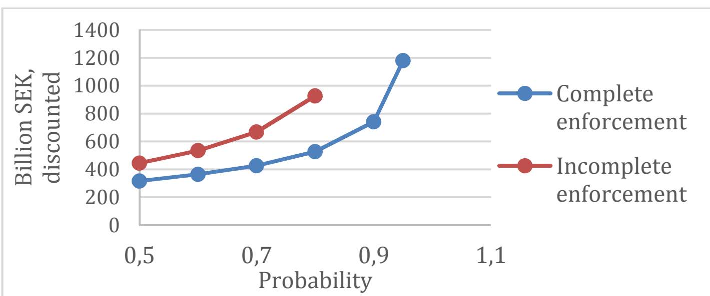


Figure 23. *Cost-effective achievement of 80% CO_2e reduction in 2050 under uncertain enforcement and different probabilities of reaching the target*

With respect to allocation of abatement among municipalities in a cost-effective solution, the sixth municipalities with the largest emission source also account for the largest abatement costs. Together, they face 64% of total abatement costs under incomplete and uncertain enforcement and for 54% with certain and complete enforcement. The higher cost share is explained by the need for more abatement under uncertain enforcement for reaching the abatement target with a probability of at least 0.80 and the capacity constraints imposed on all abatement measures. Two municipalities, Stockholm and Oxelösund, are on the top in both cases but switch positions. Oxelösund has the largest share (0.22) with uncertain enforcement and Stockholm hast the highest share (0.17) with certain enforcement.

However, the costs under uncertain enforcement decrease for a lower probability and increases for a higher probability see Fig. 23.

Under incomplete enforcement it is not possible to achieve reductions with higher probabilities than 0.8 because of capacity constraints on all abatement measures. Nevertheless, the costs are more than doubled from the deterministic case when probability is 0.5. The increase is larger with complete but uncertain enforcement, an increase in the probability of 0.5 to 0.95 raises costs by almost fourfold.

Summary and Conclusions

The purpose of this study has been to investigate the possibilities and properties of achieving a low carbon economy when enforcement is incomplete and uncertain. The study was applied to the Stockholm-Mälar region. The region has decreased its emissions since 1990 by approximately 15%, and at the same time faced increases in gross regional product. We defined and operationalized a low carbon economy as an economy with maximum 20% of the 1990 emission level to be achieved in 2050. Some initial investigation of the region revealed the asymmetric allocation of emissions among counties and municipalities. The six largest municipalities account for 65% of total emissions, and the sum of emissions in quite many municipalities already achieve the EU carbon target.

Most other studies of cost-effective solutions to the EU climate targets do not account for incomplete enforcement and technological development. Our results show considerable differences in costs with and without uncertain and incomplete enforcement. The estimated minimum costs for the Stockholm-Mälar region with certain and complete enforcement amounts to 316 billion SEK which correspond to 1.4% of cumulative gross regional product in the region. This result is quite close to that of other studies, where total abatement costs vary between 1-2% of gross domestic product. Our results pointed at the need of considering incomplete enforcement, which raises cost by at almost 300%. However, the allocation of financial burden among municipalities is not much changed with and without complete and uncertain enforcement. The same five-six municipalities face at least 50% of total abatement cost in all cases, but the costs are raised for all municipalities.

The effect of incomplete enforcement calls for the possibility to include institutional improvements as a measure in a cost effectiveness analysis. Improvements are made at a cost, such as payments for salaries and equipment for supervising compliance with regulations. An extended analysis should thus not identify and calculate costs only for different types of abatement measures, but also for policies that increase their enforcement and actual implementation. The magnitude of implementation leakage is much dependent on type of policy. For example, it is easier to implement and supervise a tax on carbon dioxide content in fossil fuel than construction and enforcement of contracts for renewable energy. This would create a cost advantage for reductions in fossil fuel. However, data on so-called transaction costs for different policy instruments are not available, and this study therefore disregarded these differences.

IV:2 The Value of Carbon Sequestration and Nutrient Recycling in Forests

Ing-Marie Gren

Forests provide a multitude of marketed and non-marketed ecosystem services, where timber outputs provide a marketed service, and biodiversity, pollutant sequestration, and recreational opportunities are examples of non-marketed services. Forest recreational opportunities and biodiversity have been subjected to valuation in monetary terms in several studies, but there are only a few estimates of other ecosystem services, such as carbon sequestration and nutrient recycling (see survey in (Pearce, 2001)). The benefits of carbon sequestration and nutrient recycling emerge from their ability to regulate the carbon content in the atmosphere and nutrient leaching at a lower cost than other measures, such as reductions in fossil fuels. Valuation of carbon sequestration for combatting climate change has been carried out at the regional EU and global scale (Lubowski *et al.*, 2006; Michetti & Rosa, 2011; Gren & Carlsson, 2013). However, afforestation (plantation of forest on arable land), which is the least expensive measure for carbon sequestration (Aklilu & Gren, 2015), also implies a reduction in nutrient leaching. Unbalanced nutrient loads can lead to eutrophication of water, as well as increased frequency of harmful algal blooms, sea bottom areas without biological life, toxic cyanobacteria, and decreases in water transparency and populations of commercial fish species (Gilbert, 2007; Heisler *et al.*, 2008). There is a complementarity between carbon and nutrient transformations in boreal forests (Boberg *et al.*, 2014), which implies that increases in carbon sequestration reduce nutrient leaching from soil. The purpose of this study is to calculate values of forest carbon sequestration and nutrient recycling in the

Stockholm-Mälar region in southeast Sweden. The choice of these services and region is based on the existence of actual targets for carbon and nutrient emissions, and of numerical models allowing for the calculations (Gren, 2010; Gren *et al.*, 2015).

To the best of our knowledge, there are no published studies that calculate the value of a forest's ecosystem services in terms of carbon and nutrient sequestration. On the other hand, there is a relatively large body of literature calculating the value of especially carbon sequestration (Lubowski *et al.*, 2006; Michetti & Rosa, 2011; Gren & Carlsson, 2013). There are also a relatively large number of studies on the value of nutrient sequestration by wetlands and coastal ecosystems (Gosselink *et al.*, 1972; Breux *et al.*, 1995; Byström, 2000; Gren, 2013), but not on forest ecosystem nutrient sequestration. Similar to these studies, we apply the so-called replacement cost method for calculating values. The basis for this method is the existence of environmental targets, and the value of a new technology is then measured as the decrease in total costs associated with achieving these targets when the technology is included as a measure. It has then been shown that inclusion of forest carbon sequestration can reduce the total cost of achieving the global target of a maximum of 550 ppmv (parts per million by volume) by 40% (Tavoni & Sohngen, 2007; Anger & Sathaye, 2008) and the EU 2020 climate target of reducing emissions to 20% from the 1990 emission level in 2020 by 30% (Michetti & Rosa, 2011).

However, pollutant sequestration may have a cost disadvantage when considering uncertainty. Uncertainty arises from stochastic weather conditions, which affect biomass growth, and thereby carbon sequestration and the release of carbon and nutrients from soil. This, in turn, implies uncertainty in reaching stipulated targets, which constitutes a cost associated with this risk. Such costs have been calculated, where cost per unit pollutant sequestration is increased by a risk discount (Gren & Carslsson, 2013; Byström *et al.*, 2000; Kurkalova, 2005; Kim & McCarl, 2009). The calculation of this is, in turn, based on the so-called safety-first principle, which has a long tradition in economics (Tesler, 1955). It is then assumed that decision makers are risk averse against non-attainment of stipulated environmental targets, and the risk discount is determined by this risk aversion and the variability in sequestration. As shown by (Gren & Carlsson, 2013) and (Gren *et al.*, 2012), the value of forest carbon sequestration in the EU 2020 climate policy is reduced and can approach zero for high levels of the risk aversion.

The current study calculates the value of forest pollutant sequestration with and without uncertainty when we apply the safety-first principle. To this end, we construct a dynamic optimization model with uncertainty, which, in addition to pollutant sequestration, includes abatement measures reducing emissions from fossil fuels and nutrient leaching. A dynamic model is needed because of the focus on future climate and nutrient targets, as well as consideration of depreciation in investment in renewable technologies and nutrient cleaning facilities, and development over time of carbon sequestration in afforested land. In our view, the main contribution of this study is the calculation of values of forest sequestration of several pollutants. Another is the consideration of uncertainty, and a third is the calculation of values of forest nutrient recycling, which have been made mainly for wetlands in other studies.

The Replacement Cost Method.

The value of the services of land use in terms of carbon and nutrient sequestration is determined by their cost in relation to the costs of other abatement measures in a cost effective achievement of certain emission targets. The higher the cost of other abatement measures, the larger is the value of the ecosystem service. This simple principle for determining value is illustrated in Fig. 24 for carbon sequestration.

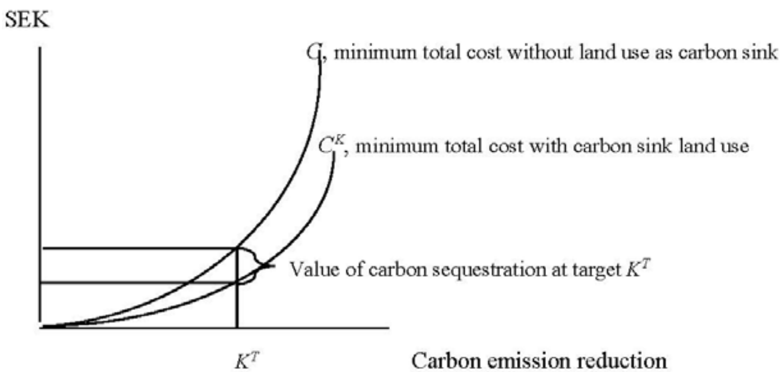


Figure 24. *Illustration of the calculation of the value of land use as a carbon sink in a cost effectiveness framework. SEK: Swedish crown;* K^T*: carbon emission reduction target.*

The horizontal axis illustrates carbon emission reductions, and K^T is the target to be achieved. The vertical axis shows the cleaning cost for different emission reduction levels. The curve C illustrates the minimum costs for achieving different emission reduction targets when the carbon sink provided by forests is not included as an abatement option in the cleaning program, and C^K illustrates the minimum costs when the carbon sink is included. Each point on C and C^K respectively reflects the allocation of all abatement measures that reach the target at minimum cost.

The value of carbon sequestration at the target K^T is now determined by the difference in total minimum costs with and without carbon sequestration, which corresponds to the distance C-C^K in Fig. 24. The value of the carbon sink is then determined by its construction cost and the abatement costs of other measures. The larger the difference between the abatement costs of other measures and that of the carbon sink, the higher the value of the carbon sink. This is, in turn, determined by the stringency in the carbon target since the costs of all abatement measures increase at higher emission reduction levels.

The value of land use for nutrient sequestration is calculated in the same way as for carbon sequestration. However, the value of both these sequestration options depends on whether carbon and nutrient targets are managed separately or simultaneously. When managed separately without consideration of the other pollutant target, the full cost of land use will be borne by the reduction in the pollutant in question. Under simultaneous management, land use measures will have a cost advantage compared with measures affecting only one pollutant and will therefore be implemented to a larger extent than under separate target management.

Although simple in principle, the calculation of cost effective solutions with and without carbon sequestration and nutrient recycling can be quite involved when considering the dynamics in investment renewable energy sources and forests, and the uncertainty in carbon sequestration and nutrient recycling. For detailed description of the numerical model see Gren (2015): Investment in renewable energy is subject to depreciation over time, and that in forest to appreciation since carbon sequestration and nutrient recycling can be increasing over time. Uncertainty is treated in a safety-first setting with probabilistic constraints on the future carbon and nutrient targets. This means that the targets are expressed as the achievement of minimum reductions at minimum probabilities. These targets are then transformed into deterministic equivalents where decision makers' risk aversion and variance in emission reduction call for extra emission reduction in order to ensure the achievement of a certain target.

Data Retrieval

The conceptual approach presented above shows that we need data on pollutant emissions from all sources under business as usual (BAU), abatement capacities and impacts on targets of different measures, cost functions for all measures, depreciation rates of investment in cleaning technologies, growth rates of pollutant sinks, variance in pollutant sink, risk aversion, and discount rate. All data are obtained from two existing cost minimizing models of the Stockholm-Mälar region. One is a dynamic model for achieving 80% reduction in carbon emission from the 1990 emission level by 2050 (Gren *et al.*, 2015) and the other is a static model for achieving nutrient targets in the coastal area of the region (Gren, 2010). Detailed documentations of the data retrieval are found in (Gren, 2010; Gren *et al.*, 2015). In the following, we therefore give a brief summary of these data items.

Carbon Emission and Nutrient Leaching

The Stockholm-Stockholm-Mälar region covers an area of approximately 34,000 km^2. Two thirds of the area, or 22,000 km^2, is covered by forests and 6400 km^2 by arable land. The region contains the capital of Sweden, Stockholm, and 50% of the total Swedish population of 9.5 million people. Sweden and hence the Stockholm-Mälar region is guided by two international commitments; the EU climate policy (European Commission, 2015) and the Baltic Sea Section Plan (BSAP) (Helcom, 2014). According to the EU 2050 climate policy, the CO_2e emissions should be reduced by 80% from the emission level in 1990, to be reached by 2050, and the BSAP envisages different reductions for the marine basins of the Baltic Sea. The Stockholm-Mälar region is located at the coastal zone of the marine basins with the highest target stringency, *i.e.*, the Baltic Proper, where the requirements are 23% nitrogen and 61% phosphorus reductions.

When calculating leaching of nitrogen and phosphorus to the Baltic Proper, retention of nutrients during the transport from the emission sources located upstream in the drainage basins are deducted since they do not reach the sea. All sources located at the coastal waters, mainly sewage treatment plants and industry, have direct discharges into the Baltic Proper. The numerical model includes 36 drainage basins in the Stockholm-Mälar region with retention rates, *i.e.*, the share of nutrient emission that does not reach the sea, ranging between 0 and 0.9 (Gren, 2010). A minor part of the nitrogen deposition originates from air-borne emissions from fossil fuel combustion in the Stockholm-Mälar region (Table 3).

Table 3. *Carbon dioxide equivalent (CO_2e) emissions, and nitrogen (N) and phosphorus (P) leaching from different sources in the Stockholm-Mälar region into the Baltic Proper. (Gren, 2015).*

	N, ton [a]	**P, ton** [a]	**CO_2e Emission, kton** [b]	**CO_2e Sequestration kton** [b]
Forest land	773	19		3531
Arable land	1825	156	840	
Sewage treatment plants	5613	94		
Transport	82		5451	
Industry	23		1527	
Energy production	70		4688	
Other CO_2e sources			1677	
Total	8386	269	14183	3531
Targets [c,d]	6457	105	3438	

[a] [9]; [b] [10]; [c] Targets for N and P are 77% of N and 39% of P loads in 2008 but without target year [24];
[d] Target for CO_2e is 20% of 1990 emission to be reached by 2050 [23].

Arable land and sewage treatment plants are the largest sources of nutrients, and transport and energy production are the major sources of CO_2e emission. Existing forest carbon sequestration corresponds to 25% of total emission.

Abatement Measures and Costs

In addition to afforestation, we include reductions in the use of fossil fuel, replacement of fossil fuel driven cars with electrics cars, and investment in solar and wind power for reducing carbon emissions. These measures also affect the emission of nitrogen oxides and associated deposition in the Baltic Proper. Measures reducing nutrient leaching include investment in sewage treatment plants, cultivation of catch crops, and reductions in the use of fertilizers. All of these measures reduce both nitrogen and phosphorus. Afforestation affects all three pollutants. The basis for choosing these measures is that they turned out to be relatively inexpensive for combatting CO_2e emissions and nutrient loads into the Baltic Sea in the Mälar-region (Gren, 2010; Gren *et al.*, 2015). Our estimates of the value of the forest as a pollutant sink are then likely to be conservative.

The effects of afforestation on pollutants are calculated as the difference in the carbon and nutrient sink per unit area of forest and arable land. Given the relatively short period until 2050, afforestation requires fast-growing tree varieties to provide carbon sequestration. According to (SEPA, 2014), the sink coefficient for forest land is 1.81 ton CO_2e/ha and −0.73 ton CO_2e/ha for arable land, which gives a net effect of 2.54 ton CO_2e/ha afforestation. This effect is assumed to be the same for all drainage basins, obtained after 20 years, and with a constant growth rate during the years.

The cost of afforestation consists of the opportunity cost of land, *i.e.*, differences in annual profit between agriculture and forestry. This information is obtained from a supply curve of arable land, which shows the profits foregone for transferring arable land into other uses (Gren *et al.*, 2015). In a similar vein, costs of fossil fuel reductions are calculated as associated decreases in consumer surplus, which are obtained from demand functions of different fossil fuel products (heating oil, coal, gasoline, and diesel).

Data on investment cost functions for wind and solar power are found in (Munnich Vass, 2015), who estimated quadratic cost functions for these energy sources for the whole of

Sweden. The cost of electric cars is assumed to be constant per 10 km and correspond to the difference in driving costs between gasoline and diesel cars. This cost depends on the type of car and the distance driven per year; the longer the distance, the lower the difference in driving cost. We evaluate the cost for the average distance in Sweden (Gren *et al.*, 2015). It is also assumed that the rates are calculated from assumptions of technical life lengths of 40 years for wind and solar power, and 25 years for electric cars. With respect to capacity constraints, assumptions are imposed on the replacement of fossil fuel with renewable energy, and of the existing car fleet with electric cars.

Concerning measures reducing nutrient deposition into the Baltic Proper, considerable investments in sewage treatment plants have already been made, and we therefore assume that further cleaning is carried out by implementing tertiary cleaning programmes. The average investment costs of tertiary cleaning at sewage treatment plants are obtained from (Gren, 2010) and converted into 2011 prices. It is more difficult to obtain information on the technical life length of the investment, but a 50-year perspective is usually assumed. Costs on reductions in the use of fertilisers are calculated as associated decreases in farmers' profits, or consumer surplus, data on which are found in (Gren, 2010). Costs of cultivation of catch crops, which are sown at the same time as the ordinary crop is harvested in autumn and thereby prevent nutrient leaching from the soil during autumn and winter seasons, are also found in (Gren, 2010).

Uncertainty, Targets and Discount Rate

Recall from the previous section that data are needed on variance in nutrient and risk aversion in order to calculate the risk discount. There are no data on any of these parameters. We therefore use the standard deviation in carbon sink for Sweden as calculated by (Janssens *et al.*, 2005), and assume that this is the same for nitrogen and phosphorus loads into the Baltic Proper. The standard deviations in (McCarl & Spreen, 2010) include measurement errors in data on carbon sinks for different land uses and uncertainty related to weather variability, which affects biomass growth and thereby carbon sequestration.

The effect on the risk discount of a certain choice of probability of achieving the targets depends on the underlying probability distribution of the pollutant sink. However, there is no information on the probability distributions. In principle, they can be quantified in two ways: by assigning a specific or parameter free distribution. The normal distribution is most commonly applied, and is frequently applied in the literature on policy instruments for stochastic water pollution (Gren, 2010; Byström *et al.*, 2000; McSweeny & Shortle, 1990; Shortle, 1990). Another way of quantifying the probability distribution is more flexible and is based on Chebyshev's inequality where no assumptions are made with respect to the probability distribution (McCarl & Spreen, 2010). There are considerable differences in the calculated risk aversion parameter Φ^{α_p}, depending on the assumption of distribution. For example, at a chosen probability level 0.95, Φ^{α_p} is 1.67 for the normal and 4.47 for Chebyshev's distribution. We have no prior expectations for the shape of the probability distribution and we therefore make calculations with both distributions.

With respect to emission reduction targets, the EU 2050 climate policy is quite clear; 80% reduction in the 1990 emissions should be obtained by 2050. This is not the case with the nutrient targets set by BSAP, where reductions in nitrogen and phosphorus are specified for different marine basins but not the timing of their achievement. It is only stated that preparedness for implementing the targets should by obtained in 2020. Since it takes some time between implementation of nutrient reductions and final achievement, we therefore simply assume that the targets of 23% reduction in nitrogen and 61% reduction in phosphorus loads into the Baltic Proper should be achieved in 2035.

Regarding the choice of discount rate, there is a large body of literature on the appropriate level of the social discount rate, which is determined by pure time preferences, growth in consumption opportunities, and utility of consumption (Weitzman, 2001). It is generally also suggested to use a hyperbolic discount rate, *i.e.*, a time-declining rate, for long-term projects exceeding 50–100 years. A simplification is made in this paper by assigning a uniform discount rate for all municipalities, counties and time periods. Following recommendations made for discounting future streams of net benefits, calculations of cost-effective solutions are made for a relatively low level of 0.015 (Newell & Pizer, 2003).

With respect to choice of software, all calculations are made with the GAMS optimization program, Solver Conopt2 (Rosenthal, 2008).

Results: the Value of the Forest for Carbon and Nutrient Sequestration

The existing carbon sequestration corresponds to 24% of the total emissions in 2011. The inclusion of this sink into the Stockholm-Mälar climate and water policy would generate cost savings since part of the emission target is obtained by sequestration free of charge. However, there is currently a debate on whether carbon sequestration should be included in the EU climate policy, which focuses solely on increases in the carbon sink from a certain reference value, which is denoted additional sinks. One argument against including the existing carbon sink is that this is already considered when setting targets, and its inclusion would tighten the emission target. In the following, we will therefore focus on the value of the additional sink, but also present results on the values of the existing sink. In our model, the only additional sink option is forest plantations on agricultural land. As will be shown, the value of the existing sink available free of charge can be zero depending on risk attitudes and assumptions that stem from uncertainty in carbon sequestration.

Value of Pollutant Sink at Different Emission Targets

The main focus of this study is the value of pollutant sinks in achieving the EU 2050 climate policy and BSAP nutrient targets. As shown in Section 2, the value is determined by, among others, the stringency in emission targets, and we therefore present results for different levels of carbon and nutrient emission targets. Starting with carbon emission, the value of forest sequestration ranges from zero to 767 billion SEK (1 Euro = 9.36 SEK, 13 July 2015), depending on the emission target and the inclusion of existing or additional sequestration (Fig. 25).

The zero value arises from the reduction in emission of 15% in the Stockholm-Mälar region from 1990 to 2011 (Gren *et al.*, 2015). When existing sinks are included, the zero value increases to approximately 40% of the emissions in 1990. The total abatement cost for reaching the emission target in 2050 without the inclusion of any sink option amounts to 900 billion SEK. The average annual cost of 24 billion SEK corresponds to approximately 1.7% of the gross regional product (GRP) of the Stockholm-Mälar region. This is reduced to 0.3% when only the existing sink is included and to 1.2% when only the additional sink is considered in the climate program.

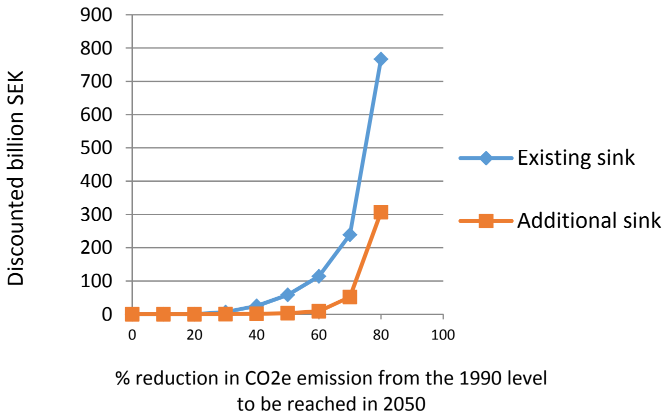


Figure 25. *Value of forests for carbon sequestration when only existing or additional carbon sinks are included at different reduction levels from the 1990 emission, to be achieved by 2050.*

As expected from the illustration in Fig. 25, the carbon sink value increases at higher emission reduction levels because of the higher abatement costs for emission reductions. The carbon sink values are relatively low at reduction levels up to 50%, and then increase rapidly. At the EU target of 80% emission reduction, the value when only existing sinks are included corresponds to approximately 767 billion SEK, and when only the additional sink is included, to 307 billion SEK. The values thus decrease the total cost without any sink option by 84% or 35%.

The corresponding values of forests for reaching different reductions in both nutrients to the Baltic Proper are presented in Fig. 26.

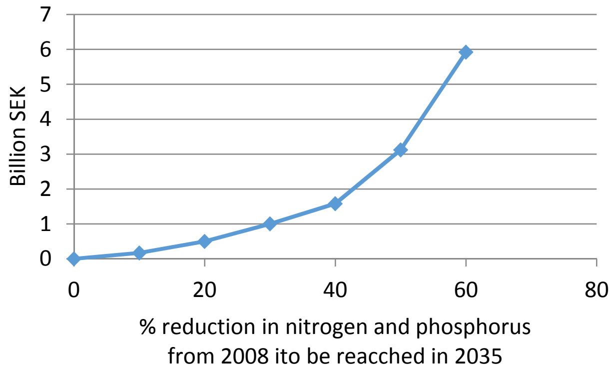


Figure 26. *Value of the forest for nutrient sequestration in reducing nitrogen and phosphorus loads from the Stockholm-Stockholm-Mälar region to the Baltic Proper in 2035.*

The value of the forest for nutrient sequestration is much lower than that for carbon sequestration. One reason is that total costs without nutrient sequestration are lower, and amount to 17 billion SEK at 60% reduction in both nutrients. This corresponds to an average annual cost of 0.5 billion SEK, also obtained by (Gren, 2010). The cost is reduced by 5.2 billion SEK, or approximately 35%, when forest nutrient sinks are included. This relative reduction is of the same order of magnitude as the additional carbon sinks.

Uncertainty in Forest Pollutant Sink

One of the main arguments for not introducing carbon sinks in any climate policy is the uncertainty associated with stochastic weather conditions affecting biomass growth and permanence in carbon sinks over time. Therefore, 1 ton CO_2e sequestration does not correspond to 1 ton CO_2e reduction in emissions. As shown in a previous section, this is treated in terms of an uncertainty discount, which is determined by the risk preference, *i.e.*, the chosen probability of reaching the targets, the variability in the sink, and the chosen probability distribution. We evaluate the value of the forest as a pollutant sink under simultaneous achievement of the EU 2050 climate policy (European Commission, 2015) and the Baltic Sea Action Plan (Helcom, 2014) at different degrees of risk aversion and for the normal and Chebyshev probability distributions (Fig. 27).

For both the normal and Chebyshev probability distributions, the value decreases as the chosen probability increases. However, the decline is more drastic with the Chebyshev probability distribution, and the value is zero at probability levels exceeding 0.95. The maximum decline in the forest sink value differs for the different probability distributions: it is 166 billion SEK, or 45%, for the normal distribution and 279 billion SEK, or 100%, for the Chebyshev distribution, both of which occur at probability levels exceeding 0.95.

The maximum value of the forest carbon sink amounts to 767 billion SEK, which occurs when there is no risk aversion. The marginal costs for achieving the targets then amount to SEK 2570/ton CO_2e reduction, and to SEK 10,300/kg phosphorus and SEK 231/kg nitrogen load reduction.

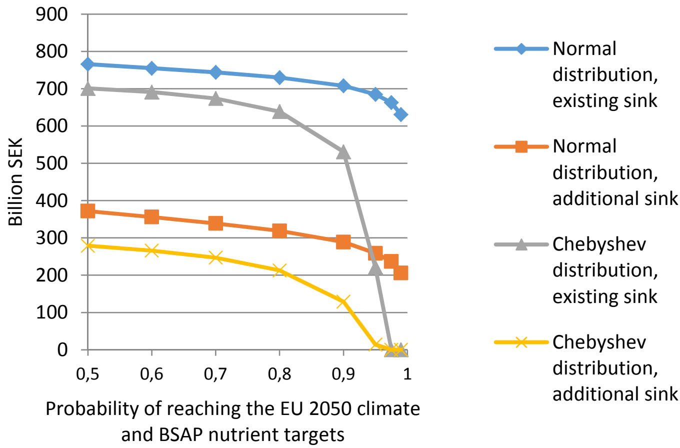


Figure 27. *Value of forest pollutant sink for reaching the EU 2050 climate and BSAP nutrient targets under different probabilities of reaching the targets and assumptions of probability distributions.*

Discussion

The calculated total cost of reaching the EU 2050 climate targets as measured in per cent of gross domestic product of the Stockholm-Mälar region, 1.12%, is within the range of that obtained for reaching the EU 2050 climate targets (Capros *et al.*, 2013). The calculated marginal cost of CO_2e reduction is also within the range of other studies. On the other hand, the marginal costs of the nutrient load reductions are slightly above the estimates obtained for the entire Baltic Sea and all riparian countries by (Gren *et al.*, 2013b). One reason that these marginal costs differs from other studies could be the relatively large level of nutrient abatement already carried out in the Stockholm-Mälar region, which raises the marginal cost of further abatement.

The calculated maximum value of the existing sink of 767 billion SEK corresponds to an average forest value of SEK 22500/ha. This value can be compared with the average assessed value of productive forests, which varies between SEK 41,200/ha and SEK 58,800/ha in the different counties in the Stockholm-Mälar region (Skogsstyrelsen, 2015). The value of the existing carbon and nutrient sink can then correspond to 50% of the value for timber products. It is reduced to SEK 8700/ha, or maximum 21% of the value of productive forests, when only additional sinks are included.

It is also of interest to investigate how the value is determined by the time path for decarbonisation as envisaged by (European Commission, 2015). In order to reach the target in 2050, it is suggested that 20% of the 1990 emission should be reduced by 2020, 40% by 2030, 60% by 2040, and 80% by 2050. This path may not coincide with the cost effective path, and the total cost will then be higher. The calculated total cost for achieving the EU and BSAP targets under optimal conditions amount to 900 billion, and under the EU budget, to 992 billion. This, in turn, affects the value of forest carbon and nutrient sequestration of both the existing and additional sink (Fig. 28).

The value of the existing carbon sink is higher under the EU time path since the total abatement cost is larger. On the other hand, the value of the additional sink is slightly lower under the EU time path than under optimal conditions. This seems counter intuitive, but is explained by the gains made by the full use of the forest sinks' ability to grow over time for optimal solutions, which is limited by the EU suggested time path.

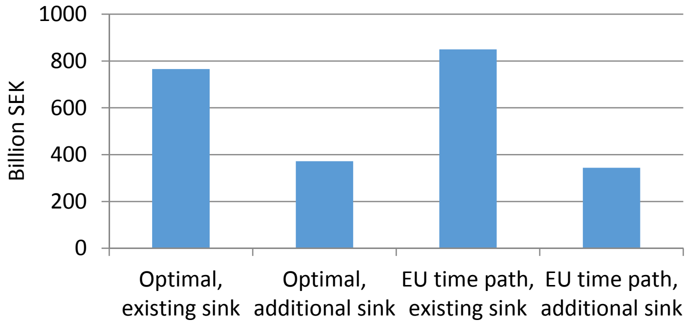


Figure 28. *Value of forests as pollutant sinks for reaching the EU 2050 climate target and the BSAP nutrient targets in the Stockholm-Mälar region optimally or under the EU time path without uncertainty.*

When considering uncertainty and the other factors influencing the calculated value of the forest as a pollutant sink, it is noted that the relative values, as measured in deviation from the reference values, are more sensitive to changes in parameter values under the Chebyshev than the normal probability distribution (Fig. 29).

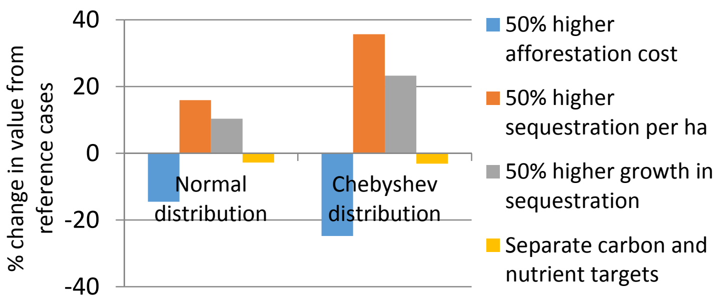


Figure 29. *Impacts on the reference value of the forest as an additional pollutant sink under uncertainty with 0.9 probability (289 billion for the normal and 129 billion for Chebyshev the distribution) of different changes in afforestation cost, pollutant sequestration and growth, and separate management of carbon and nutrient targets.*

As expected, the value decreases when the afforestation cost increases, which can be a result of higher future competition of land with food production. A 50% increase in the afforestation cost results in 15% and 25% decline in the reference value under the normal and Chebyshev distribution, respectively. The reason for the larger decline under the Chebyshev distribution is the relatively higher risk discount, which raises the cost of the forest as a pollutant sink compared with the normal distribution. A certain percentage deviation in afforestation costs then has a higher impact on the reference value. This also explains the higher increase in relative values when pollutant sequestration/ha and growth rate over time increases.

However, the decline in the absolute values when the afforestation cost increases by 50% is still higher for the normal distribution, for which it amounts to 43 billion SEK compared with 32 billion SEK for the Chebyshev distribution. On the other hand, the decline in the absolute values is of the same order of magnitude for both distributions when sequestration and the rate of sequestration increases and amounts to approximately 46 and 30 billion SEK, respectively. The choice of separate *versus* simultaneous management has a minor impact on both distributions and raises the cost at the most by 8 billion SEK, which occurs for the normal distribution.

Conclusions

The calculation of values of forest carbon and nutrient sequestration in the Stockholm-Stockholm-Mälar region showed that these can be significant. They can create cost savings corresponding to 35% of the cost of achieving the EU 2050 climate and the Helcom BSAP nutrient targets in 2035. The percentage cost saving for achieving the EU climate target is of the same magnitude as that obtained in other studies (Capros *et al.*, 2013). In absolute terms, the total value amounts to 307 billion SEK, which corresponds to approximately 0.45% of the region's gross domestic product.

However, this value declines when uncertainty in pollutant sink is considered, which is the main argument raised against its inclusion into, in particular, climate policy. Depending on risk aversion and the choice of the probability distribution, normal or Chebyshev distribution, the value can be reduced by 50% or 100%, respectively, at very high risk-aversion, where the targets are to be achieved at probability levels exceeding 0.95.

The calculated values are affected not only by the level of uncertainty, but also by factors not considered in this study, which can result in higher or lower estimates (Table 4).

Uncertainty in other abatement measures such as reduction in fossil fuels or investment in solar energy raises the cost of these measures, and, hence, the value of the forest carbon sink. This would also be the case if more forest management options were included, which would improve pollutant sink per area of forest and/or increase the rate of sequestration growth over time. Another factor contributing to increased values is the inclusion of management options for reducing uncertainty by, for example, increased monitoring of forest biomass growth and carbon sink content and/or improved management for reducing carbon releases from dead wood and soil.

Table 4. *Factors increasing or decreasing the calculated values of forest carbon sequestration and nutrient recycling, where × denotes the direction of impact.*

Factor	Increased Calculated Value of Carbon and Nutrient Sinks	Decreased Calculated Value of Carbon and Nutrients
Uncertainty in all abatement measures and not only carbon sink	×	
Inclusion of more forest management option	×	
Inclusion of measures reducing uncertainty in the carbon sink	×	
Policy implementation of carbon and nutrient sink		×
Consideration of more non-marketed ecosystem services	×	×

The calculated values can be lower when considering the difficulties associated with implementing a multi-target strategy, which requires allowance for pollutant reduction in several policy systems. For example, afforestation must be deducted from the emission of nitrogen, phosphorus, and CO_2e. This can be obtained by an offset system where actors obtain credits for pollutant sequestration, which can be deducted from their pollutant emissions allowances. Another possibility is to include the abatement measures in the policy system where, for example, forest carbon sequestration can be traded on the EU ETS (Emission Trading System), or in a national tax system. Both options face problems when including land use measures because of the difficulties in monitoring and verifying sequestration, and to secure additionality and permanence in the sequestration. Associated transaction costs can be relatively high and the potential cost savings from pollutant sequestration are then smaller than pointed out in this study.

The results are also affected by the number of included non-marketed ecosystem services. This study considered only carbon sequestration and nutrient recycling. However, increases in these two services may result in decreases in other non-marketed services, such as biodiversity, which would reduce the calculated values in this study. On the other hand, if there is complementarity in the provisioning of these services, the calculated value can be raised since increases in the carbon and nutrient sink then provides a simultaneous improvement in biodiversity. Calculations of such trade-offs or complementarities in the provision of forest ecosystem services require quantified production functions for all of these services, which are not available for forests in Sweden.

The conclusion with respect to the value of forest carbon sequestration and nutrient recycling as abatement measures in climate and nutrient programs is thus ambiguous. Although our study shows considerable cost savings in the deterministic and relatively simple case, the consideration of uncertainty, policy implementation, and other ecosystem services can eliminate these savings. This inconclusiveness points out the need for further analysis and investigations of these factors for the potential value of the forest carbon sink and nutrient recycling as abatement options in climate and nutrient programs.

IV:3 Climate Impact of Using Locally Produced Willow to Supply a Biomass-Fired CHP Plant in Uppsala

Torun Hammar and Cecilia Sundberg

Growing short rotation forestry like willow on unused agricultural land is one strategy to supply a local community with bioenergy. Assessing the climate impact of such strategy need to consider the variation within one landscape, as soil type and water availability are important for the willow growth (Krzyżaniak *et al.*). The soil properties also affect the soil organic carbon content and the potential benefits of growing the crop. Previous studies on willow have shown a potential to increase the soil organic carbon (SOC) content, which as a result could mitigate global warming by sequestering carbon from the atmosphere (Hammar *et al.*, 2014; Ericsson *et al.*, 2013). These studies have however been carried out on a stand view level, where only the soil dynamics within one field have been assessed.

In this study, the aim has been to assess the climate effect of using locally produced biomass to supply a combined heat and power (CHP) plant, and to assess how the variations within one landscape, in terms of soil quality and field location, influence the overall climate impact. The region of Uppsala (southeast of Sweden) is chosen as case study since a new bio-based CHP plant is planned to be built in the region. The region accounts for a relatively large share of the total area used for energy forestry in Sweden (about 2000 ha in Uppsala county is grown with energy forestry (Statistics Sweden, 2013)), with potential to expand since around 10% of the arable land in the region is currently fallow land (Statistics Sweden, 2013).

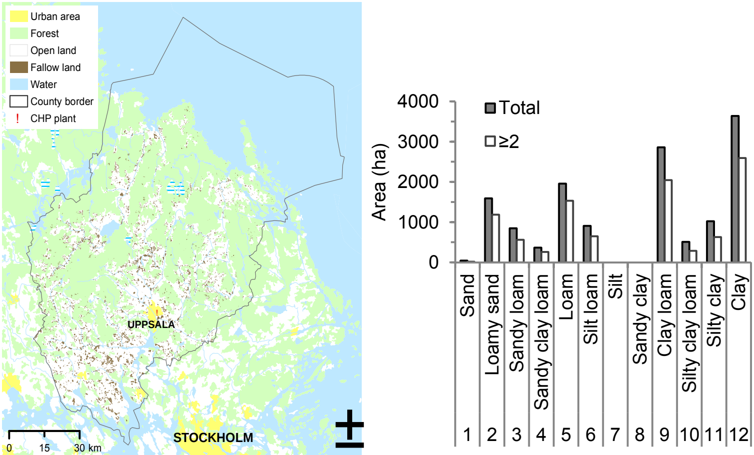


Figure 30. *Left: Distribution of fallow land (dots) in Uppsala County. Crop and field information © Swedish Board of Agriculture (Jordbruksverket); background map: overview map 1:1 000 000 © Lantmäteriet. Right: Distribution of soil texture in all fields in Uppsala County (Total) and in fields >2 ha (Hammar et al., 2016).*

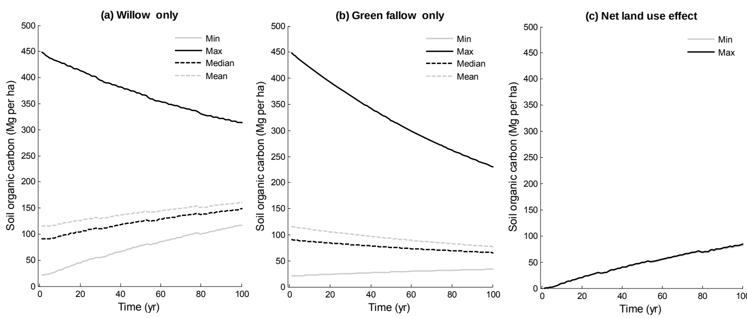


Figure 31. *Changes in soil organic carbon (SOC) content for all fields (N = 2083) when including (a) willow cultivation only and (b) reference land use only (continued green fallow); and (c) the net effect of transforming green fallow into willow cultivation and the continuing effect over time (100 years). (Hammar et al., 2016)*

To assess the climate impact of locally produced biomass in the studied region, geographical information of unused arable land is obtained to identify soil properties and transportation distances for the sites (see Fig. 30). This information is thereafter used for modelling soil organic carbon balances with the ICBM model (Introductory carbon balance model), which is a carbon balance model adapted for agricultural lands (Andrén *et al.*, 2004). All fluxes of the three major greenhouse gases (carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4)), as well as energy use, is calculated for the whole bioenergy system. The impact is assessed by using life cycle assessment (LCA) methodology, which is a standardised method for assessing environmental impacts of a product or service during its entire lifetime (ISO, 2006a; ISO, 2006b). The climate impact is assess by using a global temperature change metric, defined as absolute global temperature potential (AGTP) by the IPCC (Myhre *et al.*, 2013).

This study showed that supplying an energy facility yearly with willow biomass grown on fallow land had a negative temperature response (i.e. cooling effect) when considering spatial variations in a landscape. The climate change mitigation potential was improved by selecting the best performing fields (e.g. in terms of highest SOC increase), but all fields needed to be utilised to generate as much energy as possible. Another conclusion was that the choice of reference land use played a major role for the results. Combined GIS and time-dependent LCA method proved to be a useful way to assess land use change in bioenergy systems. Moreover, the approach can be further improved with better data availability in the future and expanded to include and compare different types of biomass. Some of the results of these studies are shown in Fig. 31, but more is found in Hammar *et al.* (2016).

IV:4 Future Scenario Modelling: An Insider's View on Uppsala

Cecilia Sundberg

The research described in this chapter began before the COMPLEX project was funded and will continue after the project has closed down. This report draws on six years of experience of collaboration on transitions to a low-carbon society between academia and public and private actors and civil society in Uppsala, Sweden. My journey started with a student project on local energy system planning in my course for Energy Systems Engineers in 2009 and has evolved since then. This text summarises some reflections on this process. Starting with a short description of the collaboration and the model, I reflect on the knowledge and understanding that has developed in the modelling process. Some examples are given on technologies of interest and how these have, or have not, been integrated into the modelling process. Then I describe some institutional aspects related to the collaboration, and summarise the findings.

The Uppsala Roadmap to a Low Carbon Society

With over 200 000 inhabitants, Uppsala (59°N; 17°E) is the fourth most populated municipality in Sweden and the central area is the fourth largest city. The public sector is the largest employer, including two universities, the municipality and the county council, occupying over 30 000 people. High technology dominates the industry, primarily within information technology and biomedicine, closely linked to the research at the universities. The current energy system is characterized by a combined heat and power (CHP) plant that distributes district heating, electricity, district cooling and steam to the central urban area, with the main fuels being peat, municipal waste and biomass. Biogas is produced at five facilities and the gas is used either in conjunction with heating or is upgraded for use in public transportation.

The biogas plant in Uppsala (top) and a local biogas bus at SLU campus in Uppsala. Photo: H. Liljenström

In 2010, the municipality of Uppsala initiated the Uppsala Climate Protocol (UCP) with the purpose to involve local and regional stakeholders and decision makers in a joint effort to reach the local energy and climate goals. The 25-30 private and public organizations participate in energy and climate efficiency actions that are accessed through collaboration (http://klimatprotokollet.uppsala.se/). The UCP members commit to systematically reducing climate impact within its own operations, implementing and declaring climate mitigation measures, contributing with knowledge and collaborating with other members to reach their own as well as the municipality's climate targets. Short-term targets for climate impact reduction are set every three years and the progress is reported at advisory round table meetings that are held at least once annually with top executives and environmental managers. Cooperative projects take place in working groups in areas such as solar energy, waste management, sustainable transports, communication and energy management, which are open also to organizations outside the UCP. The UCP is managed by a project management group and a group of environmental managers from all members.

The Uppsala roadmap was initiated with the intention to provide an overview of the current energy system and indicate possible trajectories towards the realization of a low-carbon society. The roadmap contains a number of future scenarios where emissions and energy demand are simulated. The working process was initiated in 2013 within the framework of the UCP, aiming to analyse potential pathways and measures to reach the municipality's long-term climate objective. An inclusive process was set up, bringing together members of the climate protocol and adopting a 'whole system' approach, including technical requirements, social learning and adaption, policy and legislation. The stakeholders involved include the universities, the municipality, local energy companies, politicians, non-profit associations, local residential corporations, academic building corporations and municipal companies including waste and water management. UCP workshops were organized to identify possible measures for local future scenarios, focusing on issues such as electricity generation, smart grids, bioenergy production and district heating generation. Results from the workshops fed into the scenario-building and modelling of the future energy systems.

The model covers all energy use and all greenhouse gas emitting activities and processes within the municipal borders of Uppsala. In addition to this, long-distance travel by the inhabitants of Uppsala is included. For energy use, life cycle greenhouse gas emissions of fuels and electricity have been added to the direct emissions in Uppsala.

The overall framework when developing scenarios has been a back-casting method, starting with formulating images of the future that are target-fulfilling whereby possible trajectories and measures has been identified and quantified as far as possible. Participatory back-casting is a method for system innovation and socio-technical transition with involvement of stakeholders, which includes defining first steps and roadmaps towards an envisaged system change (Robinson, 2011).

The Uppsala project group developing the roadmap and the model has included researchers, senior advisers at the Uppsala municipality, a representative from Vattenfall and a project manager from the Mälardalen Regional Energy Agency. Throughout the Uppsala project, many stakeholders from the UCP were included in the process of developing scenarios and collecting data. A number of students' projects were performed associated with the roadmap project. The collaboration that preceded the roadmap project was actually initiated as an educational collaboration between the Swedish University of Agricultural Sciences and Uppsala municipality in 2009. This collaboration may be viewed as an example of the emerging mission of universities to be co-creators of sustainable development (Trencher *et al.*, 2014).

Some Model Considerations

The roadmap and its associated model were performed with the geographical boundary of the Uppsala municipality as system boundary. This is due to the local initiative and local collaboration regarding transition to a low carbon society. Such delimitation is appropriate in the Swedish context, where the local authorities have a strong role, whereas the regional authorities are rather weak. Data on energy use and emissions are available at the local scale from the national statistics authorities, and it is this feasible to model the system at that level.

Despite the rather strong decision-making power at the local level, the operational space for energy system transformation is largely determined at higher levels, notably the European and national levels, which set frameworks as well as regulate details in many aspects of the energy system. The taxes and subsidies decided at the national level are decisive for the costs of introducing new technologies. Another way that the national government influences the local level is through Vattenfall, the 100% state owned energy utility that in Uppsala owns the district heating grid and plants, and the electricity grid. As a key stakeholder in the local energy system, Vattenfall has been an active partner in development of the roadmap and the LEAP model.

The scenario development was influenced by the local experience of the institutional landscape, especially the dependence of local development on national policy. Three of the scenarios focused on the activities at the national levels, whereas two have their emphasis on local action. For example, the selection of two reference scenarios was guided by contradictory signals from the national government, with a strong rhetoric commitment to long-term emission-reduction being combined with a perceived lack of action in the short term during the period 2013-15, especially regarding targets and development towards a fossil-fuel independent transport system.

Many other energy scenario projects in research and policy making are based on economic modelling of energy systems. In the Uppsala project, it was decided not to model the economy at all. This was primarily based on former experiences from students' projects, where it has been difficult to access reliable figures on current costs for activities and interventions in the energy system. Moreover, previous predictions of oil and electricity prices have been highly inaccurate even at the time scale of a few years. Consequently, it was considered meaningless to make prognoses about future costs and to use them to model the energy system on a time scale of decades, considering all uncertainties about future costs. However, there are often implicit considerations of costs (at least relative costs) underlying the choice of technologies in the various scenarios. Furthermore, costs at the level of users and investors depend strongly on economic incentives from EU and national government.

The future scenarios build on knowledge on the current and historical use of energy and its related climate impact. In addition to future scenarios, there is a need for establishing statistics for monitoring the development over time of energy use and associated greenhouse gas emissions. In parallel with the roadmap project, two minor projects have been performed for developing climate and energy statistics for the city (municipality) of Uppsala and the Uppsala County.

The city of Uppsala has an established routine of calculating annual greenhouse gas emissions and using that in planning and evaluating progress towards a low-carbon society. The other municipalities in Uppsala County do not have such routines in place, but the regional projects aim at establishing a common method for energy and greenhouse gas accounting in the region.

Challenges and Opportunities for Implementing System Change

During the course of the collaboration, certain technologies and system solution has emerged as interesting for various reasons, and the development is driven by different actors. A few examples will be given here, namely food, food waste, biogas, biochar, willow short rotation coppice, and hydrogen.

In the "Total potential" scenario, agricultural land not needed for food production was assumed to be available for bioenergy production. It was assumed that food production volumes will constant, but require less land due to increased productivity. For the land not used for food production, a high-yielding bioenergy production system was selected, namely short rotation coppice willow. It was assumed that the wood produced is used as fuel for combined heat and power (CHP) production. This production system is established in Sweden, for example in the municipality of Enköping in Uppsala County.

Carbon storage in soils or vegetation was not modelled. This was because there was no basis in data or method available for the work when the project started and it was not considered a priority by the local stakeholders. However, knowing the large size of carbon fluxes between the atmosphere and soils and vegetation, this was not satisfactory. Especially when changes in land use are modelled, it is necessary to include C in soil and vegetation, in order to correctly estimate greenhouse gas impacts in different scenarios. This is of particular interest in scenarios that include major changes in local production and use of biomass. As a consequence, our next step in the modelling work is to develop a new module that takes into account the fluxes of C between atmosphere, soils and vegetation when the production of short rotation coppice willow is increased to satisfy the demand for more biomass for district heating and combined heat and power. The work is performed by Torun Hammar and builds on her previous work (Hammar *et al.*, 2014; Hammar 2015, Hammar *et al.*, 2016). See also Chapter IV:3, page 176.

Knowledge about greenhouse gas emissions from bioenergy systems (including carbon storage in soil and vegetation) has to some extent guided the selection of technologies for the "Total potential" scenario. This includes the choice to produce short rotation coppice willow on agricultural land, which stores additional carbon in soil, wood and roots (Hammar *et al.*, 2014). The choice of pyrolysis of straw, to produce energy as well as biochar, a stable carbon source that is recirculated to soil, is based on knowledge about greenhouse gas balances of pyrolysis and biochar systems (Ericsson, 2015). Contrary to removal of straw for energy purposes, addition of biochar does not give reduced carbon content in soils. It probably gives an increase in soil C content, which has not been included in the model.

The Uppsala municipal council decided in 2014 on a long-term goal (until 2023) to serve 100% organic food in publicly financed food services such as schools. This could potentially lead to large changes in local agriculture, which would affect the potential for bioenergy production. This has not been considered in the model, but is of interest for future research.

Reduction of food waste is a topic that is high on the agenda, from the European to the local level. This is a target that has risen in the past few years. It was not preceded by research, so research capacity has developed in parallel with policy development and implementation. The basic message is simple: large amounts of food that could be eaten, is wasted in various parts of the food chain. This is a wasteful use of resources, including public funds for public meals such as school lunches and hospital meals. It also has large environmental impacts, including climate impacts. These climate impacts are not visible in climate statistics at national or local level, as they are distributed in various sectors (agriculture, industry, transport, buildings etc.). However, they have been estimated by life cycle assessment (Scholz *et al.*, 2015, Eriksson *et al.*, 2015). Research is ongoing regarding systematic approaches to food waste minimization, quantification of waste amounts, environmental impacts and various. At the same time, efforts are ongoing to reduce food waste in schools, food retail stores and other parts of the food chain. Discussions have emerged from time to time on how to integrate food production and food waste into the Uppsala LEAP model, but this has not yet been implemented. Various data management issues are expected to arise in such an endeavour.

In the roadmap, the biogas development was targeted towards biomass sources where biogas systems are expected to have a large positive environmental impact, and where there are few alternatives to anaerobic digestion as energy recovery method. Biogas from animal manure is a major current priority in Swedish agricultural policy. As manure has large moisture content and its production is spread in the landscape, biogas was assumed to develop in the way that is currently most feasible for small installation, i.e. for combined heat and power. Today, small scale upgrading of biogas to vehicle fuel quality is not technically and economically feasible. However, there is technology development in this field, and during the time frame modelled, opportunities for small-scale upgrading to vehicle fuel may become available.

Biochar, charred biomass produced by pyrolysis of agricultural residues of forest biomass, has been identified as an interesting technology for sequestering carbon in soils, at the same time as other benefits such as improved soil fertility are provided. The biochar research field is growing rapidly and the number of projects and researchers involved is rising steadily in Sweden as well. There is also a practical development with farmers, energy utilities and various entrepreneurs looking for opportunities with these technologies to contribute to climate change mitigation as well as improved productivity in agriculture or more efficient energy systems. The technology has been included in the Uppsala roadmap and is further explored in an ongoing MSc thesis project (Isaksson, 2016). Planning and application for funding is ongoing for a collaborative research project in Stockholm and Uppsala on quantification of climate impacts and other environmental impacts, for potential biochar-pyrolysis projects of interest for public and private actors in the region. This is a result of the Uppsala climate collaboration, as well as other research at SLU and KTH (Ericsson, 2015).

Hydrogen is being promoted as an interesting energy carrier for the low carbon economy. Benefits are that it has better storage properties than electricity, that it provides clean exhaust when combusted, that it is an excellent fuel in fuels cells, and that it can fairly easily be converted to and from electricity (although with considerable heat losses). Toyota is promoting hydrogen as a preferred energy carrier for the future (Toyota, 2016). The first hydrogen cars are now available on the market and there is an ongoing effort to provide infrastructure for hydrogen cars. Just like electricity, hydrogen is an energy carrier that can be produced from both fossil and renewable energy sources, so hydrogen is not necessarily a low-carbon technology. The local authorities in Uppsala have been approached by various private actors interested in the establishment of a hydrogen vehicle fuel station. The roadmap project and the academics involved were not prepared to give advice on this issue, as hydrogen was not a technology that had been investigated in the roadmap project and thus no data or technology assessment were available. Hydrogen is however now being investigated in an ongoing MSc project (Isaksson, 2016). This is an example that new technologies emerge, that have not yet been analysed. However, it is fairly straightforward to analyse the system implications of the new technologies on the Uppsala energy system under different future scenarios, using the Uppsala LEAP model.

In this section, a number of technologies of interest for the low carbon society have been described. They are examples of how the roadmap model can be used for assessment of new technologies that were not originally included (hydrogen), how technologies assessed and found interesting in the model can be further developed in other projects (biochar & pyrolysis), how the model is being expanded with a more explicit geographical and land-use – perspective (willow, see Chapter IV:3) and how adjacent challenges could be included, but would require more work as perspectives and system boundaries do not match (food waste).

Institutional Support and Limiting Factors for Collaboration

The model and collaboration was developed most intensively during a year and a half from the end of 2013 to the beginning of 2015. Though there is a joint interest from several parties for continued collaboration, there is no established plan or funding for the future. Although it has been a very successful collaboration in many ways, there are institutional challenges for the collaboration. Certain success factors, as well as limiting factors can be identified.

Success factor have been the common interests and complementing competences. Uppsala University and SLU together teach a 5-year combined BSc and MSc programme in Energy Systems Engineering. These students have an excellent understanding of technical aspects of energy systems at a level of relevance for the programme, being able to make quantitative and qualitative models of the energy system as it is now, and simulating various future developments. They have been able to make useful contributions in the project course Energy System planning as well in MSc thesis projects (Byfors, 2014; Lantto, 2014; Isaksson, 2016). Having projects defined by, and in collaboration with external actors such as the local authority and Vattenfall have been a strong motivating factor for the students, which has increased their learning in the project.

The research group at SLU, with a basis in biomass and biofuels, was complemented by a team from Uppsala University with expertise in energy use in buildings and solar power. Together, these teams have been able to provide the required technical expertise for the project. The researchers and students have had the capacity to combine and complete pieces of information from many different sources, both local information from the various actors involved, and information from the scientific literature and national government reports.

Considering success factors and challenges in the long-term perspective, the following perspectives can be made. On the one hand, there is an opportunity in the transition to low-carbon society being a long-term endeavour. The public and private bodies can have the patience for the slow development of knowledge in research and higher education. Having a PhD student work for some years before delivering results is not a major problem. The UCP is an excellent format for collaboration, and its three-year planning period is a cycle that works well with the time-perspectives of academia.

However, in this long-term perspective, i.e. planning for longer time collaboration between academia and the local authorities, it is not well institutionalised within the organizations in Uppsala. There is a need to develop these institutions and formalize the collaborations, and until they are in place, this work rests on the initiative of individuals within each organization. There is no long-term funding for the academic work in the collaboration; it depends on externally funded projects and educational funding of students´ projects.

With regard to institutional challenges, the issue about collaboration within academia is important. The Uppsala low-carbon society collaboration has benefited from collaboration between various individuals and departments at SLU and Uppsala University. We share students who study energy systems from a wider range of perspectives (though mainly technical and natural science-related) and many of the senior academics have working relations across subjects in their role as university teachers. However, universities are decentralised organizations and it has proven difficult to coordinate academic competence to provide it to the project and to the UCP in general. Both Uppsala University and SLU entered the UCP from the administrative side, with the environmental management as part of the infrastructure and support side of the university. Organizing collaboration across the administrative-academic divide within the university has proven even more difficult than cross-subject academic collaboration, as there is a strong need for top management support.

Institutional opportunities and challenges for funding are other, but associated issues. There is plenty of funding for research and for collaboration between research and other sectors, in the fields of sustainability, as well as energy systems within the Swedish research funding system, but there is hard competition for funding. For good and for bad, the funding is fragmented among many funders. Many projects require co-funding, which is more demanding regarding networking and administration, than applying for fully funded projects.

EU-projects are planned in advance and there is limited flexibility as to channelling them in new ways that were not perceived at the time of application. For the future, Horizon 2020 projects in international collaboration demand large investment in resources for the application process.

There are European regional strategic funds that in the current period (2014-2020) have transition to low-carbon society as one of their targets areas. Discussions have been ongoing in the Stockholm-Mälar region on how these can be used strategically for collaboration between various stakeholders, including academia. An over-arching project, aiming at long-term strategies and roadmaps, could be useful to support development and prioritization of more targeted development projects in various fields, all together contributing to a low-carbon society.

Efforts to make joint applications, i.e. research projects with strong external collaboration, can be excellent meeting points. Researchers are dedicated during the application process and can be accommodating for concerns and interests from other parties. However, the intensive application processes are followed by long periods of waiting for the evaluation of the research proposal, and the momentum is lost. In case the proposal is not funded, the resources invested in planning and building the collaboration is often lost. After having been through such a cycle a few times in very different constellations, I begin to see this as an unplanned and unwanted result of the way the system with project application and funding is set up. As researchers are often opportunistic, it is easy to move on to applying for some other project instead, rather than taking up the lost case and looking for other sources of funding for the same project idea.

The large variety of sources for funding and the proliferation of small projects results in a "project landscape" of various activities. This may be good for giving bottom-up initiatives a chance to grow, but is hardly a way to strategically manage a transition to a low-carbon society. At least some kind of coordination, so that the various actors have an understanding of the project landscape that they are part of, would improve the chances of channelling funding to projects that can have wider impact for regional development.

There are also institutional challenges, both at local and regional levels. The local collaboration in Uppsala has worked well, but scaling to a wider collaboration with a wider impact has proven difficult. Sweden has a tradition of planning being strong at the local level and weak regionally. A regional (county) strategic plan is being developed every four years. In the Uppsala County, it is planned to be decided in 2016. In preparation for this, a series of seminars and workshops were held during 2015, to give input to the plan, and to discuss its aims among various stakeholders. As part of this process, development towards a low-carbon society has been in focus in one seminar and integrated into several other seminars, including the seminar on rural-urban relations. The Uppsala road-map was used as input into the process and several academic partners have been involved in the seminars. The regional (county) strategic plan is a guiding document that is supposed to guide investment and development projects.

In addition to this, the Uppsala county board, has an assignment from the national government to coordinate energy and climate issues at the regional (county) and municipal levels. At the Uppsala county and municipal levels, it is evident that data support, in the form of statistics of energy use and related greenhouse gas emissions, are needed. Work has been ongoing to organize this, as described above. However, the other municipalities in the Uppsala County are considerably smaller (i.e. up to 40 000 inhabitants) than the municipality of Uppsala (with currently 213 000 inhabitants). The small municipalities lack the capacity to manage their own data, which should be needed to support planning and evaluation of actions to reduce greenhouse gas emissions (Bryntse and Sundberg, 2016).

In total, there are good opportunities for collaboration, in terms of common interests among various public and private actors and academia, as well as available students with a relevant educational profile. In addition, various potential funding opportunities exist. Topics suitable for long-term academic collaboration are possible to identify and institutionalized collaboration at the local level exists (e.g. the UCP).

Challenges for collaboration lie at the less well organized county level. Difficulties in collaboration within and between universities exist. There is also a lack of stable financing of research activities and lack of structures for joint project development. In addition, acquisition of more specific project-based funding is problematic.

Modelling has shown to be a versatile tool for technology assessment and strategy development. It is not just in the numbers and data it presents that its strength is manifested. It is also a starting point for discussions around choices for the future development of energy production and use. The model developed in the UCP context could be a basis for future collaboration between actors who have been already involved in its development. However, it may also be a hindrance to those who have not been involved. The model has already served in the established collaboration in Uppsala within the Uppsala Climate Protocol. It may also have potential to be a piece in a future strategic collaboration between academia and the public and private sectors for the entire Uppsala County, or even the entire Stockholm-Mälar region. At the municipality level there is a collaborative structure for the low-carbon society in the UCP. At the county level, the institutional framework is not yet developed.

Cities have been identified as central for the transition to a low-carbon society. Within the city setting, actors such as universities, public and private companies, can find ways to collaborate, to develop processes of change, of introduction of new technologies, of planning for a low-carbon future. But cities do not exist in isolation, they are in contact with the surrounding countryside and with neighbouring cities.

Conclusion

In this chapter, some results from collaboration within Uppsala on modelling future scenarios for the low-carbon society have been described. Opportunities and challenges for consolidating this collaboration, and for expanding it to a wider region, have been discussed. The transition to a low-carbon society can be helped by models of local and regional energy system futures and their climate impacts. Models can give guidance on the ability of certain technologies to contribute to the energy system, and for the combination of technologies in the energy system to provide required energy services and contribute to long-term climate change mitigation goals. However, wide-reaching long-term collaborations to support development require not only good models and data management, but institutional support for connecting stakeholders from various sectors with common interests, developing and funding projects and disseminating results. Thereby, projects can result in development of knowledge, beyond individual learning and archived project reports.

IV:5 A Neuro-Cognitive Model for Decision Making in Everyday Travelling

Azadeh Hassannejad Nazir and Hans Liljenström

A central issue related to climate change and the regional path to a low carbon society is how we can change our mind-sets, including our associated behavioural patterns. It is related to how complex systems can be dealt with, conceptually, psychologically, as well as socially. To what extent can we change our mind sets and life styles? Which are the means? What are the drivers? Which are our preferences and priorities today and tomorrow? How can individual decisions result in system flips?

In order for us to change our society, i.e. to meet the challenges ahead of us – not least with regard to climate change and associated challenges – we have to understand the human capacity to deal with complexity, e.g. with regard to our capacity to adapt and to innovate. To reformulate this challenge: we need to consider the relation between internal and external complexities i.e. the relation between mind and nature. Thus, the path towards a low carbon society relates both to deep human issues, as well as to a vast array of more practical considerations and actions. In order to understand our situation at large but also to support the decision making at various levels and by different stakeholders we need to improve and design new types of models of various kinds. These could be conceptual as well as formal, such as computational models that can be used for simulations and scenario building for decision support.

When dealing with complex systems from the point of view of an individual, which in the end is the basic element of our societies, we have to consider his/her cognitive functions, notably perception, learning, anticipation, decision making, and intention/action. In particular, action is necessary for change in our external environment, but it is based on change of perception in our internal environment. We explore our world in a perception-action cycle (Freeman, 2000). This cycle is at the heart of human mind, where cognition transforms the primary aspects of consciousness, attention and intention, into perception and action (Liljenström, 2011).

The development of our cognitive and conscious abilities depends on an appropriate interaction with the complex and changing environment, in which we are embedded. Our perceptions and actions develop and are refined to effectively deal with our external (and internal) world. This also means that all human understanding is shaped by the interaction between these "worlds". In particular, our cognitive processes are related to the spatial and temporal aspects of our environment, and thus have to be understood in this context (Freksa, 1997; Burr & Morrone, 2006). The sense of agency is also based on these spatio-temporal relations, specifically on cause-effect relations and correspondence between goals and actions in space and time (Balconi & Crivelli, 2009). An understanding of these relations is important when we discuss e.g. agent based models below.

What are the consequences of all this for our approach to climate change? How can we go from cognition and understanding to policy and action? In the literature, perception and action is often in focus, but intention is generally neglected. There is a need to link perception to action, and this should include intention, our conscious will to change. Information is not enough, but intention needs to be transformed into (appropriate) action (Liljenström, 2011).

So what are the cognitive and behavioral limitations - or barriers - that the public is facing in responding to climate change? These may be placed in three categories:

1) psychological/conceptual barriers,

2) social and cultural barriers and

3) structural (political economy).

Barriers to effective engagement in response to climate change exist on all scales from the individual to the institutional, and these dimensions clearly interact. Hence, many well informed individuals feel unable to make change in a world where the fossil fuel industry has so much power (Norgaard, 2009).

Four stages in the decision making process may be differentiated (Risbey *et al.*, 1999):

1. Signal detection, where it is decided what is adapted to (the signal) and what is ignored (noise);
2. Evaluation, where the signal is interpreted and foreseeable consequences are evaluated;
3. Decision and response, which results in an observable change in the behaviour and performance of the system;
4. Feedback, which involves monitoring of the outcomes of decisions to assess whether they are as expected.

It is now commonly understood, partly due to the fundamental studies on intuitive assessments and judgements by Daniel Kahneman and co-workers, that human decisions are often more irrational than we like to believe, in particular when acting under uncertainty (Tversky & Kahneman, 1974, 1981; Kahneman, 2011). Even if this view has been challenged (e.g. Gigerenzer, 1991), there is a need for further studies on the processes and drivers that determine our decisions and behaviours (Simon, 1992; Lawrence & Nohria, 2002).

Neural basis of human decision making

This chapter concerns the development and application of a *neuro-cognitive model* with a focus on the decision making process (DM) of an individual in a social context. The objective is to contribute to an understanding of the relation between individual decisions of citizens and the decisions to be taken by policy makers. Our computational model includes effects of *personal factors*, *behavior* and *environmental factors*, based on neural structures, dynamics and functions.

Our main approach is using neuro-computational methods to tackle personal factors and behavior of individuals in DM. At the individual level, we have used Kahneman's ideas of "thinking fast and slow", as a paradigm when modeling the interaction of emotion and cognition in DM. The amygdala, orbitofrontal cortex (OFC) and lateral prefrontal cortex (LPFC) were considered as the major neural structures underlying decision making. The interaction of the first two structures plays a remarkable role in the emotion perception and the emotional response, while the rational decisions are evolved at the latter structure. The resultant of emotional and rational selections infers the final decision making strategy.

The neural networks of the three modeled brain structures control DM with respect to some individual and environmental parameters. Stored emotional/rational experiences and individual principles are the basis of the attitude formation. Internal states such as fatigue, anger, happiness, etc. are considered as influential parameters on emotional decision. The self-control power, the contribution of emotion and rationality in making decisions, determines the result of the competition between these two systems. Considering the human being as an isolated agent, internal stimuli and environmental conditions (e.g. availability of options) are the only parameters affecting the behavior.

To the extent that individual behaviors can be considered the basis of society, social interactions are crucial for determining our attitudes and actions. In our model, social influences are confined to social advice received from other agents close to the decision maker (*principal agent*). The other agents condition the decision of the principal agent regarding the social distance (degree of trust) and attitude similarities. The mentioned parameters at the individual and social levels considering the personality of the agent are adapted to get a suitable behavior.

Emotion and cognition

We are constantly subject to a huge amount of information received from the environment. The processed-assessed information, together with our inherited traits, provides a basis for our behaviors, which is dependent on our decision making process. Psychologically, this process can be categorized into three phases. Initially, the prevailing options concerning the internal and external states are emotionally evaluated and prioritized. In the second phase, the emotional process is followed by a cognitive assessment of the options and the selection of actions, depending on needs. Finally, the execution of an action and evaluation of the resulting effects allow for a comparison between actual and expected values. Based on the "prediction error", the assigned values to the choices in the first step are revisited and learnt, possibly resulting in a change of mind (Ernste & Paulus, 2005).

However, human DM may not be as rational as often believed, which has been demonstrated by Kahneman and colleagues (Kahneman & Tversky, 1979; Kahneman, 2011). According to their hypothesis, DM is the result of an interplay between an intuitive/emotional and a rational/cognitive system, represented as *System 1* and *System 2*, respectively. This dual process model posits the integration of a "bottom-up", intuitive, fast, implicit, emotional system (1) and a "top-down", deliberative, slow, explicit, cognitive system (2) (Frank *et al.*, 2009). It is important to note that rationality and cognition are two terms defined differently in different areas. In this chapter, we use the concepts interchangeably, and assume cognition is rational, although this may not always be the case.

The two systems we consider here, *System* 1, a bottom-up, automatic, intuitive, emotional, and implicit system (Amygdala, OFC), and *System 2*: A top-down, controlled, rational, cognitive, and explicit system (LPFC) may correspond to *fast* and *slow "thinking",* respectively (Kahneman, 2011).

Focus and Objectives

There may be several environmental and intrinsic contexts influencing or modulating our DM (Doya, 2008). For example, expectation of a high reward can motivate an individual to go for an action despite a large cost. Uncertainty of action outcomes can promote risk taking and exploratory choices, while predictable environments could facilitate consideration of longer-delayed rewards. Much of this involves various neuromodulators, such as serotonin and dopamine (Doya, 2008), but these are not considered here. There is also a number of other factors affecting our decisions and learning, such as needs, desires, and risks, as well as knowledge and uncertainty about the environment. We will treat these factors more specifically elsewhere. The focus here is on certain external and internal factors that influence our choices and form the basis of our DM. As an example of DM at an individual level, which also has implications at a societal level, we take the choice of transport at an every-day basis. Given a set of options, this has relevance for reaching a climate neutral society (see Liljenström *et al.*, 2014).

In this chapter, we model and discuss the neural processes associated with individual DM, applied to semi-realistic societal choices with consequences for climate and environment. We base our modelling approach on the notion that DM is influenced by cognitive, as well as emotional considerations, as discussed by e.g. Kahneman and colleagues. However, in contrast to examples from classical framing and gambling, as is usual in Kahneman-Tversky simulations, we deal with socially embedded decisions concerning various forms of consumption patterns, in particular the choice of transport between home and work.

One of the influential parameters in reward evaluation is time. During the process of *inter-temporal decisions*, rewards are discounted in line with a hyperbolic function. Therefore, humans (as well as other animals) are more tempted to short term rewards than long term ones. Based on this hypothesis, humans, in general, ignore large-value/long-term benefits, in favor of small-value/immediate rewards. It is also assumed that the short-term goals are pursued by neural structures involved in emotion, while long term rewards are evaluated by rational cognition.

The execution of some selected actions is due to suppression of other interests, which can be interpreted as some kind of "*self-control*", apparently involving primarily LPFC

(Christodoulou *et al.*, 2010). Considering the nature of inter-temporal decisions and rewards associated with e.g. climate change, which will emerge after a long period of time, the issue of self-control is also of interest to us, but is not further discussed in the present work.

A successful DM is an adaptive process, based on social interactions and individual experiences. It is also dependent on our attitudes, preferences, mood etc. Attitudes are however rather stable and usually do not change on a shorter time scale. Yet, attitudes may change as a consequence of knowledge and insight, and also as a result of experience and interaction with others. This is the subject of further research and modelling. A more detailed description of our neuro-cognitive model can be found in Hassannejad & Liljenström, (2015), but the major parts are sketched in Fig. 32.

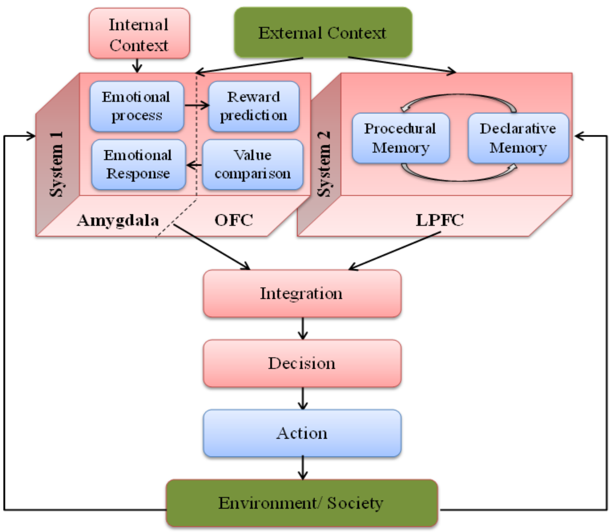


Figure 32. *Schematic flow chart of the subsystems and information flow in the modeled decision making process.*

Decision Making in Choice of Transport

Transport is one of the largest contributors to CO_2 emissions and climate change. In order to reach a low carbon society by 2050, as has been decided for the EU countries, it is important to change our life styles and habits, including how we travel to work and for leisure (Liljenström *et al.*, 2014). This is the motivation for the current example, where the decision making concerns the choice of transport for an individual who is traveling from home to work at a regular basis. (Our approach is at a later stage intended to be embedded in a social context, where a distribution of individual choices will influence each other and the society/environment).

Different transport options available to commuters in the region. Photo: H. Liljenström

Considering this example, we have simplified the impact of individual's attitudes, both cognitively and emotionally, to fit with the three pillars of sustainable development (SD): Ecological (eco), social (soc), and economic/monetary (mon). The various options are also associated with these three categories of attitudes and values.

The choice of action, i.e. which optional means of transport we will take, depends on various external (distance, traffic situations, cost etc.) and internal (motivation, attitude, mood etc.) factors. Here, we suggest the different options are to take either *bike, car,* or *public*, (where the public transportation could be e.g. bus, train, or metro), which all are considered to be available, albeit with different levels of convenience. We also assume that individuals have different preferences, depending on their living conditions and general attitudes with regard to environmental, social, and economic concerns. Accordingly, each option has an ecological/climate value, a social/temporal value, as well as an economic/monetary value, but these are considered to be different for different individuals.

In our model, an individual's preferences/priorities are determined by the neural activity of cell assemblies in the three brain structures considered, amygdala, OFC and LPFC, which represent the attitude, expectancy value, and rules towards the outcome of a decision. Amygdala is considered to form emotional memories, and give an emotional response, depending on varying external and internal stimuli/contexts. The emotion towards different options depends on external and internal contexts. Given the number of options, various contexts can be defined.

As mentioned above, OFC associates the different options to the probable outcome. The total number of cell assemblies is computed as the product of the number of options and their associated outcomes. The oscillatory activities of these cell assemblies represent the expectancy signals. Based on the type of transportation, there are different attitudes and rules governing cognition, and the cognitive analysis is a result of a combination of declarative and procedural memories.

Combined System 1 and 2 DM Process

Fig. 33 shows the simulation result of the whole DM process, including the emotional and rational/cognitive processes. As mentioned above, both these two systems are simultaneously active, but we present them below as subsequent processes, to demonstrate more clearly the difference between the time required to process the options in System 1 ("fast") and System 2 ("slow"). The different period lengths of the activities in System 1 and 2 illustrate in relative terms the fast and slow processing of emotional and rational systems, respectively (though the time scale in reality would be different). The oscillation frequencies of the both systems differ from each other, depending on the values given to an option in each system. The first 3000 ms illustrates the oscillatory activity of the cell assembly in System 1, and the following period, 3000-10000 ms, displays the activity of System 2. Different frequencies correspond to different preferences given to any of the options. Regarding the figure, any decision taken during the first 3000 ms is only based on emotion, while a decision taken during the second stage, 3000-10000 ms, is the result of an integration of emotion and cognition.

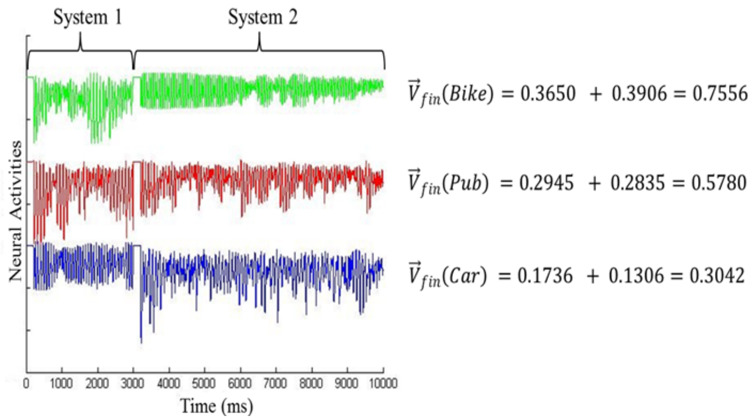


Figure 33. *Cell assembly activity in both Systems 1 and 2, representing the entire process of choosing between the available options, (car, public, bike). From top to bottom, the cell assembly activities, illustrated in green, red and blue, represent the predicted emotional/cognitive values of taking bike, public transport and car respectively. The first 3000 ms show the emotional oscillatory activities and the last 7000 ms show the cognitive analysis of the options. If a decision has to be made during the first three seconds, it is based on emotion alone, if the decision can be taken at a later stage, it can be based on an integration of emotion and cognition. In this case, bike has the highest value and will thus be our chosen option, followed by public transport.*

Fig. 33 shows the process of emotional-rational decision making, for one trial. In a following step, we studied the decision making process, while the system interacts with the environment and is fed with the feedback representing the actual value of the option chosen. The "actual values" that are introduced to the system are generated randomly, to illustrate the behavior of the system. A value larger than the expected value results in increasing the motivation for taking that option, and perhaps enlarging the cell assembly size. Similarly, a value smaller than the expected value results in decreasing the motivation and weakening the connection strengths in the associated cell assembly. Successive negative feedback from the environment might lead to the exclusion of that option from all possible ones.

As mentioned above, the value of each option depends on some internal (personality, mood, experience) and external (environmental conditions, accessibility to different options) parameters. In any trial, the decision maker valuates the options considering all those parameters. Afterwards, the expected values are compared with the rational/emotional actual values. Regarding the sign of the prediction error, the structures and dynamics of OFC and LPFC are updated and the predicted values are computed anew.

A Spatio-Temporal Application

In order to apply our neuro-cognitive model of decision making to a situation where different options have different societal and environmental consequences, we model a case with transport along different paths and with different means. We use our neuro-cognitive model as a basis for our smart agents to explore pathways between two points in a grid. Accessibility to the means of transportation, the map of pathways and personality are influential parameters in selecting among transportation options. We are interested in knowing, for example, how societal system flips can happen as a result of consumer shifts in attitudes and habits, based on individual decisions.

The decision making process (DM) could be divided into two steps, which can be followed either simultaneously or sequentially by a *principal agent* (PA), who is considered to be the decision maker under study. The first step is to estimate the outcomes of different options. In our case example, time, cost and CO_2 emission, are considered as outputs of the options. Considering the “personality” of the PA, the order of emotional and rational priorities is defined based on their salience, i.e. which one of the three sustainability categories which is prioritized. There is a one-to-one correspondence between the “pro-social” personality and the importance of time, the “pro-economy” and cost, and the “pro-environment” and level of CO_2 emission.

Estimating the output of the options considering the priority order and computing the probability of success in meeting the outputs would be the first steps in DM. The probability estimation is based on the previous success/failure of the options in satisfying the priorities of the agent with the help of *Bayesian analysis*.

Two concepts of individual and social DM are developed regarding the involvement of individual and society in DM. Making decisions based on individual experiences, attitudes and moods alone, regardless of the effects of society is here defined as an individual process. We define social decision making as involving social considerations and interactions.

The PA is part of a society which would affect her decision. Environmental impact on individual decisions is an inseparable part of the DM. The probability of being influenced by the advice of other agents is associated with some parameters: the social capital/distance (trust) between the PA and the other agents, the personality similarities between the PA and the others, and finally the history of agents in providing useful advice. The probability of following an agents’ advice is computed based on Bayes theory.

Combining the first and second steps results in estimating the expected emotional and rational values of all options.

The option with the maximum expected value would constitute the inputs (stimuli) to the neural networks of the neurocognitive model. Regarding the external/internal contexts and emotional/rational attitudes, the values of all options could be computed from the neural activity, and a decision could be taken based on these values.

As mentioned above, the whole system is subject to environmental contexts (e.g. car/bus accidents, delays, weather conditions, etc.) that might affect the measure of the actual value and the prediction error (e_p). Regarding the sign and magnitude of e_p the expected values and history of taken options and of interacting agents are updated, forming the basis for change of priority order.

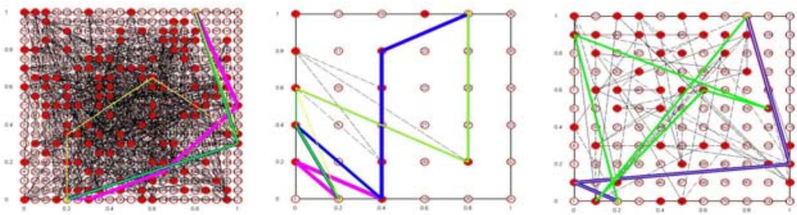
With regard to the described steps in the process, some influential parameters on attitude change include: the outcomes of different potential decisions, social advice, social attachments, distribution of society in terms of attitudes, environmental contexts, the level of self-confidence, role of emotion and cognition in decision making. The outcome of an option is resulting from the natural external context and from policies applied in the society. For example, the cost and required time for traveling are affected by traffic situation, toll fees, accessibility to public transport, weather conditions, etc. The level of CO_2 emission is influenced by the accessibility of convenient public transport, the age of cars, the use of modern technology, etc. Policy makers should also be concerned about the trust between citizens and authorities, including governments.

Trust between the agents in our model is conditional. Conditional trust, and the level of trust between agents is based on the expected reward or value, which is estimated with respect to the benefits of cooperation, the risk of defection, past experience, and the value of past decisions. Unconditional trust between agents, on the other hand, depends on the characteristics of the agents and their relations, and is not (so much) affected by previous performance. All the above mentioned parameters are represented in our model with different values. By tuning these values, the influence of different parameters on attitude/behavior change can be analyzed.

The example of transport options

Three means of transport, car, bike and public transport, are considered as available options. Different grids of pathways in terms of density are designed for the three modes of transportation, as illustrated in Fig. 34. The path intensity of a) bike, b) car and c) public transport, are suggested to decrease from high to low level, respectively. Different colors in the grids determine the shortest pathways in terms of time, cost, distance and CO_2 emission. Some environmental states, traffic jam, infrastructure situations, etc. provide conditions that traversing the shortest distance does not necessarily take the shortest time, has lowest cost, or lowest CO_2 emission. As a result of the randomly generated values of time, cost, distance, and CO_2 emission, it might happen that the shortest pathways overlap.

The categorization of agents into three types, pro-environment, pro-economy and pro-social, is based on the three pillars of sustainable development, where we study the DM at an individual, as well as a societal level, taking the example of transport. As mentioned above, society consists of a group of agents with different personalities, attitudes, preferences, and social distances. Evaluation of the various options, regarding the individual preferences and social influence, is the first step in the DM, followed by action selection. The next two steps involve modifying the expected values of the options, with regard to the actual value of the taken option. First, the desirability of the selected action (error prediction) should be measured, and then the stored information about the values and attitudes should be updated (learning) to improve the quality of future decisions. Maximizing the net reward that the agent receives to traverse a pathway between two points in the grid is the goal of the PA).



a **b** **c**

Figure 34. *Roadmaps for the three modes of transport; a) bike, b) car, and c) public transport. Four colored lines illustrate the different shortest pathways in terms of distance (red), time (blue), price (green) and* CO_2 *emission (black). Occasionally, as in roadmap (c), the lines determining the shortest distance and lowest amount of* CO_2 *emission happen to overlap.*

We consider the emotional and rational priority as based on the PA's personality. The behavior/decision is based on the personal attitude, but can be modified depending on environmental conditions, internal state, and social influence (e.g. advice). The value of each option is computed based on objective and subjective considerations. Decision can be taken at the social/individual rationality and social/individual emotion.

Individual decisions

Emotion and cognition constitute the major basis of DM (see e.g. Kahneman, 2011), and thus individual decisions could be analyzed considering emotional as well as cognitive/rational aspects. The individual *rational decision* is based on the outcomes of the options, and on the history of success/failure in DM. Considering our case of transport, the options have three different outcomes, in terms of time, cost and the amount of CO_2 emission. Regardless of an agent's personality, the first step is to compute the outcomes of different options. Hence, the time, cost and the level of CO_2 emission of any means of transport would be estimated.

The individual agent's *emotion* in terms of the level of satisfaction towards the actual value of a selected option could be estimated and recorded as the history of the agent's feelings towards the options. Bayesian probability theory estimates the contingencies of the selection of all options, regarding the levels of satisfaction based on previous decisions taken.

Social decisions

The role of emotion and cognition is undeniable also in a *social* decision making process. The decision of a decision maker is normally under the influence of the society. Hence, measuring the impact of society on an individual's decisions is an inseparable part of DM. The probability of being influenced by the advice of other individuals (agents) is associated with the similarity of personality between the PA and other agents, with social distance (trust), and with the history of other agents in providing useful advice. Bayes' theorem can be used to calculate such a probability. Social rational decision is based on the advice given by other agents, and on the history of success in taking their advice, i.e. on the trust of the advisors. Personal satisfaction from the received advice, according to the actual value of the decision taken, guides the agent through its following decisions.

Decisions and the prediction error

A combination of individual and social considerations determines the expected emotional and rational values of any of the options. The combined value of each option is considered as input to the neural networks of the neuro-cognitive model. The stimulated cell assembly is determined based on the maximum expected value. Regarding the external/internal contexts and emotional/rational attitudes, the values of all options, are computed by the neural networks, and a decision is made based on this computation.

As mentioned above, the whole system is subject to environmental contexts (e.g. car/train accident, delays, weather… etc.) that might affect the experienced actual value and the prediction error (e_p). Depending on the sign of e_p the expected values are updated that might influence the selected shortest path.

Scaling issues

Our model can be analyzed temporally on two time scales. The neural activities of the structures underlying the DM take place at temporal scales of seconds or less, while the social interaction and attitude change can be considered at a scale of hours, months or longer. The spatial modeling of this process can be scaled in the same matter, at a micro and macro scale, respectively. The micro scale here corresponds to the neural networks of the brain structures involved in DM, while transport behaviors are studied at a macroscopic scale of landscapes.

Interaction between Neural and Social Models

In order to make a decision, in particular on societal issues, the interaction between neural and social models is required. The loop sequence diagram based on the data transfer between these two models is illustrated in Fig. 35. According to this figure, the value of each option is calculated based on the possible outputs of the option (here; time, cost and CO_2 emission) and social advice. Considering the calculated outputs, the salience of the options is signaled by the neural structures based on the neural properties (frequency, amplitude and *q* value (motivation)). Regarding the influence of emotion/cognition and the attitudes of the PA, one of the options is selected. Executing the selected option results in experiencing the *actual value* of the option, and subsequently signaling the prediction error (e_p) in the neural structures. Regarding the sign and magnitude of e_p, the size and property of the cell assemblies change. Hence, the attitude and personality of the PA are subject to changes. Moreover, the properties of e_p (magnitude and sign) and the learning rate, update the social trust and the trust to transportation means. Updating the neural and social structures prepare the decision system for the further decisions with new variables and parameters.

Assumptions and scenarios

Our model is based on some pre-assigned variables and parameters, considered to be semi-realistic. In the current setting, we have a total of five interacting agents, where one of them (the PA) is considered to be the decision maker under study, while the others are various agents in society who can influence the PA with regard to the available options. The agents interacting with the PA could be family, media, government, neighbors, with varying social distance (trust) to the PA. Here, the trust levels of the PA to the four other agents are 95, 80, 65, 50 percent, respectively.

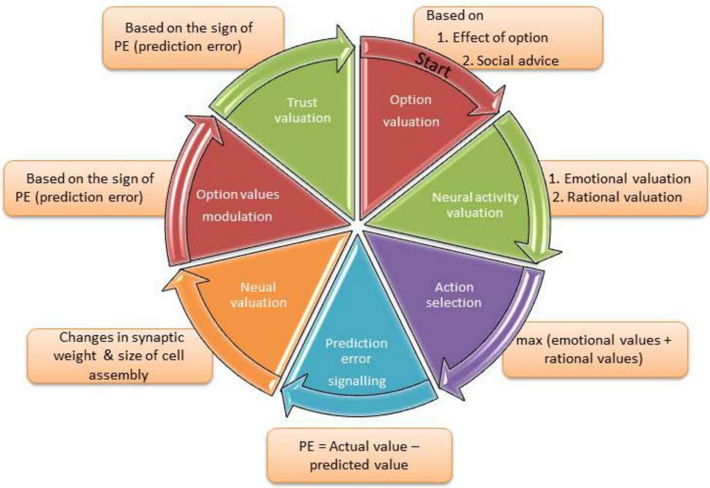


Figure 35. *Loop sequence diagram illustrating the interaction between the neural and social models of the decision making process.*

In this model, the PA is supposed to be pro-social, and her decisions are based on rational aspects, rather than emotional ones. Also, her attitudes are based on rational priorities. Emotional and rational priority orders are given as [2 1 3] and [1 2 3], respectively, where the numbers, 1, 2 and 3, represent time, cost and CO_2 emission as the potential outputs of the available options. In our example, a pro-social person gives, rationally, higher priority to time over the other outputs, whereas she may have different emotional priorities. As mentioned above, there is a one-to-one correspondence between the pro-social personality and the salience of time, pro-economy and the importance of cost, and pro-environment, and the concern of CO_2 emission.

Hypotheses and scenarios

Based on the assumptions and underlying factors in our model, we could formulate a *hypothesis* concerning the role of negative *prediction error* and *trust* in behavior change:

> *As long as there is no negative prediction error, there is no behavior change, at least not in a short time.*

To test our propositions, we have designed and simulated three scenarios. Through these simulations, we study the impact of different parameters on attitude changes of the PA. We also analyze the impact of varying the probability of unpredicted events, the length of time that any particular policy is applied, as well as the level of trust.

Scenario I

In the first scenario, we study the influence of unpredicted events (noise) such as accidents, traffic jams, delays, bad weather, etc. on the decisions of the PA. In this regard, the model is simulated for 250 trials (e.g. days), divided into five intervals of 50 trials each. As stated above, a trial corresponds to an occasion when a relevant decision (of means of transport) is made. For simplicity, we can assume that one such decision/trial is made by the PA once a day, for example when going from home to work in the morning, in which case the total length of the simulation period corresponds to 250 days. The probability of an unpredictable event increases linearly, with a uniform distribution.

In order to find causal relationships within our system, we have varied the values of parameters and variables, such as emotional/rational motivation, size of the cell assemblies, learning rate, trust level, and actual values of options.

As mentioned above, Q_{emot}/Q_{rat} represents the emotional/rational motivation of an agent for selecting an option. The first priority of an agent in taking an option is resulting from his high motivation for that option. Hence, one of the parameters that may change during the time is the emotional/rational motivation towards options. Mathematically, Q is a vector with a length equals to the number of options. Sorting out the Q values in a descending order depicts the priority order of the agent. Therefore, changes in Q values might affect the priority order. Regarding the fact that the PA is considered rational by character, the motivation to satisfy the rational attitudes is higher than for the emotional ones.

Throughout the simulation, the number of unpredicted events increases, and accordingly the number of time that the PA experiences this, the negative prediction error increases. There is a relation between the number of negative prediction error and the sign and magnitude of the slope of the motivational change. A lower frequency of unpredicted events results in a steeper slope of motivational change. An increase or decrease of motivation in selecting an option might lead to a change in priority order and subsequently in the decision.

The simulations show that a lack of enough negative external feedback (environmental and societal) is the main cause of increasing the motivation for taking the *car*, instead of any other option. The higher frequency of unpredicted events reduce (the slope of) rational/emotional motivation for taking the *car*, while the motivation for taking *public transport* increases with a steeper slope. Here, we assume trust to other agents is based on rationality. Increase of rational motivation for taking the *bike* is due to the advice of those who are pro-environment, with a high trust level. The process of emotional motivation changes is the same as the rational one, except that motivation for taking the *bike* is constant.

Emotional and rational motivation changes might result in a change in priority order. Generating sufficient negative prediction error causes priority order to be changed.

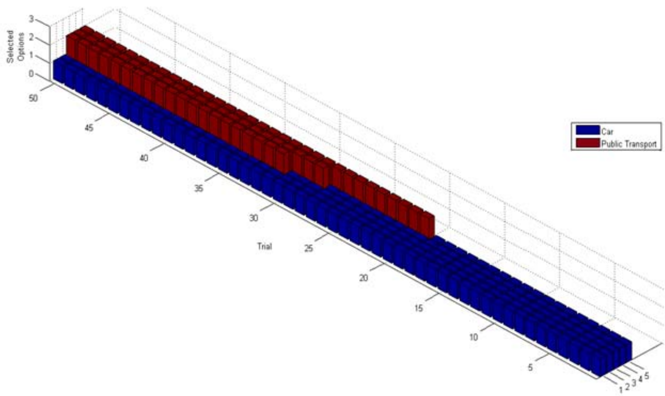


Figure 36. *Priority order change. The bars in blue represent the situation where the selected option is car, and the bars in red are the representation of public transport.*

In the example of Fig. 36, public transport has priority over car after 31 trials/days (i.e. decisions to take the car) when the probability of unpredicted events is 50%. The *time* required for the PA to change her priority order shortens with increase in frequency of unpredicted events. This is an example of a "system flip" of individual behavior that can result in a system flip at a societal level, if a large enough set of individuals are involved.

Another impact of unpredicted events is on the trust of the PA to different options. For example, trust in taking car is subject to negative influence of unpredicted events. During the first two frames, while the probability of unpredicted events is 10 and 30 percent, respectively, the level of trust to car is greater than the trust to public transport. Interestingly, an increase of the unpredicted event probability to 50% would provide a suitable base for changing the priority order. Trust to options and other agents is affected by a change in motivation. Despite the larger initial value of trust to car, trust to public transport is higher towards the end of the simulation.

Finally, the list of selected options during 250 trials is illustrated in Fig. 37. It is clear that the frequency of selecting car decreases, and taking public transport becomes more probable.

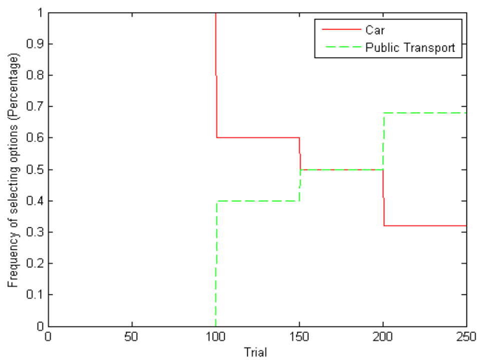


Figure 37. *Frequency of selecting different options during 250 trials.*

It is important to mention that changes in priority order should not be interpreted as a change of personality or attitude. Due to negative external feedback, the agent decides to change his behavior but not necessarily his attitude. As is illustrated in Fig. 38, after some trials the agent decides to change the means of transport, but not his attitude. The shortest line depicts the shortest path, with respect to required time to reach the goal.

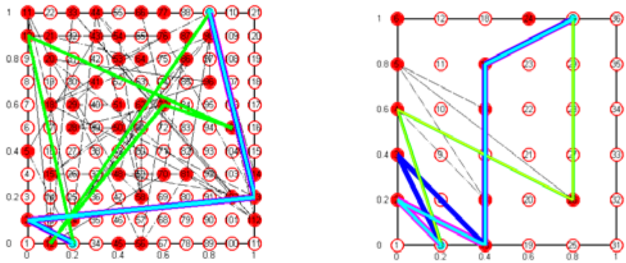


Figure 38. *Turquoise color in both figures shows the selected shortest path. The left figure represents the car pathways, and the right figure illustrates the public transport pathways.*

Scenario II

In the second scenario, as in the first one, generating negative prediction error is the basis for changing the behavior and attitude of the agent. We study the influence of implementing temporary policies on the change in priority order and trust, while there is no unpredictable event. The policies are implemented for a fixed period of time, after which return to initial situation. Such policies could be, for example, changes in toll fees, parking fees, public transport availability, road development, or as was tested in Uppsala, a one month free bus ticket if leaving car at home. Changes of this kind may result in generating negative prediction error. The length of a policy implementation (required time) plays an important role in behavior change and attitude internalization.

We ran the simulation for different lengths of time, to study the effect on trust and behavior. At five time intervals, temporary changes are imposed which might influence the DM. The policies start to be implemented from trial/day 10, and lasts temporarily for 10, 30, 50, 70, or 90 trials/days, respectively, during each of the five time intervals.

In the second frame, the imposed changes last for 30 trials/days. Interestingly, immediately after the end of this period the behavior of the PA is changed as she changed her decision to travel by public transport instead of by car. This process is repeated in the other frames. Although the period of changes is longer, in all other frames, after 31 trials/days the priority of the PA in selecting means of transport change. In other words, the least required time to change the behavior of the agent is 30 days, and longer temporary change is not required.

In Fig. 39, the first frame when the imposed negative feedback lasts for 10 trials, is not sufficient to change the priority order. Therefore, during 100 trials the PA consistently select the option car to reach her destination.

Failure in satisfying the goal of the PA affects her trust level to the options. As is illustrated in Fig. 40, trust to car is significantly greater than trust to public transport. It shows that policy implementation during 10 trials is not enough to change the trust level of the agent towards these options. Increasing the length of temporary changes will increase the trust level to public transport and decrease the trust to car.

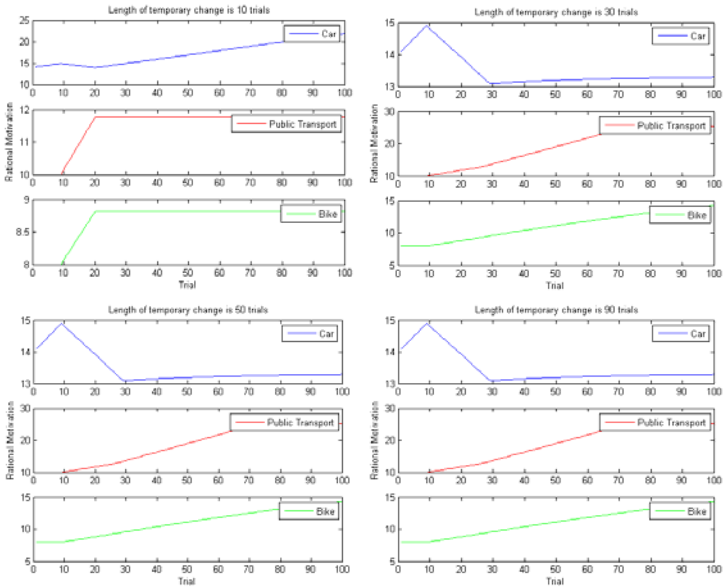


Figure 39. *Rational motivation changes during four time intervals. The length of implementing policies varies from 10, 30, 50 to 90 trials, respectively. Blue lines are for car, red for public transport, and green for bike.*

Scenario III

In a third scenario, we wanted to find the influence of trust in changing attitude. Our simulations indicate that the trust level is not the only influential parameter that might affect the attitude change. The influence of this parameter should be analyzed regarding the probability of unpredicted events. We studied the influence of society on the agent's attitude, with a fairly high (80%) probability of negative prediction error generation. In this process, different levels of trust between the PA and society were applied, ranging from 10 to 90 percent with a step size of 20 percent.

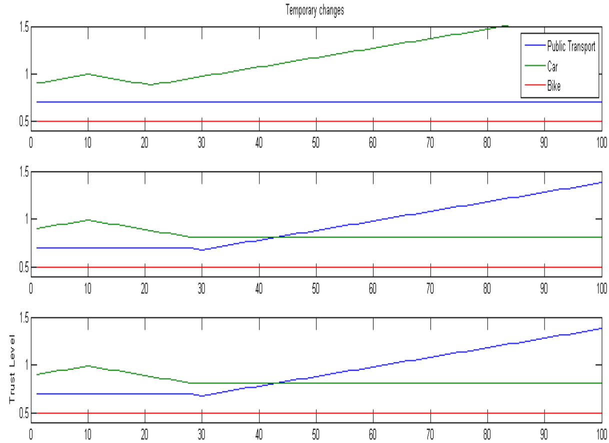


Figure 40. *Trust to the three options, bike (green), car (blue) and public transport (red) for five different lengths of policy implementation, going from 10 days at the top to 90 days at the bottom frames.*

The simulated model produced some interesting results concerning change in motivation and in priority order. Motivation is considered one of the most important parameters behind a change in priority order. Figs. 41 and 42 illustrate the change in emotional/rational motivation of the PA under the influence of different trust levels. Interestingly, a decrease of motivation to car has an inverse correlation with trust level. Higher social trust level leads to lower motivation for taking car. On the contrary, there is a direct relationship between the level of the trust and increase of motivation for taking public transport. In other words, in cases with higher social trust, the advisor is more successful in changing the behavior of the PA. (Again, the motivation for bike is not affected, and therefore left out in these figures).

Since the probability of unpredicted events is high, the motivation of the PA for taking the car decreases in all four frames and increases for taking public transport. The difference between frames is the rate of increase and decrease of motivations.

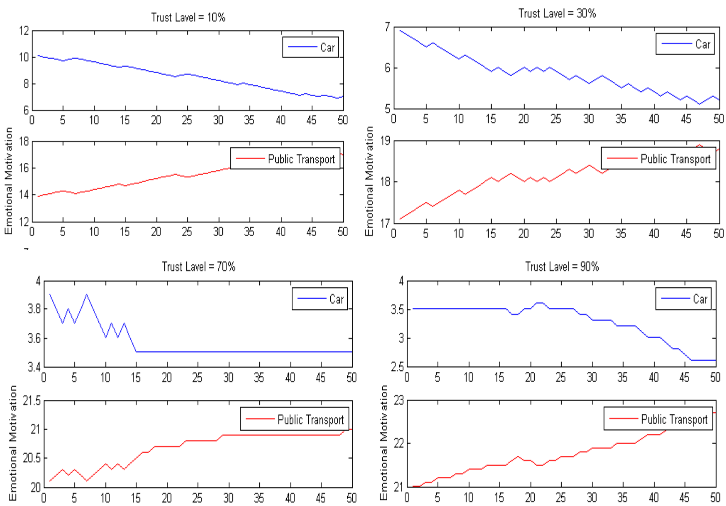


Figure 41. *Emotional motivation changes considering different trust levels between the decision maker and society. Higher level of social trust brings out higher motivation for taking public transport and lower motivation for taking car.*

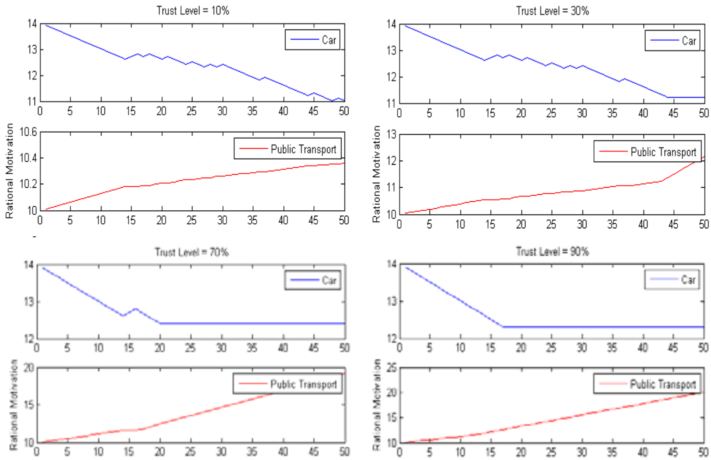


Figure 42. *Rational motivation changes considering different trust levels between the PA and other agents. Higher level of social trust brings about higher motivation for taking public transport and lower motivation for taking car.*

As mentioned above, the rate of increase in rational/emotional motivation for taking car is much greater in a society with higher trust level. Considering the results from the motivational change, it can easily be seen that there is a relation between the priority order change and trust level.

As illustrated in Fig. 43, the required time for a changed behavior is a function of level of social trust. The behavior of the PA changes quicker when the trust level is high. For very low trust levels (level 1=10%) the behavior never changes, while for higher trust levels, the behavior of several individuals may change rather fast, which may result in a system flip. Changing of the attitude in a society with a high level of trust is much easier than in a society with a weak trust network.

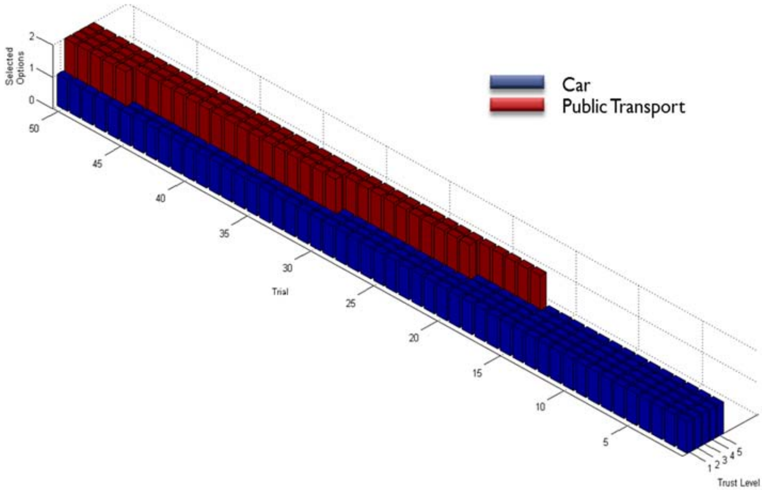


Figure 43. *Change in priority order, depending on the trust level between the agents.*

Discussion and Conclusions

In this chapter, we have modeled some major parts of the neural system involved in decision making (DM), including amygdala, orbitofrontal cortex, and lateral prefrontal cortex. These systems represent emotional, as well as rational aspects of DM. We have also considered the interaction of several agents for social DM, exemplified by choice of transport and with consequences for climate change.

With our neuro-cognitive model, we have demonstrated how different cell assemblies, representing different optional choices available to an individual may compete with respect to their activity levels. This level, or intensity of the activity, was suggested to be a combined measure of the size of the cell assembly (number of network nodes), and the frequency and amplitude of the oscillatory activity of the nodes. The "winning" assembly is simply the one with the strongest neural activity, measured as the product of the three assembly characteristics (number, frequency, amplitude). That assembly determines the option that will be taken. The different options get different values, depending on internal and external factors. Internal factors could be attitudes, values, mood etc., while the external factors include traffic situations, availability, distance etc., but also the influence of other individuals in a social context. In fact, *context* could be considered the combined internal and external context, while a stimulus *signal* could also be either internal or external. A signal is typically specific, having information content that usually is transmitted to the DM system via our sensory systems, or via other brain areas.

Hence, for any particular input signal, the final decision made by an individual could shift depending on internal and external context. In the case of choice of transport from home to work, given the available options (*bicycle, bus/train, car*), the choice could depend on e.g. either mood, weather or traffic situations any particular day. The experience of our decisions/choices is also learnt and may influence future decisions. For example, if I have decided to take the bus instead of my car one morning, and the bus is delayed or maybe even does not show up, this experience will affect my willingness to take the bus the next day. Similarly, if I end up in traffic jams almost every morning taking my car, I (eventually) may decide to try another means of transport. In addition to these contextual influences, our neighbors in our social networks also influence our decisions, depending on the psycho-social distance (trust). This influence may either be informational, through direct communication, or by adopting the decisions/behaviors of the trusted ones.

In a larger frame of context, our own decisions and actions will in turn affect the context of other individuals in the society, according to some distance measure, for example, a psycho-social distance and strength of interpersonal ties (Granovetter, 1973). This could correspond to what is sometimes referred to as "social capital", or trust. We have previously shown that neural network dynamics and properties can change dramatically, depending on strength of network weights (Halnes *et al.*, 2007), which may also be the case of social networks, and which will be further explored. Attempts to relate neural network properties to social networks have already been made for belief polarization, where it is shown that social relations rather than individual beliefs matter most (Sack *et al.*, 2013), but the analogy may be taken further, where the link between the micro level of individual decisions and macro levels in society can display interesting dynamics at several temporal and spatial scales. It is clear that a sudden or quick change in individual attitude and behaviour also may result in quick changes in society, such as has happened for example with regard to smoking or recycling.

Understanding the DM process of an individual may be helpful not only to that individual, but also to those interacting with that individual, as well as to policy makers and businesses who want to influence our behavior. Apparently, our decisions are based on biological (genetic, neural, physiological) factors, but also on social and environmental factors, that constitute a complex web of causation, making it hard or even impossible to predict a behavior for any given individual. Yet, taken *en masse*, the behavior of hundreds or thousands of individuals may be more or less predictable, and to some extent controllable, depending on our knowledge of internal as well as external signals and contexts. This knowledge can be used (and misused) for such activities as spreading of information, nudging, advertisement and propaganda.

There are of course many simplifications and assumptions made in our modeling that could be discussed and re-examined, and which may be crucial for the behavior of our model system. In a future development of our decision making model, we want to include more biological, as well as psychological and social facts, that could make the results even more realistic, and hopefully useful for various types of stakeholders and policy makers. Given the proposed models and assumptions, and based on the computer simulations, we can still make some preliminary conclusions, which need to be confirmed by empirical data to be fully appreciated.

For example, negative prediction errors and trust levels are both strongly affected by the behavior change, and we observed a causal-effect relation between these two parameters. Simulation results confirm our hypothesis related to the role of negative prediction error. In cases with low probability of negative prediction error, a changed behavior does not happen or will take a long time to occur. In *Scenario III*, the role of trust in face of negative prediction error was clearly illustrated. We found that, despite a high trust level between the agents, a low probability of negative prediction error prevents or postpones behavior change. On the other hand, cases with high probability of negative prediction error, but low trust level, requires a long time for behavior change. The required time to change the priority order is more influenced by the number of unexpected events rather than by the trust level. These results lead us to propose the following *theorem*:

> *To change the behavior of individuals, providing situations resulting in a negative prediction error, is necessary but not sufficient, while the trust level can be considered a sufficient condition.*

Moreover, experiencing the actual value of the selected option might cause the trust level to be increased or declined. Therefore, generating negative/positive prediction error play an import role in all three scenarios. The actual value of the option may change regarding the temporary or permanent environmental conditions. Changes in external situations, e.g. the occurrence of unpredicted events, can be considered as noise in the system. The probability of noise generation in the system affects the trust level. For example, the higher probability of unpredicted events in road traffic causes the PA to have a higher propensity to trust public transport rather than the trust to the car.

All scenarios provided some interesting results, based on the parameters that were under study. Considering the *Scenario I*, there is an inverse relation between the number of unpredicted events (UE) and the time required to change the priority order. The higher probability of unpredicted events causes the PA to step across the threshold of behavior change faster. Hence, the time required for behavior change is shorter.

Scenario II demonstrated that the mere implementation of policies is not enough, but the required time for implementing the policy is equally crucial to change behaviors. Based on the results, a minimum length of implementation is required to change attitudes and longer time does not make any difference. This example relates to an experiment made in Uppsala municipality, where car drivers could get a free bus ticket for one month, if taking the bus rather than their car to work.

Based on the results from *Scenario III*, increasing the trust between the PA and society shortens the required time period for attitude change. The time elapsed before attitude changes increases nonlinearly with linear increase of trust level. The time required to change the attitude of a citizen with high trust level to society, when the probability of UE was low, is significantly greater than the one in a more noisy conditions (high probability of UE).

A negative prediction error results in a decline of motivation in taking the associated option. There is a direct relationship between policy framework on higher costs/longer time and negative prediction error of taking car as a decision. Therefore, when implementing policies for, in this case, transport, the outcomes of the various options (time and cost) should be a special target. A recent example of this in the Stockholm-Mälar region is the tendency of commuters to change to public transport, as the toll fees for Stockholm increased. An opposite effect was observed when new roads/tunnels were built, facilitating car driving through Stockholm.

However, not only rational prediction errors have a negative sign, but the agents are affected also emotionally. The model simulations suggest that an efficient strategy for policy makers would be to target both emotion and cognition. The cost and required time of travel, traffic, road conditions, use of modern technology, etc. are among the strategies that agents are both emotionally and rationally affected by.

A part of the agents in the "society" of the PA is government and policy makers. To increase the level of trust between government and the citizens should be of major concern for policy makers, in order to gain public acceptance and for promoting behavioral change. On the other hand, the policies formulated by the policy makers affect not only the PA, but all the agents interacting with her. Therefore, attitude modification of other agents, as well as the PA engenders trust and attitude similarity. Building trust between the agents in a society is likely to result in social stability. We believe computational models can contribute to a greater understanding of causal relationships in society, e.g. between individuals and institutions, and suggest effective pathways to a low carbon society.

Key points for policy makers and societal planners:

- It takes time to change attitudes, habits and life styles. Hence, any change in infrastructure must take this in account, and allow for people to adjust.
- Trust in transport systems is based on reliability of arriving in time, and more important than too tight schedules with too small margins that may result in delays and interruptions.
- Societal system flips may result from a large number of individuals shifting travel habits, as a result of actual or perceived discomforts and irregularities of some means of transport.
- Higher travel costs may initially have an effect on travel habits, but people may soon get used to the higher costs and can easily return to previous behaviour.
- Rational arguments and advice are not enough in recommendations and nudging; emotional messages are at least as important in making people change their habits.
- People prefer small benefits that come quickly, rather than waiting for larger ones coming late. It is important to point at the immediate (small) gains in any desired societal transition.

V. POLICY RELEVANCE AND CONCLUSIONS

Hans Liljenström and Uno Svedin

What have we learnt throughout our four year EU project COMPLEX? First of all, the relevance of our approach to deal with climate change issues within a regional perspective seems to have been, step by step, consolidated. In fact, due to the development in the surrounding world, in particular the UN Climate Change Conference in Paris 2015, the importance of actions at various levels, including the regional one has been emphasized. Hence, our initial intuition to focus on the regional level and its constituencies seems to have been confirmed. However, during the project period, the "landscape" of regional policy in Sweden has undergone some changes. For example, suggestions to lump together a number of counties ("län") to larger "regions" have very recently been put on ice, since no agreement among the political parties at a national level could be made.

International connections

When we started our project in 2012, the ambition of Sweden to become one of the first fossil-free developed societies in the world by 2030 was not on the agenda (although pieces of policy were at hand already half a decade ago). Now, by the end of our project in 2016, there is a strong intention in the Swedish political system to drive such an aim. In addition to the targets themselves, there is a considerable rise of attention and urgency with regard to the implementation aspects.

Technical development issues

In our opinion, our Swedish case illustrates a wide range of interesting moves, such as the transformation of the transport sector. This includes not only technical developments of new types of biofuel driven, or electric vehicles, but also societal solutions, e.g. in terms of combining the logistics capacity in better ways to improve the overall performance. Thus, the strategy is pointing at a better and more efficient way of use of the resources utilized for the transport purposes. Similar ideas are voiced with regard to other sectors.

Planning issues

With regard to the municipal level, there has been several reform plans by different city actors in our region (e.g. Uppsala – where some of us have been involved in the Uppsala Climate Protocol, which deals with climate change related reforms). New forms of public acknowledgements have been installed over the last years, highlighting the efforts of early institutional forerunners as cities (or municipalities in general), with quite some prestige attributed to various actors for their environmentally oriented efforts, where Uppsala is a good example.

Also the big efforts by the largest actor in the region – Stockholm – point at strong reform intentions. However, it is less what the plans say – but what they mobilize in terms of action - that will count, both in the short and the long term. Hence, it is very important that action is taken with the speed, efficiency and efficacy needed to reach the low carbon, or fossil-free, conditions that are called for, considering the imminent challenges of climate change.

Time development

A time development process in several steps could be envisaged already from the beginning. On the one hand, the years up to 2030 have grown in importance for planning, mobilizing and start-up activities at various institutional levels (through the establishment of strategic plans and of setting up implementation groups etc.). In addition, efforts by a wide range of actors, including business and industry, have shown to be of key importance. Yet, in relation to the ultimate goal of a completed low carbon transition by 2050, this process has to keep the strong momentum both before and beyond 2030. For example, the transport sector is supposed to have reached politically set goals already by 2045, and other sectors have similar or faster ambitions. Many of these strategical goals are related to various assessments of conditions – international, as well as national.

What then would we, at the end of our COMPLEX project, like to stress for Sweden, and particularly for our Stockholm-Mälar region? Below is a list of four central areas of reflection.

- It is a *total transformation of a social kind* that is needed - not only partial technical solutions. This understanding seems to have been absorbed, step by step, by many of the central actors, although the operational consequences are not very clear, so far.
- Within the goals set by various promoting actors, primarily in industry, *emerging technical solutions* have been voiced and even activated (e.g. the development and market introduction of hybrid and electric cars). In most cases, however, it is still difficult to see when a commercially based breakthrough may come. In fact, earlier en-

couraged vehicle fuel switches, notably to ethanol, have proved to be very problematic. This experience has raised some hesitation with regard to other innovations that first seem promising. So, the endurance in the constant efforts to find new solutions is important and deeply connected to the *investment momentum,* as well as the supply of *appropriate conditions for this to happen* (e.g. in terms of foreseeable and steady rules of the development arena). This includes the intention to keep steady the support to the innovation process of various kinds - especially in its pre-commercial phase.

- The development of means to involve *changes of individual behavior,* and associated emotional and cognitive aspects, has very quickly emerged as an important issue. Our project has contributed to such avant guard research activities. While still in its infancy, this kind of research, where drivers and obstacles for change of habits and life style are explored, is likely to become increasingly important in the near future.

- The stronger the need for change is perceived, the more relevant will be the strategic *choices of research efforts*. In our view, it is *reflections of systemic kind* that are the holders of future advances. While we are still at a very early stage, systemic insights - as a key strategic factor - are becoming more frequently addressed. Yet, much more needs to be done, especially by defining such systems connections at a high level of priority.

Synthesis of our research work

Already at an early stage of our regional project, we realized that we had to deal with the following research issues:

- Multiple scales
- Multiple types of stakeholders
- Associated different time frames
- Associated different types of pivotal considerations and "world views" connected to these approaches

We responded to this demand of connected perspectives by identifying certain key elements associated with different geographical and institutional levels, different stakeholder concerns and timeframes. For example, we had to consider that the characteristics and time frames for the planning of societal functions at a regional level are quite different from the neuro-cognitive processes involved in individual decision making.

This means that we have provided a set of very different perspectives on problems involved in the required societal transformation for the next few decades, until 2050. We hope we have been sufficiently transparent and clear about the considerations and assumptions made in each case. We have also provided backgrounds to the theoretical approaches we have mobilized in these diverse cases, and indicated how our methodological choices have been made. In this way, we have presented a "landscape" of concern in several dimensions, which can serve as a basis for further discussions among decision makers on paths towards a low carbon society. Of course, in all of these analytical "segments", we have indicated our preferences for a certain interpretation of the outcomes. However, we have not given a unified measure of how all the positions in the various segments shall, in the end, be linked together. This has to be done by the interested and knowledgeable decision makers from their own particular situations and outlooks.

We hope that the experience and understanding we have gained throughout our four year project can be of interest to a general reader. While acknowledging the limited perspectives our own research may have given, we would also like to share the lessons we have learnt with other researchers and decision makers of various kinds, including those in public, industrial and financial sectors. Our advice should be seen in this perspective, where obviously there is an array of concerns that are outside the realm of our analysis.

In the last part of this book, we thus provide our own policy considerations aiming primarily at decision making in the Stockholm-Mälar region.

V:1 Policy Considerations Aiming at a Path Towards a Fossil-Free Society

The following main points could be seen as suggestions to the top political structures in the region. It could be the municipalities, the counties ("län"), or the Council for the Stockholm-Mälar region, i.e. *Mälardalsrådet*. (We have, since the beginning of our project, followed the work of this Council, especially in its efforts to outline transformations of the region, including the path to a low carbon society. We have also contributed to the Council Annual Meetings in 2015 and 2016, presenting some of our findings).

1. *The transformation to a low carbon society includes all aspects of our society*. That involves all the different levels of society, all sectors and forms of stakeholder types. It also involves civil society at large and relates to the living conditions of all the citizens of the region. This means that it is not only an issue of change of the technical aspects that is at stake, e.g. of the energy system and related infrastructural mechanisms. The transformation also connects to consumer behavior, and in more general terms issues about where we want to live and work in the future, and how the inhabitants of this region within a few decades would consider what a well-functioning society might entail, especially caring for the particular needs of persons of all ages and gender.

2. *The transformation process could not only be used to meet the challenges of change, but might also open up for many new possibilities that may emerge*. This means that although the change is necessary and deep going, it may also provide new competitive means in an international context – given that a change trajectory is chosen that encourages such possibilities. Thus, the region should use the transformation

process to serve these purposes - also as input to discussions at national and European levels to demonstrate solutions developed in the societal, technical and ecological domains. In practice, this means to foster avant guard forms of societal competitive ways to operate – as well as serving other countries with less initial advantages for such performances. This may also be a competitive advantage for Swedish interests abroad.

3. *The transformation requires a mobilization of the entirety of our society*. This means that our democratic processes are fully used to invent and implement changes using a deepened planning process with democratic consolidation. Innovations should be encouraged – not only with regard to technology, but also with regard to how society could be changed, e.g. through changes of laws, rules, administrative processes, stimulation to risk taking and renewal in all sectors and by all actors - as well as through the creation of new patterns of collaboration. There will be a need to creatively scrutinize our current patterns of values, facing the new challenges within all strata of society – public official structures, the business community and civil society alike. The further move towards an increased interest in future oriented activities and openness towards change will be of considerable importance. But this will also put pressure on the "stronger" and more affluent segments of society to responsively care for parts in society with more limited capacities.

4. *The transformation is made within a very large complex system with many partial couplings*. This means that the complexity will have to be orchestrated in partially new ways. This can be prepared through various ambitious experiments both at limited levels and in a variety of actor spaces, but

also in large constellations involving the needed investments for such actions. Such transformation experiments must be conducted in line with the goals of a fossil-free society – and be done through strong encouragement, maybe deliberate relaxation of certain rules in combination with appropriate new ones. This must be done by setting up a metric of several diversified tests reflecting varied starting points. However, the total overview of the process will never exist at any one time. Thus, the constant upgrading of the vision in relation to path experiences has to be developed in a dynamic interplay over the time.

5. *The transformation is being performed in a societal context within which there are several interplaying levels* (e.g. the level of the individual, of the local municipality, the county, the subregional, the region, the national and the EU-levels – also influenced by the constantly changing international conditions at larger frames). This means that the interplay between levels has to be given considerable attention. What once was a reasonable distribution of labor and responsibility might not be the same in the future due to changed conditions. The pressure to move quickly to a fossil-free society also puts stress on the governance architecture. Different versions of interplay between "bottom-up" and "top-down" solutions have to be conceived, developed and tested.

6. *The transition towards a fossil-free society is necessary*. Regardless, it can provide advantages for other aspects of change in society. This means that a diverse set of solutions developed for the purpose to bring us to a fossil-free society might also be supportive of other changes that are needed. One already well-known example is that

goals related to the handling of climate change may go well hand in hand with efforts to reduce health effects from harmful components in the atmosphere – not least in heavily urbanized areas. Such synergies have to be better explored and mobilized – much better than what is the case today. This also calls for more cross sectorial connectivity innovations.

7. *The broad transition has distinct regional operational connotations.* This means that the societal conditions that historically have been developed over long time in our specific case region also in the future must be guarded and cared for – but now in a directed fossil-free context. The new possibilities that probably might be generated should be encouraged. An essential factor for success in this endeavor is a well spread sense of participation in the change process by large segments of the population in society. This means that all persons in society should be needed in one way or the other – and this should be conceived of in a multi-generational perspective.

Alert 90+ citizen Pia Berg, responding to Stockholm environmental questions. Photo: U. Svedin

V:2 Conclusions

In this book, we have approached our core issue ("how could we in our region reach a low carbon society in the year 2050?") by applying different perspectives on 1) complex systems, processes, and challenges, 2) a green economy, 3) bioenergy, land use and local transition, and 4) governance, policy instruments and stakeholder positions. This has been done with focus on the Stockholm-Mälar region in Sweden.

These perspectives are complementary – and could be seen as "lenses" of investigation, in the sense that certain issues have (deliberately) appeared several times – but have been handled differently for the different contexts. In this way, we wanted to stress the plurality and complexity of the challenges in the transition to a low carbon society. Thus, also the theoretical and methodological leanings have been adapted to this approach. It includes identification and analysis of links, feedbacks, thresholds, opportunities, barriers, preferences and drivers for change at individual, as well as at societal levels. This complex mix of system properties and indicators feed into our different types of models, which are aimed at supporting the policy and decision processes within our region.

Many insights have been extracted from our research process - including our set of stakeholder meetings. We have, as part of these findings, also identified some "knowledge gaps" within but also between the various perspectives. For example, it was obvious that we needed to use different modelling approaches in our work, depending on the questions asked. Some were aiming at identifying optimal solutions, where optimization was based on cost-efficiency or general stakeholder preferences. Others were more explorative and illustrative in purpose and character, aiming at describing a range of potential future scenarios.

It is obvious that many of the transformation processes that the European society has to undergo in the next few decades will have to be played out also in our region. Thus, the decision making in the region (including an advanced planning process) will have to be supported by instruments that can simulate different types of outcomes, depending on the various scenarios.

An interesting venue of study was how different views on interactions between researchers and stakeholders could be explored. This included how researchers could participate as observers of ongoing stakeholder activities, or how researchers could act as knowledge providers within stakeholder activities. It also included how researchers could act as contributors with their own interests, as integrated in stakeholder processes, e.g. in terms of functions as initiators and mediators within stakeholder processes.

The multi-level governance structure in the Stockholm-Mälar region is in itself a very interesting topic that we have explored. On the one hand, this region is the geographical home of the national government, and the Stockholm County (*Stockholms läns landsting*) has developed forceful regional planning processes. The wider Stockholm-Mälar region, on the other hand, with all the counties around Lake Mälaren, has considerable challenges to face, in terms of further needs of streamlining the regional governance in a stronger and more collaborative way. While the municipalities within the region have rather strong and semi-independent governance capacities in themselves, the collaborative functions at county and regional levels need further development, as the joint regional challenges increase in importance - which the low carbon transformation processes illustrate in a clear way. Obviously, more of lateral and vertical collaboration seems to be needed.

Thus, after the initial phase of our study, we moved from a multi-disciplinary descriptive-analytical science to a trans-disciplinary transformational activity, aimed towards the low-carbon society. All the time, we were driven by the ambition to maintain scientific integrity and rigor.

To sum up, the work of the COMPLEX WP4 has been dealing with integration of knowledge and action preparation for stakeholder and decision maker communities in the Stockholm-Mälar region. In this work, we have both been using specific models of a quantitative and of a qualitative kind. In the interplay with stakeholders of various types there has been use of their inputs for the upgrading of understanding, as well as for providing feedbacks to them as community in different ways. Thus, the aim has not primarily been integration of the partial models themselves, in a technical way, but using our developed array of model understandings in a broader sense, to create a platform for reflection by decision makers/stakeholders. The participatory modelling has thus emphasized the process in the overall interplay of knowledge co-creation, mutual understanding and outreach. In addition to this, we have used emerging possibilities to feed the results into the public debate about the WP4 thematic topic. The service of WP4 has thus been both to provide a set of computational models and to have positioned them in various contexts. In a more general sense, we have created an overall test case for integrated understanding of these thematic issues on paths towards a low carbon society - now so highly debated, not only in Sweden.

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In this book, we have concentrated our presentation on the contributions from the Swedish research groups at SLU and Stockholm University to the EU COMPLEX project, with regard to the Stockholm-Mälar region. We acknowledge the financial support we have had from the EU 7th Framework Program during the four year project period, 2012-2016. The Swedish focus in this book does not mean that we have lacked ample connections with COMPLEX partners in the other countries. In particular, we have had extensive interaction with the project coordinator, Dr. Nick Winder (of Newcastle University), who has partly been based in Sigtuna, Sweden. We express our gratitude for all the connections we have had within COMPLEX, which have been reported more extensively elsewhere, (primarily in the final report volumes of the same series as this book is presented in). We are happy to acknowledge the contacts with all our collaborators in the consortium, but at the same time, we take full responsibility for the research activities performed by our Swedish research groups - as reported in this book.

In our work with the Stockholm-Mälar region, we have had a substantial collaboration with a wide range of stakeholders, in various forms. These interactions and connected contributions by individuals from the field of practice, but also from various domains of academics outside our own core groups, are happily and gratefully acknowledged. Our project could not have been carried out without their willingness to participate. In a broad sense, we are talking about hundreds of persons, too many here to be mentioned by name. We want to express our deep gratitude to all these individuals – mostly from Sweden – who have freely put their time and knowledge to our use. (Many of them have been listed in

connection with the reporting to the EU on specific events).

For the general reader of this book, a glimpse of our discussions in a wider frame of participation is provided by edited video coverage of two of our stakeholder workshops. One of these recorded workshops (in English) were held at the Sigtuna Foundation on 21 January 2016, and organized together with the entire COMPLEX consortium. We also present a video (in Swedish) from a nationally policy oriented workshop held at the Sigtuna Foundation on 20 September 2016. These videos, together with other WP4 material, including models developed and used, are available on our website:

http://www.slu.se/complexwp4

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The transition to a low carbon economy by 2050 will involve irreversible changes in the cultural, economic and natural domains. This implies a potential for emergent qualitatively different societal conditions. By the time the low carbon policy has been implemented, many problems conceived today will have been resolved. Some aspects of socio-natural systems will then have been changed irreversibly. Thus, the design of the transformation will have to consider long-term social, environmental and economic conditions.

Within the EU project COMPLEX, the Stockholm-Mälar region was chosen as one of the case studies for the transition to a low carbon society by 2050. COMPLEX work package (WP) 4 has had the aim to provide a process understanding and instruments for support of such a transition in the region.

This book contains work performed by the WP4 team, with researchers from SLU and Stockholm University, as well as expertise and other resources at the Agora for Biosystems and the Sigtuna Foundation. The different chapters are collected from WP4 deliverables and other WP4 texts, which also partly appear in the various volumes of the COMPLEX Final Scientific Report. The motivation to make a separate volume for the WP4 work is to provide an overview for those who have a special interest in the "Swedish" part of the COMPLEX project. It is thus primarily aimed towards stakeholders and others who have been in contact with the WP4 team and its activities, but also those with a general interest in how a region like the Stockholm-Mälar Region can address the problems of climate change.

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