# Adoption of Bioenergy Technologies for a Sustainable Energy System

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## Abstract

A future sustainable energy system must achieve great improvements in energy efficiency and the energy supply must be based on renewable energy sources. Bioenergy will be an important part of this system. Changing from the current fossil-dependent energy system to a truly sustainable energy system will require fundamental changes in basic structures of society, in the technologies we utilize in the living of our lives and in the way we as citizens and consumers behave relative to energy use. Radical innovations along multiple dimensions are needed to achieve this change.

In this thesis the focus is on the role of bioenergy technologies in this system. Specifically, the diffusion of bioenergy based heating technologies is analyzed in four separate research papers. Empirical analyses are based on data from relevant markets in Norway and Sweden. In **Paper I**, the supply curve of the potential forest fuel supply of a Norwegian county is analyzed, based on an engineering economics approach. Can differences in cost structure in forestry explain why Norway is lagging behind Sweden in terms of bioenergy use? The answer is that there is no lack of low-cost supply of forest fuel raw material in Norway to explain this difference. **Paper II** takes a forest owner's view and assesses effects on the optimal timing of the harvesting of the forest, when two important additions to the classical Faustmann model are assumed. The market value of the biomass in the tops and branches (harvesting residues) *and* the value of carbon fixed in the living trees are added to the value of the stem (timber). The value of wood residues shorten the optimal rotation length, while the carbon storage value of the tree lengthens it. The optimal rotation length is very sensitive to the relative size of these two added value components.

In **Paper III**, the initial phase of the development of biomass use in the Swedish district heating sector is scrutinized. A central conclusion is the importance of long term and stable policy signals and the development of an innovation system around this sector. The last article, **Paper IV**, takes a look at the effects of the Norwegian Household Subsidy Programme for new heating technologies, including pellet stoves. It shows that households put relatively little weight on purely economic factors in assessing the success of their investment in such technologies.

*Keywords:* bioenergy, forestry, innovation, adoption, energy behaviour

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# Dedication

Without the support of many good people, this work would not be.

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Thanks to friends and former colleagues at North-Trøndelag Research Institute and North-Trøndelag University College for fruitful discussions and companionship.

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To my core academic support team, Bengt Hillring and Anders Skonhoft, for their endurance.

And last, but certainly not least: To the patience, understanding and love of the best people to share a life with: Odin, Isak, Amalie – and Jorunn.

In memory of Arne Christian and Helge.

*There is a crack in everything*
*That's how the light gets in*

L. Cohen

# Contents

# List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Bjørnstad, E. (2005): "An engineering economics approach to the estimation of forest fuel supply in North-Trøndelag county, Norway". *Journal of Forest Economics* 10, 161–188.

II Bjørnstad, E. and A. Skonhoft (2002): "Wood Fuel or Carbon Sink? Aspects of Forestry in the Climate Question". *Environmental and Resource Economics* 23, 447–465.

III Bjørnstad, E. and B. Hillring: Early adoption of biofuels in the Swedish district heating sector (manuscript).

IV Bjørnstad, E.: Diffusion of renewable heating technologies in households. Experiences from the Norwegian Household Subsidy Programme (manuscript).

Papers I and II are reproduced with the permission of the publishers. Papers III and IV to be submitted for publishing.

The contribution of Even Bjørnstad to the papers included in this thesis was as follows:

I Bjørnstad: 100 %

II Bjørnstad: 70 %, Skonhoft: 30 %

III Bjørnstad: 70 %, Hillring: 30 %

IV Bjørnstad: 100 %

# Abbreviations

| | |
|---|---|
| CAC | Command and Control |
| CFL | Compact Fluorescent Lamp |
| GHG | Greenhouse Gas |
| HSP | Household Subsidy Programme |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| NIMBY | “Not In My Back Yard” |
| NOU | Norges Offentlige Utredninger (Official Norwegian Reports) |
| NUTEK | Swedish Agency for Economic and Regional Growth |
| NVE | Norwegian Water Resources and Energy Directorate |
| OED | Norwegian Ministry of Petroleum and Energy |
| SDHA | Swedish District Heating Association |
| SSB | Statistics Norway |
| STEM | Swedish Energy Agency |
| TPB | Theory of Planned Behaviour |
| WCED | World Commission on Environment and Development |

# 1 Background and aim

The scientific community now agrees that there is a *very likely* causal link between the emissions of greenhouse gases from human activities and global warming over the last 50 years (IPCC 2007). Increased and rapid global warming can have severe effects on ecosystems, geophysical systems and ultimately on social systems. $CO_2$ is one of these greenhouse gases of concern, and the issue of emissions of $CO_2$ from fossil fuels used in a wide array of human energy production and use processes illustrates how tightly integrated the problem of global warming is with economic activity and human development. As a result, climate change and energy policy have become top issues on both national and international political agendas, and even in popular debate.

We have witnessed the development and growth of an economic system with advanced technologies and a high level of economic welfare enjoyed by a great number of people, particularly in the northern and western world. This would likely not have been achievable without ample access to inexpensive fossil fuels. Currently, around 80 % of the primary global energy supply stems from fossil energy sources in the form of oil, coal or gas (IEA 2007). This number illustrates how fundamentally dependent the global economic system has become on fossil fuels. This strategic dependence, combined with the problem of climate change, represents the greatest challenge facing the human community today.

This situation motivates another concern, in addition to that of climate change. In 2008 the price of a barrel of crude oil reached more than USD 140 in the spot market. Although the economic turbulence has later caused a sharp price fall, the spot price has risen back to above USD 100 in the winter of 2011. This indicates that there is an increasing pressure on the supply of this commodity to keep up with global demand. As demand for oil is expected to keep growing, e.g. by the rapid economic development in large economies such as India and China, it is not unlikely that this situation of high oil prices could continue. The *peak-oil hypothesis* predicts that the supply of crude oil will, at some point in time, not be able to keep up with increasing demand, and lead to upward pressures in the price of this commodity. Some analysts believe that the significant price increases we observe now are related to a peak-oil situation[1]. However, as fossil fuels, including oil, are non-renewable resources, supply is bound to peak at some point, and an economy largely based on such resources can not be sustained. Therefore, in addition to the climate change challenge, there is also the important issue of security of energy supply in the current energy debate.

The observations referred to above describe a recent historical development path where human ingenuity coupled with the ample supplies of fossil fuels have made possible an extraordinary growth in material welfare. The dependence of this development on fossil carbon has two strategic side effects. First, net emissions of $CO_2$ to the atmosphere are likely to contribute to unwanted climate change, and second, the non-renewableness of fossil fuels makes their strategic supplies uncertain. The need to break this link between fossil fuels and economic development and develop a sustainable energy system is the strategic context of this thesis. Its aim is more concrete in scope, it focuses on how biomass resources (bioenergy) can be utilized in the heating sector in a Scandinavian setting and on the processes of societal change that are required to achieve such utilization.

Not only biomass resources can contribute to sustainable heating systems, renewable resources such as wind, waves, solar rays, ambient heat etc. are also important resources. However, the long forestry traditions in Scandinavia, the ample supply of forest resources and the availability of "off the shelf" biomass-based heating technologies represent a strong incentive for looking into bioenergy issues in this thesis. The official policy to reduce the use of electricity for heating in Norway reinforces this choice. The fact that a resource is classified as "renewable" is a necessary but not sufficient condition for sustainability. For biological resources in particular, many examples exist that resource stocks have been jeopardized due to bad management practices (Swanson 1995). "Sustainability" in this context

[1] On a regional level, we have witnessed numerous examples of a peaking oil production. Domestic US oil production peaked in 1970. British North Sea oil production peaked in 1999 and in the Norwegian sector of the North Sea it peaked in 2001 (Leggett 2005, Blanchard 2006). Many analysts believe that we are close to reaching the global peak of oil production, see www.peakoil.net.

therefore requires a management regime that secures the ability of the resource stock or system to continue delivering the given flow of services over the relevant time scale while maintaining the quality of the resource stock or system. More on this issue below.

One might argue that the transportation sector deserves more attention than the heating sector in Norway, especially when we know that most energy use in transportation is fossil based, and much in the heating sector is based on renewable hydropower. This argument is valid, however the challenges in transportation are of a different scale and complexity as fundamental system changes might be called for in order to establish alternatives to technology- and logistics systems centred around the internal combustion engine. Within the heating sector there are mostly known technologies, a multitude of "low-hanging fruits" in the form of heating projects in residential and commercial buildings just waiting for a bioenergy solution, and also good availability of biomass resources. Many positive initiatives are made, within both the supply and demand sides, and also in the educational sector. Still, the general impression that the Norwegian bioenergy potential is underutilized, lingers. An additional argument is that green hydropower saved in the Norwegian heating sector can be exported and possibly replace fossil-based electricity in Europe.

It follows from this introduction that the key concept of this thesis is "sustainable energy systems". The context of the thesis, which is sketched above, is overwhelming in scope, both politically and socially. The aim of this work, therefore, cannot be more than an intention to contribute with a few pieces of the great puzzle that must be lain in order to reorient our communities from non-sustainable growth-oriented economies to ecologically sustainable and more robust societies. It is the author's intention that this work can represent some scientific contribution within the ecological economics field, and also to forestry and energy policy. Policy makers within the energy sector and regional development and practitioners within the heating sector and forestry also belong to the target group for this work.

The concrete research questions are discussed in the four stand-alone research articles that make up the core of this thesis. Before that, the remainder of this introductory part will present a brief discussion of the central concept of sustainability and relate it to the growth paradigm which is the dominant ontological orientation within several central social sciences, including neo-classical economics. On this basis it is pointed to the alternative position of ecological economics as a fruitful platform for trying to understand the fundamental challenges we are facing, and suggesting solutions. A core argument of ecological economics is that human societies ("the economy") must develop within the limitations set by the Earth's ecological and geophysical systems. Particularly, the economy cannot outgrow the ecological base on a permanent basis. As energy services are fundamental for social development, also long term energy systems must adhere to these principles of sustainability. More on this in chapter 2.

In chapter 3, principles of a (more) sustainable energy system are discussed, and the development and diffusion of bioenergy technologies in Norway and Sweden are discussed as interesting contrasting practical cases in chapter 4. The process of transition from a largely fossil-based non-sustainable energy system to an energy system based on principles of sustainability, including bioenergy technologies, is the main theme in these cases and in the research papers. Chapter 5 discusses the concrete research papers within this context, extracts their contribution to the scientific knowledge and suggests new research that could contribute to further outward movements of the frontier of knowledge on this important topic.

# 2 Sustainability – ecological economics

Research is always performed within a context, which functions as an underlying "mental map" that gives us some idea of the constitution of the world, society or other system we are investigating. Joseph Schumpeter (1954) used the term *pre-analytic vision* to describe such an ontological position, while Thomas Kuhn (1970) has been associated with giving the term *paradigm* a similar meaning. Different (research) paradigms are usually not very compatible or comparable, they typically define different knowledge needs and prescriptions to a given problem. For reasons of space constraints this discussion will not be pursued here, however the main arguments in a reasoning that has set out to challenge the central paradigm in social/economic theory and politics will be presented.

The technological progress following the industrial revolution has enabled a dramatic transformation of many societies of the world, into ways of life characterised by the high standards of living many people experience today. *Economic growth* has been a central instrument in this transformation, and has become a central tenet in both the economic policies of the modern world, as well as in the dominant paradigms of social science, such as neo-classical economics. During the last couple of decades, this growth-focused paradigm has become increasingly challenged by a world view that claims that constant growth in material output is not compatible with long term and stable sustenance of society. This criticism is directed mainly towards (i) how the neo-classical paradigm understands (implicitly and explicitly) the relationship between nature and society, and the fundamental workings of important natural systems, such as ecosystems (Perrings 1998); and (ii) the paramount power given to the individual, by distributing decision-making power regarding resource allocations to the "rational" actors through their market behaviour. This principle is extended from standard commodities such as bread and butter to complex environmental "goods" through different market emulating valuation methods (consult e.g. Vatn and Bromley 1994). This important debate is briefly illustrated below by looking more into three central issues.

## 2.1 The society – nature relationship

The classical economists treated land as a central capital asset in their models. In neo-classical theory, however, production functions typically comprise of labour and (man made) capital as the main inputs. Natural capital, in the form of assimilation capacity or natural resources, is treated as external to and separate from the economic model. Critics of this position claim that this model obscures the fundamental dependence of society, i.e. the economic system, on nature, i.e. the ecological system. A robust functioning of the ecological system is a prerequisite for the economy to function. This alternative world view implies, at this level, two important differences from the neo-classical model: (i) the economic system is not separated from nature, but the economic system is a subsystem of the ecological system of the Earth. This is illustrated in the figure below with the circle representing the global ecosystem enclosing the square of the economic system. A neo-classical version of this model would omit this ecosystem circle.

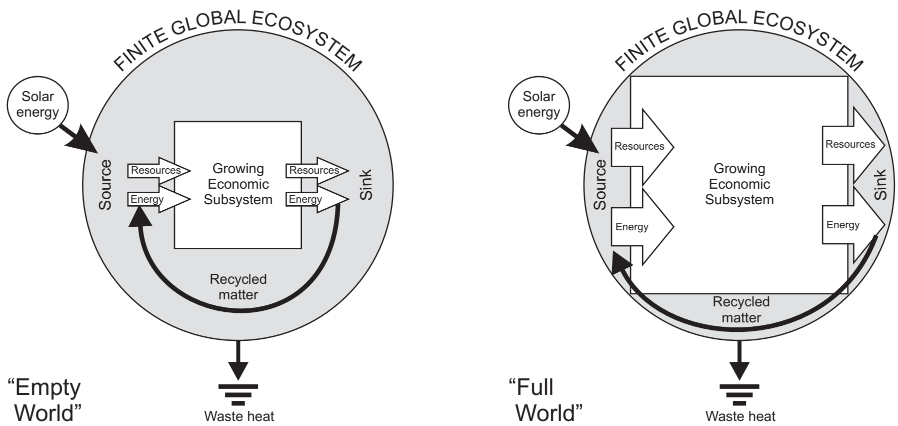


*Figure 1: "Empty" vs. "full" world (Costanza et al. 1997)*

(ii) As the ecological system and its capacities are limited, illustrated by the fixed size of the ecosystem circle, the ultimate size of the economic system must also be limited. This is illustrated in Figure 1 above. In an "empty" world situation, left panel in Figure 1, the demands by economic production on the ecological system are small. Such demands are in the form of extraction of resources (renewable and non-renewable) and assimilation of wastes from the economic system (sink functions). For the economic system to be sustained over time, it must not outgrow the constraints set by the ecological system. The right panel in the figure illustrates a situation where this is about to happen. Thus, there exists some optimal size for the economic system in terms of material throughput and demands for ecological services.

The "Environmental Kuznets Curve" (EKC) is a good illustration of this problem. Observations showed that the emissions of certain production-related pollutants were lower in wealthier countries. This formed the basis for the hypothesis that the relationship between the volume of economic activity and environmental degradation resembled the shape of an inverted U (Grossman and Krueger 1995). The logical consequence of the EKC is that countries can grow out of their environmental problems.

The paradigm challenging the growth-paradigm is referred to as *ecological economics*. Proponents of this alternative position claim that we are now in a transition from a frontier economy ("empty world"), where growth has been possible, to a spaceship economy ("full world") where the *growth* in material throughput should cease (Boulding 1966). The "Limits to growth" (Meadows et al. 1972) is another classic early text in this debate. Long term ecological sustainability implies that the demands of the economic system (its "size") should not be larger than that they can be handled by the ecological system. Costanza et al. (1997) give an overview of these issues, see also Faber et al. (1996). Let us end this discussion by indicating at a more concrete level a few areas where ecological economics and mainstream neo-classical economics disagree.

## 2.2 Substitutes or complements?

Let us start by specifying the concept of capital such that the term *natural capital* represents the resources and services that are provided by nature, and *man-made capital* are the artefacts and structures made by humans. Hartwick (1977) demonstrates that it is possible to sustain a non-declining consumption in an economy if one assumes perfect *substitutability* between man-made capital and natural capital (for the latter even in the form of an exhaustible natural resource). This is a crucial point in the growth debate. Ecological economists take the opposite view that the fundamental relationship between these two classes of capital is one of *complementarity*, an important implication of which is that man-made capital is of no value in the production process unless combined with natural capital. Further, this implies that a certain level of natural capital must be part of the capital portfolio maintained over time in order for the economic system to function. (Daly 1992). This fundamental insight is derived from applying the laws of thermodynamics to the closed system called Earth (Georgescu-Roegen 1971)[2]. The key in this reasoning is the inflow of solar energy, which powers a gigantic carbon cycle, with photosynthesis as the key process in regenerating low entropy resources, that has proven capable of sustaining life on earth. The proponents of the application of the laws of thermodynamics to this problem claim that the maximum sustainable size of the economic system, represented by energy and material flows, is defined by the flow of energy from the sun and the capabilities of the photosynthetic system to utilise that energy. In this perspective, an economic system based on the use of geological minerals and fossil fuels is not sustainable. A human development path based on the view that the laws of thermodynamics are relevant, must aim at some steady state, defined in terms of material and energy use. There must be a switch towards renewable energy and material sources, and there is a limit to how large the world's population can become. This is a key position among ecological economists (Daly 1992, 2000; Costanza et al. 1997).[3]

The principles of ecological economics help discover the problems implied by the neo-classical paradigm relative to environmental issues. They further give meaning to the concept of sustainable development, and

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[2] One may view the Earth as a thermodynamic system and apply the laws of thermodynamics. The first law says that the amount of matter or energy is constant, i.e. it cannot be created or destroyed. An isolated system thus must do with the resources it initially is endowed with. Further, wastes generated by any production or consumption process cannot disappear, and must be fed back into the system again. The second law (the entropy law) says that entropy (disorder, dissipation) increases when resources are used, and thus that complete recycling of material or energy resources is impossible. Burning of energy resources inevitably implies some loss of heat, precluding full recycling of energy resources, and the recycling of materials to reduce entropy is in itself resource demanding. An isolated system that is alive will thus sooner or later use up its useful low entropy resources. The Earth is not an isolated system, as it is open to the inflow of solar energy.

[3] All processes and value chains that depend on carbohydrates as raw material are limited by the capacity of the global photosynthetic process. A sustainable global energy supply is not necessarily dependent on photosynthesis, as other sustainable energy sources exist. Examples include direct utilization of sunlight (solar collectors, photovoltaics), "indirect" solar energy (wind, ambient heat), gravitational/tidal forces, ground heat (radioactive decay), etc.

lay the foundation for changes in our social systems toward increased sustainability. In sum therefore, this is a very relevant framework for discussing diffusion of bioenergy technologies in the Norwegian energy system.

These criticisms of the neo-classical position imply how the term *sustainable development* can be understood. This term entered the political vocabulary following the report “Our Common Future” of the Brundtland commission (WCED 1987). Here it was emphasised that sustainability is a question of equity both across and within generations, the latter discussed within a developing world perspective where the relationship between economic development (poverty), social development and environmental degradation was central. Putting less emphasis on the social and cultural dimensions of the term, sustainability can be understood as a question of handing over to the next generation a world (capital, knowledge, etc.) that enables future citizens to enjoy at least as high a level of human welfare (consumption or utility) as the current generation has been able to enjoy. It is difficult to specify clear cut and universal operational rules based on the principle of sustainable development. Even though one agrees that a minimum level of natural capital is required to ensure the workings of the fundamental ecological processes, how best to compose this portfolio of natural capital is unclear. Economic valuation of this capital stock and different ways of composing it is difficult. Further, the complex dynamics of ecosystem processes makes ecological and economic effects of different development choices highly uncertain. This calls for some rule of a safe minimum standard of the ecological structure (Ciriacy-Wantrup 1952) rather than a rule of optimisation. Consequently, many development paths towards a sustainable economy are available.

Natural capital (or natural resources) are usually categorized as either non-renewable or renewable resources. Non-renewables are finite in availability, but technological progress and new discoveries have pushed ahead in time the exhaustion of key resources, such as oil and certain mineral ores. Our understanding of renewable natural resources is partly as one of devising an optimal harvesting strategy over time for species which have a market value, but also as a need to uphold fundamental ecological functions necessary to ensure stability in the ecological infrastructure. (Gordon 1954, Clark 1990). Which of these aspects of the natural capital will represent the strongest constraint on further human development is hard to predict. Our path towards sustainability must be found within this framework of fundamental uncertainty.

Independent of the chosen development path, an increasing recognition of our dependence on natural resources and the ecological system will be part of a sustainable economy. A natural consequence seems to be that production and consumption activities must strive towards a minimal use of the scarce natural resources. This is obtainable by developing products and services that are more efficient in terms of resource use, better product lifecycles in terms of closed material loops, and other supply side innovations. However, the institutional framework for developing a sustainable economy is also important, including the preferences of the demanders.

In addition to efficient resource use, it also seems to be necessary to direct the future economic system towards greater integration with natural systems, in particular the carbon cycle. This implies that in order to be sustainable, an economy must be based on renewable rather than exhaustible (non-renewable) resources. The scale of the total physical throughput must be within the limits of what a well managed natural production system is capable of producing on a continuous basis. Refer once more to the “full world” part of Figure 1. Understanding the concept of *bioenergy* within this context is not straight forward. Bioenergy as biofuels replacing fossil fuels helps reduce fossil carbon emissions. On the other hand, increased utilisation of biofuels reduces carbon storage in biomass and contributes to increased atmospheric carbon levels. Increased extraction of biomass from an ecosystem affects other ecological processes of the system, perhaps negatively. There is also a potential competition for land area between energy and food production purposes, at least in a global perspective. The discussion on bioenergy and sustainability is therefore not trivial. More on this in the research papers.

These issues illustrate the contents of the concept of “sustainable development”, however space constraints prohibit a more in-depth discussion of this central term.

## 2.3 Individualism versus holism

The *rational actor* represents the fundamental unit of some approaches within the social sciences, including neo-classical economics. Basically, the rational actor is assumed to be characterised by a (moderately) stable set of preferences. Preferences are transitive, meaning that there is a consistent ordering of preferences relative to available choices of action. The “value” attached to the different preference orderings is usually expressed through a utility function. Rationality then is postulated to involve the maximisation of the expected utility of the individual, within the bounds set by possible riskiness and information limitations related to the choice in question. (von Neumann and Morgenstern 1947, Sugden 1991).

Such an approach to understanding human behaviour is referred to as *methodological individualism*, and implies that society may be understood as an aggregate of atomistic individuals. This means that the individual is the fundamental unit in constituting society. This position is challenged by a more holistic view of society, where over-individual structures or *institutions* to a greater degree define and restrict the choices of the individuals. In other words, society is more than the sum of individuals' actions. (Gunneriussen 1999, Vatn 2005).

This issue on individualism versus holism represents the fundamental question on how society is constituted, and its answer represents the society analogue to the nature-economy world view discussed above. The significance of this issue within the context of this thesis, is related to how we understand social change, and how we, as a society, can *make* society change. Translated to an individual level, this is asking how preference structures are formed and how they change, and further: How do we understand and how may we influence processes of change in the perspective of social development in general, and particularly, how does the sustainability paradigm enter and affect this issue?

One may use the more common term *innovation* to represent social change. Achieving a sustainable energy system implies a long successive chain of innovations, both in basic structures of society, technology and the everyday behaviour of individuals. Knowledge on innovation and diffusion of environmentally friendly technologies is supported by a large body of literature. Current usage of the term innovation can be traced back to Schumpeter's (1934) analysis of the modern capitalist economy. He emphasized the role of the entrepreneur, who played an important role in bringing about change and progress in the economy, disturbing market equilibrium and fuelling the process of "creative destruction". We rely, however, on Rogers' (2003:12, first edition 1962) definitions, according to which an *innovation* is understood as

> "an idea, practice, or object that is perceived as new by an individual or other unit of adoption".

The (potential) units of adoption constitute a social system, and *diffusion* is referred to as

> "the process in which an innovation is communicated through certain channels over time among the members of a social system" (ibid:5).

One important characteristic of innovations is the degree to which the innovation is compatible with the existing structure and function of the social system. *Incremental* innovations improve the existing, while *radical* innovations imply the establishment of new structures and/or functions, and thus a low degree of compatibility with the existing. A well established empirical fact related to innovations is that many diffusion processes over time are described by an S-curve, implying an initial phase with an increasing diffusion rate, followed by a decreasing rate of growth up to some satiation level of diffusion. A classical work in this respect is Griliches (1957), who studied the diffusion over time of hybrid corn among American farmers, and demonstrated that it followed the logistic curve. Different models to explain this diffusion process, based on the technical and economic abilities of the potential adopters, are described in comprehensive papers by Geroski (2000) and by Stoneman (2002).

A fundamental question related to technological change, is whether this process is endogenous or exogenous to the economic system. Hicks (1932) proposed the *induced innovation hypothesis*, which implies that innovations may be understood as induced or caused by changes in the relative prices of the inputs in the production process. According to this, innovations would be technological changes that economize with the resources becoming more expensive, that is, scarce. Empirical studies give some support to this hypothesis, see Hayami and Ruttan (1985) for illustrative examples within agriculture. The fact that at least part of the process of technological change may be viewed as a response to characteristics of the economic environment, implies that innovations and technological change may be steered, or at least biased, in some desired direction by altering the parameters that the economic actors face. A variety of quantitative or technological command-and-control instruments, together with market based instruments such as subsidies and taxes, may represent such parameter changes.

Within this view, a desired social change in technology towards a more ecologically sustainable economy is obtained by the imposition by some central authority of changes in relative prices or constraints faced by the economic actors, thus inducing individual choices that in aggregate will represent a change in the desired direction. Viewing this from a neo-classical perspective, the preference structures of the individual agents remain constant.

However, is this latter a reasonable assumption? Preferences and actions are and should be associated with individual actors. Could one still envision a process of social change that is best represented as a more collective effort where the preferences of the actors involved may be assumed to change, thus opening for the view of rationality as a wider concept than the one implied by the rational choice theory? The collective social process of establishing what is regarded fact is a central part of the theory on social constructivism (Berger and Luckmann 1967). Understanding and acting in response to the environmental challenges described here may, within this view, be a question of how we interpret the signals of "brute facts" given by nature within the socially constructed reality we live in (Rappaport 1994). In other words, could the development of society towards a sustainable future be understood in terms of processes and mechanisms that are more deeply rooted in our cultural and social "institutions" than what is implied by the "mechanical" rational reactions to changes in economic parameters? See Vatn (2005) for an in-depth discussion on this topic.

It may therefore be argued that it is worth the effort to extend the model of the atomistic rational actor and consider alternatives that include super-individual structures in attempts to develop an even wider understanding of social development and ecological sustainability. Again, space does not permit an elaborate discussion on this, but it is worth while to point to the insights obtained from the study of innovation systems, which indicate how innovations, and thus social change, are best understood not in isolation, but within the context made up by the joint efforts of a number of sectors or actor groups in society. Vollenbroek (2002), in discussing this problem, emphasises the pivotal role of such mechanisms in innovation toward sustainability. Using the terms *society pull* and a *shared future vision* he claims that innovation towards sustainability is not likely to be the result of some process of unguided technology push. To achieve a transition towards a sustainable economy, a shared future vision of the coherence between technological development, innovation, the workings of institutions and societal progress must be established. Actors sharing such a vision must represent all interests central in the social development process, policymakers/authorities at different levels, private businesses, different organisations, etc. Specifically, the political system must create conditions that attract private actors, who on the other hand must commit themselves to public goals. Such a shared vision may represent the framework that over time develops the embedded knowledge among the actors that is necessary to induce innovations toward sustainability. See also Fischer (2001). On the basis of this holistic view, the need to transform the energy system toward sustainability, together with the ambitious goals for cuts in carbon emission that are stated in many policy papers, can be viewed as elements in an increasingly shared future vision for energy use. What then is the practical contents of such a change process?

# 3 Changing energy use

Energy use in some form is implied by all activities in our modern societies. Direct uses are apparent in the transportation sector and for machines and processes in the industry, and for heating, lighting and appliances in homes and other buildings. We also demand energy indirectly through the goods and services we consume as participants in a global economy. Turning energy use from a dependence on non-renewable fossil fuel sources to a state of ecological sustainability therefore is a challenge that must be met across a broad range of sectors of society. This will involve most technological subsystems of the global energy system.

## 3.1 Principal strategies for sustainable energy use

In spite of this complexity, there are some principles or strategies for such a transition, that are valid across most sectors. These principles can be illustrated by the following four steps. *1) Reduce the need for energy*. This principle implies that basic structures and installations of society are planned and constructed such that energy need is minimal, given that the installations or technology deliver the services required by society. Low-energy or passive houses, buildings that deliver very substantial energy savings compared to traditional houses while maintaining amenities, are examples from the building sector that illustrate this principle. Principles for location and concentration of dwelling areas relative to commercial areas, systems for transportation of goods and people, are other important structures that affect energy need. *2) Increase energy efficiency*. Given the basic structures and installations necessary for society as described above, their services should be provided in an energy-efficient way. This implies that the required energy services are provided by energy technologies that minimise energy wastes. Domestic services, e.g., such as lighting, cooking and entertainment should be provided using A-labelled (or better) appliances, in many cases CFLs or other energy-efficient lamps should replace traditional incandescent light bulbs, and a low-flow shower head should be installed. The principle of energy efficiency thus implies, that within a given technological platform, the most energy-efficient technologies are chosen in providing a given service. Compared to some baseline situation, development of a social structure according to principles 1) and 2) implies that a given level of services to society is maintained, only in a less wasteful way in terms of energy use. Achieving further reductions in energy use implies a reduction in amenities related to the energy use. We could call this next level *3) Energy curtailment*. This entails that some reduction in comfort and service level from the installation is accepted in order to further increase energy conservation. To stay within the realm of buildings, examples of this principle include accepting a lowered indoor temperature in a situation where space heating is required, shorter, fewer and cooler showers, and reduced lighting. The principles described so far are generally applicable in order to achieve conservation of energy, which is important to achieve sustainability.

A fourth principle that addresses the fuel mix, applies in addition to the energy-related principles above: *4) Increasing the share of renewable energy*. In the long run, and independent of the level of energy efficiency and conservation achieved by the structural, technological and habitual principles described above, sustainable energy use requires a fuel mix in which renewable sources replace fossil and other non-renewable sources of primary energy. It is unlikely that renewables can be supplied in quantities and at costs that make possible a continuation of the current wasteful energy use that we have become accustomed to. The relative weights of the four principles above in achieving a truly sustainable energy system, will therefore be a result of a dynamic process of society setting political goals and frameworks for changes in the energy system, combined with developments in technologies and the different markets affecting energy use. These four proposed strategies for sustainable energy use can be regarded as valid principles for the development of any energy system.

These strategies are compatible with an ecological economic philosophy. Recognizing that *material* economic growth is likely to be limited by availability of natural resources, strategies that maintain the same level of economic welfare, but with less use of natural (energy) resources, can be regarded robust strategies. Strategies 1) and 2) are clearly such strategies. Producing more with less is a good resource husbandry strategy independent of paradigmatic position. Our near history, with plentyful supplies of fossil energy and little concern for the climate and general sustainability issues, has been paralleled with capacity expansions on the supply side as a main strategy for keeping up with increasing demand. An implication has been that we have locked in inefficiencies in our energy system, that is plain wastes of energy. We are increasingly becoming aware of the great potentials for energy efficiency that exist, and the significance of these strategies for achieving a sustainable energy future. Examples in this respect are the McKinsey report on the US Economy (Granade et al. 2009) and the Enova report on Norwegian industry (Enova 2009a). Both demonstrate huge potentials for profitable energy efficiency investments in the respective sectors, and thus support the robustness of the priority of demand side strategies proposed above. And clearly, supplying the demanded energy from renewable sources (strategy 4) will be less difficult with a reduced energy demand.

## 3.2 Barriers

The need to restructure energy use towards a sustainable future energy system entails the development of generally less energy-demanding structural solutions in society, including technological and habitual innovations that improve the efficiency in energy use, probably even with a resulting reduction of total energy demand, and a transition to renewable energy sources. In such a situation, there generally is a divergence between the socially desired energy behaviours[4] and the choices actually made by the different actors along the energy value chains. The socially desired behaviours are (implicitly or explicitly) defined by current (energy) policies and their operational instruments. Different barriers hinder the spread of the technologies and behaviours that society would like to see, and society often finds it worth to speed up this transition by the application of different policy tools.

However, many changes in energy behaviour, typically investments in energy related technologies, often including adoption of bioenergy technology, are profitable for an individual decision-maker from an ex-ante perspective also under the existing market conditions. Viewed as an isolated and purely economic investment problem, this means that the

[4] The term *energy behaviour* as used in this text refers to all actions and decisions made by a decision-maker (household, firm) that affect the stationary energy use of the decision-maker, and includes decisions and actions related to structure, technology, curtailment and heating system. The term includes the range of behaviours from investment behaviour to habitual behaviour.

discounted (present) value of all energy savings less operation/maintenance expenses over the lifetime of the investment equal or exceed the investment cost. Many such investment opportunities are still not exploited. This sluggishness in diffusion of many of these energy technologies is what has been known as the *energy paradox* (Jaffe and Stavins 1994). The energy paradox is a good starting point for understanding barriers to diffusion of sustainable energy technologies.

This problem was much discussed up to the 1990s, and its main points are discussed in a comprehensive article by Golove and Eto (1996). An important point of this discussion was the question if this observed behaviour (or lack thereof) is a result of some market failure, which needs to be corrected, or if it is the result of a perfectly rational choice made by the decision maker. Such rational reasons could be uncertainties regarding future energy prices and thus savings potential relating to the investment, combined with the irreversibility of many such investments. This implies the existence of an option value of postponing the investment decision. Adoption costs related to acquiring the relevant information and applying it to the concrete investment project are also often non-trivial, and could further explain hesitancy in adoption. Heterogeneity among the potential adopters in their economic and technical ability to take advantage of the investment is an explanation why some “energy actors” do not invest, even though the investment is profitable for the average energy actor. These explanations are all perfectly rational, and do not warrant any government intervention.

When market failures do exist, government should intervene. A direct externality related to the investment, is information. Once provided, such information is regarded a public good, which may be underprovided by ordinary market activity. The early adopters of the technology will, through use experiences, have to bear the cost of providing such information, which can become a positive externality for later potential adopters. The potential principal/agent problem between e.g. a landlord and a tenant, where the investor is different from the one who enjoys the savings, is another example of potential market failures relating to the energy paradox. (Ibid). Sorrell et al. (2004) expand this discussion further by placing it in a context of transaction costs and behavioural economics.

This introduction of the energy paradox serves two functions. First, it provides an implicit definition of the term *barrier* to sustainable energy use. A barrier is present when there is a divergence between the socially optimal energy solution and the solution chosen by a presumably rational energy actor. The proper identification and theoretical understanding of such barriers is a fundamental prerequisite for the government to be able to design effective policies to achieve the desired changes in energy use. Second, the discussion indicates that there could be more to the choice of energy solution than the pure economic rationality implied by the investment model that forms the basis for the energy paradox. In the following we will look at three approaches that help expand the purely economic reasoning to such behaviour.

### 3.2.1 Crossing the chasm

Let us follow up on the recognition that the potential adopters of a technology or other energy behaviour may constitute a rather heterogeneous group and relate this to the theory on innovations and their spread. The concept of innovation and the S-shaped diffusion curve was introduced in section 2.3, along with models of diffusion that focused on the technical and economic abilities of the potential adopters. We now turn attention to the insight to this problem that can be gained by looking also at the psychographic characteristics of the decision makers relative to a given innovation. Assuming some technical innovation and a suitable target group of potential adopters, Rogers (2003) relates the different stages of the diffusion process to different characteristics of the adopters. To illustrate these differences in psychographics he divides adopters in five groups. Sorted along the time scale these are: (i) Innovators, (ii) Early adopters, (iii) Early majority, (iv) Late majority and finally (v) Laggards.

Moore (2002) adds further insight to this model in his analyses of the diffusion of high-tech disruptive products (i.e. radical technical innovations). He postulates that there are gaps between the different categories or segments (i - v) of the target group, implying that diffusion does not proceed in a smooth fashion. Indeed, these gaps indicate that fundamentally different marketing or communication strategies need to be employed in addressing the different market segments, and that diffusion of such products almost never proceeds by its own force, even in situations where the innovators have started adopting. Specifically, Moore focuses on the challenges of bringing the innovation from the segment of Early adopters to the Early majority. The gap between these two segments is described as the *chasm* that needs to be crossed in order to achieve widespread mainstream adoption of the innovation.

To simplify while still maintaining the essence of the problem, the five different market segments can be grouped into two. The Innovators and Early adopters are classified as Early market. The Innovators are the gate-keepers to new technologies, interested in technology for technology’s own sake. The Early adopters are not technologists, but are able to imagine, understand and appreciate the future benefits of new technology, and can translate this insight into a strategic opportunity to “beat the herd”. Early adopters are risk-takers and often base decisions on intuition rather than rational analysis. An innovative and promising new technology thus often gets diffused in a limited Early market without too much marketing effort.

On the other side of the chasm lies the Mainstream market. Actors in these segments are characterised by pragmatism, problem solving, a risk-averse analytic “staying with the herd”-approach. (Egmond et al. 2006). Mainstream market actors need well-established references to consult before making the decision to adopt the technology/innovation. In other words, the mainstream market actors are hesitant to the innovation before it has become mainstream, but the innovation (or technology) can hardly become mainstream without adopters. It is this catch 22-situation that characterises the core of the problem of crossing the chasm, and that also illustrates the fundamental differences of the Early market actors and the Mainstream market actors. (Moore 2002).

This obtainment of peer references as a prerequisite for adoption is parallel to the market failure problem related to information discussed in the section on the energy paradox. In addition this approach introduces the importance of various psychographic variables in making the adoption decision and the issue of how the different segments along the diffusion curve differ on these variables. In fact, this approach to understanding diffusion of an innovation seems to emphasize such variables more than the economic and technical variables which formed the basis for heterogeneity in the discussion on the energy paradox.

Moore’s crossing of the chasm addresses the diffusion of high-tech and disruptive innovations. He brings up (psychographic) heterogeneity among the potential adopters of a technology as an explanation why diffusion occurs as often observed, and the mechanism of crossing the chasm consequently becomes an important barrier to adopting new energy technologies. Generalising this hypothesis, one can postulate a similar mechanism working among decision makers related to energy technology in both households, public and commercial buildings, and industry. A further interesting question is whether similar mechanisms are relevant for other energy behaviours than investment, such as efficient energy use and curtailment behaviour. These questions are still only hypotheses, but this approach to diffusion of innovations adds important insight and complements the model of the rational economic agent implied by the energy paradox.

### 3.2.2 Theory of Planned Behaviour

Adopting bioenergy and other energy technologies that contribute to a sustainable future energy system, is the result of decisions made by decision makers, either in municipalities, by owners of commercial buildings or by households. Following the arguments above, we have augmented the domain of such decisions from a basis in a purely economic rationale, to suggesting that "decision-makers" are much more heterogeneous and make decisions based on a much more diverse and complex rationale. However, we need to follow the hypothesis inspired by Rogers one step further: given that different decision makers end up at a different decision under a given circumstance, *why* do they do so?

To suggest an approach to that question we look at a much referenced model of planned behaviour by Ajzen (1991). This model aims at explaining the mechanisms behind a given behaviour and how the motivation behind the behaviour may vary among different individuals (and households). The *theory of planned behaviour* hypothesizes that a certain behaviour of an individual is strongly correlated with the intention to perform that behaviour. In this model intention represents the individual's readiness to perform some planned behaviour. There are three classes of variables that affect the intention to behave. First, there is the *attitude* to the behaviour. The attitude represents the individual's (subjective) evaluation of the behaviour in question, and may be favourable or unfavourable. Second, the *subjective norms* are the individual's perception of society's acceptance of the behaviour. If the purchase of an air to air heat pump is supported over a public programme, and the neighbours who have installed one speak of it in positive terms, then the behaviour of buying and installing a heat pump could be considered socially acceptable, even encouraged. Generally, the more supportive the perceived social norms are, the more likely will the intention to behave result in actual behaviour.

The third main category of variables affecting the intention to behave, is the individual's *perceived behavioural control* of performing the behaviour, in other words how easy one perceives it will be to perform the behaviour. Perceived control over the behaviour increases the more resources and opportunities the decision-maker perceives to possess, and the fewer barriers that are anticipated. Control beliefs which affect the perceived behavioural control could be past experience with the given behaviour, obtained information about other individuals having performed the behaviour, experiences with the behaviour by friends and neighbours, etc. Also other factors, such as technical and economic conditions, can

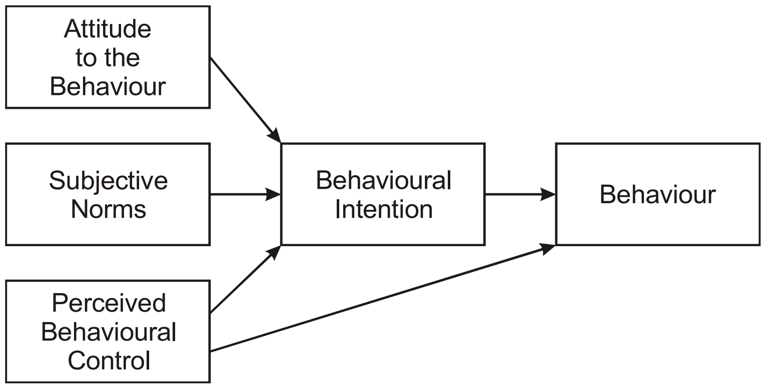


*Figure 2: Ajzen's Theory of Planned Behaviour*

affect how the individual perceives his or her ability to go through with the behaviour. Perceived control can also affect behaviour directly. This effect is assumed to reflect the actual control an individual has over performing a given behaviour. (Madden et al. 1992). See also Fishbein and Ajzen (2010).

Ajzen's theory of planned behaviour is not meant to represent the final answer to the problem of changing energy behaviour. However, being a much referenced and tested model in the behavioural sciences it adds insight to behavioural choice, its determinants and also gives a basis for policy instruments for behavioural change. Around a core of the Ajzen model, background variables related to demographics, economy, geography etc. add context that also affect behaviour. Stern (2000) emphasises the need of understanding the specific context and the danger of generalising when analysing "environmentally significant behaviour".

### 3.2.3 Technological lock in

Above we have discussed models that explain specific energy behaviour (or lack thereof) mostly on the basis of characteristics of the individual decision-maker. As a final approach to understanding energy behaviour we turn focus more on the system level.

The system level of household (or any other sector's) energy use of a country or region can be understood as a "superstructure" defined by various strategic factors. Climate and exposure to the powers of nature together with size and distribution of the population are important underlying determinants of the system. The stage of economic development and the level and distribution of disposable income further influence the demand for household energy services. The given endowment of natural (energy) resources in combination with the strategic energy technologies are instrumental in supplying the demanded energy services to the society. Together with long term energy- and R&D-policies, these factors represent a technological and social structure that defines the dominant rationale of household energy use in a society. Over time the energy system becomes embedded within the social fabric of society, giving directions to energy policies, technological development and micro level energy behaviour. The energy system can thus be likened to an "energy paradigm", with reference to Kuhn's (1970) description of the development of academic paradigms.

Unruh (2000) uses the term *carbon lock-in* to describe the central characteristics of the global energy system. Through a path-dependent process of co-evolution between technologies and institutions, driven by increasing returns to scale, a techno-industrial complex develops in which many sources of quasi-irreversibility emerge. The techno-industrial complex gives direction for research, development and diffusion of relevant technologies; policies and institutions reinforce the co-evolutionary process, and market actors adapt to the process in terms of developing preferences, expectations and routines that feed back and contribute to continued system dominance. Unruh's case is to demonstrate how the utilisation of fossil fuels in an increasingly global economy has become a process of fossil carbon lock-in in sectors such as transportation, heating and electricity production, a lock-in that is very costly and difficult to break out of.

A situation of technological lock-in can be viewed as a system framework for individual behaviour. Although individual choices are free to be made, they will always be affected by the social, technological and knowledge structures that describe the lock-in situation. This will be an important part of the context that embeds the Ajzen model discussed above.

## 3.3 Policy instruments

The various theoretical approaches to understanding central aspects of energy behaviour discussed above, help identify barriers to and determinants of desired energy behaviour. Different policy instruments are available to the authorities to help overcome barriers, stimulate behavioural determinants and thus induce the desired behaviours. There are alternative ways of categorizing the available instruments. One central distinction goes between command-and-control (CAC) and economic instruments.

Command-and-control implies that behaviour is achieved through direct regulation, usually legislative, in the form of appliance standards, building codes, bans, certifications etc. Banning of certain heating technologies (e.g. oil stoves) and mandatory hook-up to the local district heating grid are examples. Although potentially effective, direct regulations usually do not guarantee an efficient allocation of resources, and some instruments of this type carry significant costs also in terms of monitoring/control and enforcement.

Economic instruments are motivated by their ability to achieve a certain aggregate behaviour through voluntary choice by the economic actors (households). One form of economic instruments are incentives, which work by altering the relative prices or costs of the behavioural decision, increasing the perceived behavioural control, thus inducing the behaviour in question. In economics this academic debate can be traced at least back to the classic works of Pigou (1932). Taxes, subsidies and grants are examples of such instruments. Another form of economic instruments are market-emulating instruments such as tradable permits/quotas and green or white certificates. With these economic instruments the target behaviour can be reached on the basis of optimising behaviour among the economic agents, thus improving the cost-efficiency of the programme. Although more efficient from the viewpoint of society, however, economic instruments are generally less effective in meeting a quantified target relative to CAC-instruments. (Baumol and Oates 1988; Jaffe et al. 2002).

Information and voluntary action programmes represent a third broad category of policy instruments. These instruments can be aimed at altering a momentary purchase decision (labelling, energy rating) or they can have a more strategic perspective aiming at developing the preferences of the decision makers toward inducing the desired behaviour as a rational "voluntary" behaviour. In other words, attitudes and norms important to a certain behaviour, can be affected. General awareness raising, school- and professional education programmes and information campaigns are examples of such instruments. (Egmond et al. 2006). The challenge for the policy makers is to design the optimal mix of these policy instruments, as described by Uitdenbogerd et al. (2007).

# 4 Illustrations

Thus far we have discussed the important framework for the diffusion of bioenergy technology into a modern energy system. This discussion has included fundamental ontological questions concerning society's relationship to the natural environment, the challenges emerging from society's increasing dependence on fossil fuels, and important elements of theories aiming at understanding barriers to such a desired development, in addition to a brief discussion of different policy instruments available to help reduce such barriers. This is the reference framework for the subsequent concrete research articles. In this section we give some practical illustrations of how this challenge can be framed.

Following the increased focus on climate change from the mid-2000s, ambitious visions and goals regarding GHG emissions and energy use have been formulated. Most noteworthy is the European Commission's 2008 commitment to the "202020"-vision, which entails a goal to reduce greenhouse gas emissions by at least 20 % and to increase the share of renewables in the energy mix to 20 %, all by 2020. Similar national goals have been formulated. Sweden shall reduce GHG emissions from domestic sectors by 40 % and achieve a 50 % renewables share by 2020 (Miljödepartementet 2009). In Norway, the goal is to achieve a 30 % cut in emissions by 2020 and carbon neutrality by 2050 (Miljøverndepartementet 2007). The key issue then is *how* to reach these ambitious goals by changing the energy system and attaining long term sustainability, and it is this issue that is being addressed in this thesis. For illustration a brief review of national policies and programmes in Sweden and Norway in this area, leading up to the new ambitious goals and focusing on bioenergy diffusion, is presented.

## 4.1 Bioenergy in Sweden

Sweden has become regarded one of the pioneers in the innovation and diffusion of bioenergy technologies. Although these changes have occurred in several areas of the Swedish society, they have been most prominent in the district heating sector. During the 30-year period after 1980 we have witnessed a radical restructuring of the Swedish district heating market. From a situation with an almost total dependence on fossil fuel-oil in the late 1970s, this sector has developed into a state in which solid biofuels represent the base fuels for the sector. In this period the total fuel use in this sector grew from 22 to near 60 TWh, while biofuel use increased from around 2 to 42 TWh, now constituting 70 % of total fuel consumption (STEM 2001, Energimyndigheten 2010).

The motivation for this policy has varied somewhat over time. A major trigger of the development of an explicit energy policy in Sweden was the oil crisis in 1973. A result of this event was that oil supplies to the world market were restricted and the world market oil price increased substantially. This demonstrated to the Swedes that imported oil had become a strategic resource, reflected by the many vital social functions that depended on the supply of this resource. It also was a manifestation that the supply of this resource was beyond national control. (Hillring 1998). A new energy policy was designed, mainly based on taxation, which aimed at substituting fuel-oil by alternatives that were less intertwined with world politics. The result was that oil consumption in the district heating sector was substantially reduced during the 1980s, while coal and biofuels were in growing demand. Climate change did not become an important driver in Swedish energy policy until later in the 1980s, and all fossil fuels were imposed a $CO_2$-tax in 1991. In addition to taxation, instruments such as investment subsidies for a general expansion of the district heating grid, combined with specific support for solid fuel boilers, were important in this development, but also efforts in R&D, particularly related to extraction, handling and combustion of wood fuels, have been central instruments. See Bohlin (1998) and Hillring (1996) for more comprehensive analyses of policy instruments applied in Sweden to stimulate the development of biofuels use within the district heating sector and NUTEK (1995) for a more general analysis of Swedish energy policy and instruments. See also Summerton and Björk (1992). Space does not permit a discussion of related and relevant policies aimed at combined heat and power production, the 2003 Swedish green certificate system, the EU greenhouse gas emissions trading scheme, and programmes aimed at the household sector.

This short review of Swedish energy policies towards the district heating sector during the last 30 years has been given to illustrate a number of important points that are highly relevant relative to the more theoretical discussion of sustainability and social change presented in chapters 2 and 3. First, undertaking such large scale and fundamental changes in energy infrastructure is in fact possible. Although changes in the way we burn wood and wastes to heat water are not particularly “sexy” in our age of nano- and electronic technologies, the long chain of innovations necessary to supply forest based fuels in a large scale and in an increasingly cost efficient way, represents significant innovations along the dimensions of climate neutrality and ecological sustainability. However, although significant innovations have been made, the fact that biofuel based combustion technologies are easily compatible with the existing district heating infrastructure is an important prerequisite for the magnitude of this success. Improved bioenergy technology thus represented, in many respects, incremental innovations of the existing oil-based heating system. Radically new energy technologies and systems would be much more difficult to deploy in the magnitude and speed we have witnessed in this case.

The second important observation is that the political and economic framework is an important driver of this process. Although the basic motivations for the restructuring of the district heating sector has changed, from security of supply to climate change, partly also the phase-out of nuclear energy, the long-term practical solution to the challenge has remained fixed in the form of bioenergy technology. The political goals have been clear, and the different policy instruments have all pulled in the same direction. In sum this has represented relatively stable, long term and predictable framework conditions for private energy investors, utilities, R&D actors, financing institutions, households and other relevant actors.

## 4.2 Heating in Norway

Although similar to Sweden in many respects, Norway differs from its Scandinavian neighbour in several energy-related areas. The section above described how the Swedish transition toward bioenergy solutions over the last 30 years has been motivated mainly by the climate challenge, but also security of supply and public and political will to reduce nuclear capacity have been important drivers. The primary characteristic of Norwegian energy use is the intensive use of electric energy. This situation has historical roots; ample waterfall resources have made possible a growing stock of hydropower installations during the 20’th century together with a power-intensive industry that became an important instrument in the modernisation of the Norwegian society. Also households and the service sector benefitted from the expansion of the hydropower capacity in the form of a secure supply of inexpensive electric energy. One important effect of this development is that heating solutions in homes and buildings in general often were based on direct heating technologies. And consequently, district or local heating networks and hydronic heat distribution systems in buildings are rare.

The need to break this “lock-in” is motivated by two main reasons. First, during the 1990s and 2000s, Norway came in a situation with a tightening supply/demand-situation for electric energy. Most remaining waterfall resources are protected for environmental reasons, thus the era of the large hydropower development projects is over. Since the supply of hydropower in a given year varies with the seasonal precipitation, there were winters such as 1996/97 and 2002/03 when the domestic supply of electricity was insufficient to maintain the low price which the society has become accustomed to. The resulting fluctuations and increases in the electricity price triggered a wide public debate around this dependence on electric energy. The 1990 Energy Law had mandated a deregulation of the Norwegian electricity market, which came to effect in 1991, and had as one of its purposes to reduce such fluctuations through trade of electricity. This, together with the establishment of a common Nordic market for electric energy in 1996, did not fully cancel these fluctuations, since precipitation variations seem to be quite similar across Scandinavia. Increasing capacity for electricity exchange between Norway and continental Europe is further dampening these weather-related price variations, but has the added effect of reducing the difference between the traditionally higher electricity price on the European continent and the lower Norwegian price. Norwegian demanders are thus forced to face a higher electricity price and a new logic in terms of energy use.

The climate threat is the second argument for reducing the electricity dependence. The establishment of the Nordic, increasingly also European, market for electric energy, implies that the Norwegian production system no longer can be viewed as a separate and isolated system. Although Norwegian hydropower is carbon neutral and renewable, the marginal production in the European electricity system is likely to be fossil-based. A unit of Norwegian hydro-power saved can thus be exported and replace a unit of fossil-based power in this larger system. Reducing demand for electric energy in Norway, for instance by energy efficiency measures or by reducing demand for heating based on electricity, will therefore be a positive contribution to combating climate change. As a result of these arguments, reducing the demand of electric energy for heating has become an important issue in Norwegian energy policies, and the increased use of bioenergy is a part of the answer to this challenge.

There exists a "natural base" for bioenergy use in Norway. This more traditional consumption is related to use of firewood in homes and internal wastes for heat production in sawmills and other wood processing industries. According to official statistics, this use of bioenergy has been around 10 – 12 TWh annually during the 1990s. Typically 4 – 5 TWh were used in the industry, the rest for traditional heating in households. The issues around climate, energy supply and bioenergy entered the political discussion in Norway during the 1990s[5], and implied a need to develop and adopt more modern bioenergy technologies than these traditional ones.

In 1999 the government published a white paper on energy (OED 1999). This was the first real political manifestation of the necessary paradigm change in Norwegian energy policy. It stated as an overarching goal for Norwegian energy policy to limit energy consumption significantly relative to an unchecked development. Further, it quantified goals for energy use in terms of increasing the use of water-based (hydronic) heat distribution systems based on production from new renewables, heat pumps and waste heat by 4 TWh and deploy wind-power installations with an annual production of 3 TWh, all by 2010.

Bioenergy is part of the solution to this challenge, and since 1997 there have been public programmes aiming at increasing the diffusion of bio-energy technologies. The first programme was administered by the Norwegian Water Resources and Energy Directorate (NVE). In 2001 the

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[5] This development is illustrated with a few examples: St.meld. (White paper) 41 (1994-95) is the first document on climate, and is a response to the initial work of the IPCC. St.meld. 38 (1995-96) on natural gas based electricity production, NOU 1998:11 On the energy- and power balance toward 2010 and St.meld. nr. 29 (1997-98) on Norway's response to the Kyoto protocol, all discuss bioenergy as part of the climate and energy supply challenge. Then, in 1999, the fundamental White paper on energy policy (St.meld. 29 (1998-99)) was published. Bioenergy and the climate issue has subsequently been addressed in St.meld 54 (2000-2001) and 15 (2001-2002) on Norwegian climate policy. The report from the low emission commission (NOU 2006:18) claims that it is necessary, doable and not excessively expensive to reduce Norwegian climate gas emissions by 2/3 by 2050. In St.meld. nr. 34 (2006-2007) on Norwegian climate policy it is stated a goal to increase the utilisation of bioenergy by up to 14 TWh by 2020. The goals in this paper have been reinforced in a political "addendum" to this White paper, which was signed in 2008 by all but one of the major political parties in the Norwegian parliament (Klimaforliket).

state-owned enterprise Enova SF was established. Enova's purpose is to be the operating agency for implementing these energy-political goals, and it is owned by the Norwegian Ministry of Petroleum and Energy. Enova is the main instrument for designing and implementing programmes for stimulating a marked-based and efficient transition of the Norwegian stationary energy system by addressing both the supply side (new technologies, including wind-power, district heating networks and heating centrals) and the demand side (industry, commercial and public buildings, and households). Enova's activities are financed over a public energy fund and by a grid tariff. Being quite successful, Enova's ambitions in terms of energy result (savings and conversions) were risen from 10 to 12 TWh in 2005 and subsequently to 30 TWh by 2016 (OED 2006).

Enova's portfolio towards bioenergy has addressed larger scale projects on (i) heat production based on renewables, including biomass, (ii) heat distribution systems and (iii) biofuel upgrading facilities (pellets, briquettes). A household subsidy programme was launched in 2003, which gave economic support for investment in pellet stoves. Enova's programmes are periodically evaluated and adjusted in response to the market conditions. It is estimated that these public programmes for the diffusion of bioenergy technologies have triggered private and public investments that represent an annual contribution of around 3 TWh of new bioenergy and waste based heat production by 2008 (Enova 2009b).

# 5 Conclusions – what is learned?

There are three main “red lines” running through this thesis. First, there is the concept of *sustainability*. At a general level this concept is multidimensional and both could and should be understood from ecological, social, cultural and other approaches. In this document it is the ecological dimension that is emphasized; a main hypothesis is that ecological sustainability is a necessary fundamental characteristic of the energy system of the future. A second main line is *bioenergy*. In the principles governing the energy system of the future, bioenergy will be one important element of a much more efficient, diverse and robust energy system. In this work, key parts of the value chain of bioenergy from the standing forest to household end use application are analysed. At the same time, the ecological limitations to bioenergy use must be recognised. The third red line is the need for *societal change*, that is the changes in technological, economical and social structures that are necessary in order to transform our current fossil fuel based energy system into a more efficient and renewables based system. Understanding innovation processes and the complex actions of economic actors is central in this process.

The issue of ecological sustainability is fundamentally important. A main message is to emphasize the likely limiting role of fundamental system functions of the biological and physical environment, including the climate system. On this basis, it is of importance to distinguish the current dominant growth paradigm from a potentially alternative paradigm of sustainability. These world views have, as discussed above, incompatible methodological approaches to issues such as substitutability vs. complementarity between natural and human made capital, and to the economic valuation of the functioning of complex ecological or geophysical dynamic systems. These differences in world view have consequences for policies and management systems for natural resources.

There are four research papers attached to this thesis. They will now be briefly discussed and related to the overall research context of this thesis.

**Paper I: An engineering economics approach to the estimation of forest fuel supply in North-Trøndelag county, Norway**

There seems to be a basic logic in the sequence in which wood based raw materials enter the heating market. Wood wastes and secondary products from wood processing and other industries are usually the first choice of wood fuels. These fuels are often inexpensive, have a sufficient quality, and are suitably located for energy utilisation. When the sources of these low cost fuels are exhausted, the next step seems to be to enter the forest for the extraction of fuels. Both Sweden and Finland have developed fuel extraction technologies based on the idea of a tight integration between traditional forestry and forest fuel harvesting. In parallel with the development of the fuel harvesting technologies, we have observed a steady reduction of the real price of forest fuels in the Swedish market.

Paper I presents a study aimed at estimating the cost structure for a similar production of forest fuels in North-Trøndelag county, Norway. Since this production is largely absent in the region today, we had to infer the relevant cost structure from the existing traditional forestry production, and based on certain assumptions regarding production technology. Thus, the study attempts to find the hypothetical supply curve for forest fuel production in the county based on the existing production technology, that is without "importing" the specialised technology that has been developed in Sweden and Finland. There are two reasons for making such assumptions. First, both the relatively small scale ownership structure and the topography of the North-Trøndelag forest make instant transfer of such technology an unjustified assumption. Second, it is a point in itself to demonstrate the economic performance of the existing technology as a basis for a joint timber and biofuel production, since this technology is likely to be used in the early phases of North-Trøndelag forest fuel production.

The starting point for the analysis is to describe the current forestry system, specifically in terms of volumes of potential annual harvest (final felling, thinnings, low quality trees, and hardwoods), distributed by harvesting technologies (manual harvesting, mechanised harvesting and winching). Adjustments of these technologies to accommodate forest fuel production was specified, resulting in an engineering economics production function of the forestry in the county. With the aid of biomass functions and market prices for relevant production inputs, this model estimates the supply curve for forest fuels as a collection of a large number of small segments of quantity and marginal cost-combinations.

Some interesting findings may be extracted from this cost model. First, the marginal cost level for production of forest fuel in North-Trøndelag is, with the assumptions in this model, in the same ballpark as the observed Swedish market price for forest fuels. However, only 25 % of the available amount of forest fuel in North-Trøndelag would have been produced profitably given Swedish forest fuel market prices. Second, we find that the most cost-effective way of producing forest fuels is within the manual harvesting technology. This is the technology where integration between timber and forest fuel harvesting is obtained most easily. The assumptions underlying this model imply substantial potential for innovations in more cost-efficient, and perhaps locally adapted technological solutions for joint timber and forest fuel harvesting.

### Paper II: Forest fuel or carbon sink? Aspects of forestry in the climate question

In the second paper we take a more theoretical view on the role of forests in light of the climate question. In the study referred to above, "An engineering economics approach to the estimation of forest fuel supply in North-Trøndelag county, Norway", the implicit view on the role of forest fuels relative to energy and climate has been as a substitute for fossil fuels in the production of heat. In other words, to reduce the emissions of $CO_2$ from combustion processes. Extending the scope of the climate problem opens for one more important aspect. The concentration of atmospheric carbon is a function not only of emissions, but also of the amounts of carbon withheld or fixed in biomass and other materials. Forests thus play an important role in addition to the role as supplier of renewable "carbon-neutral" energy, namely the role as carbon sink. An expansion of forests, either by increasing the areas covered by forests or by increasing the standing volumes of existing forests, implies an increase in fixed non-atmospheric carbon and is a positive contribution towards the climate problem. Exploring these different roles of forestry is the subject of this second article.

Commercial forestry is usually viewed as a capital management problem, with the basis in a biological forest growth (production) function, which is assumed (with strong empirical support) to eventually display a diminishing marginal product over time. With given assumptions regarding prices, costs, and discount rate, the forest owner's decision problem is when to cut the forest in order to maximise the present value of an unending sequence of plantings and cuttings. The solution to this problem is the classical Faustmann formula, and it represents the reference starting point for our analysis.

We expand this forestry problem in two steps. First we add the value of the fuel biomass, which is not considered part of the production function in the classical analysis, by developing a joint timber and forest fuel production function. The functional relationship between the timber only and bioenergy raw-material growth functions is based on the same biomass functions as used in paper I. It follows from the theoretical analysis that the rotation length will decrease within the joint timber and forest fuel production, compared to the timber only production. This is mainly due to the fact that the share of energy biomass decreases relatively to the timber part as the tree grows. A numerical simulation model based on North-Trøndelag data, indicates that this reduction in rotation length is not dramatic, usually less than five years. However, and this is the main point, the gains that are obtained relative to the climate problem by the supply of renewable forest fuels, are diminished by the reduction in forest carbon storage that is also implied by the shortened rotation length. Thus, the use of forest fuel as substitute for fossil fuels comes with a cost in terms of reduced forest carbon storage.

The second augmentation of the forestry model is an attempt to include also the carbon value of the standing forest. Assuming some market price for carbon storage (which could be derived from, e.g., the emissions trading system), this can be modelled as a payment flow to the forest owner which is proportional with the change in forest biomass. This payment is positive as long as the forest is growing, and negative when the forest biomass decreases, e.g. when it is harvested. There is also an element in the model to capture the degree to which the harvested biomass goes into permanent structures, thus postponing the release of the fixed carbon. This carbon storage element of the expanded Faustmann forestry model works in the direction of extending the rotation length of the "multi-functional" forestry modelled here. Moreover, compared to the effect of the forest fuel extension only, the optimal rotation length seems to be much more sensitive to parameter changes relating to the carbon storage payment addition. Indeed, within the range of perceived reasonable parameter values, optimal rotation lengths may be extended to values that in practical terms mean that the forest should not be harvested.

In order to obtain a socially optimal resource allocation, one must make sure that the economic actor is faced with all the relevant parameters in the decision making process. Based on our theoretical and numerical analyses of the climate-expanded forestry model, we have shown that the forest owner's decision becomes much more sensitive to changes in the economic environment compared to the timber only model. Such a situation, with a potential for a greatly fluctuating supply of forest raw materials, would represent a challenge to both the wood processing industries and the forest fuel-based energy industry. Thus, the design of policy tools to include the value of carbon storage in the forest owners' parameter set is also a challenge.

The two last papers move us from the forest to the end users of bioenergy, namely the district heating sector and the households. In both papers a focus is on understanding the motivation of the early adopters in emerging markets for bioenergy technologies.

### Paper III: Early adoption of biofuels in the Swedish district heating sector

After 1975, there has been a remarkable diffusion of bioenergy technology in the Swedish district heating market. This has been due to an increase in the total annual volume of heat produced in this sector from 22 to around 60 TWh and an increase in the share of biofuels from 5 to 70 %, statistics referring to the 1975 to 2009 period. Relative to the climate issue, this seems to be a remarkable development. The aim of this paper is to gain understanding of the early phase of this process in light of the theories of social change discussed above.

Looking more closely at this process of early adoption of biofuels, we observe that development of bioenergy systems and technology was not a given outcome of the restructuring of the district heating sector that took place from the late 1970s and onwards. The current focus on climate change as a main premise for the development of energy systems, was not present at that time. The Swedish heating sector grew increasingly dependent on imported fuel oil during the post-war period, the consequences of which became clear during the oil-crisis in the early 1970s. A reduction of this dependence became a paramount goal of the energy policy, and by the end of the 1980s this goal had been achieved. Bioenergy entered the fuel mix in the district heating sector as one of several alternatives to fuel oil, among which another alternative was coal. The adoption of biofuels in the district heating sector in the 1980s was thus not due to explicit policies aiming at this particular category of fuels, but more a result of a policy to reduce the use of imported oil. It was not until the late 1980s, and through the implementation of the carbon tax in 1991, that the climate dimension entered the Swedish energy policies, and biofuels were preferred over fossil fuels in general.

Is then the expansion of biofuel use in the Swedish district heating sector a truly radical innovation? Partly yes, but it seems clear that it would be difficult to achieve these results without the existence of the (large scale) district heating grids and their subsequent expansion. In this respect no really new system innovations have been made here. Further up the value chain, however, in the harvesting and logistics system, radical innovations have been made in order to fundamentally change the fuel logistics of the district heating system from one based in the international oil trading system, to a system integrated with the domestic forestry industry supplying renewable resources to the district heating sector. As mentioned, 60 TWh of heat is now produced annually from biofuels in this sector. From a sustainability and climate perspective, therefore, the technical innovations in this value chain must be characterised as radical.

A second perspective that should be mentioned in this respect, is the role of policy. This case is a good example that it is in fact doable to induce radical changes in a basic infrastructure of a modern society. A clear and long term energy policy with a dynamic mix of suitable instruments has been the backbone of this change process. Long-term security of the direction of development has further stimulated the active involvement in this process of other actors and stakeholders such as heat plant owners (private and municipalities), finance institutions, R&D institutions, the forestry industry and their supply industries, etc. A strategic innovation system has been created around the value chain of the district heating sector, producing the results we see now.

### Paper IV: Diffusion of renewable heating technologies in households. Experiences from the Norwegian Household Subsidy Programme

The last paper looks into the diffusion of bioenergy heating technology at the household level. In section 3.2 above, barriers and theoretical perspectives that help explain household energy behaviour (or lack thereof) are explored. A central hypothesis in this discussion, following from the energy paradox, is that traditional economic rationality only is an insufficient explanation of energy behaviour in households. In this paper, this and related hypotheses are tested using household survey data from Norwegian households who have been participating in the Household Subsidy Programme in 2003, investing in pellet stoves and heat pumps. The purpose of this programme was to introduce electricity-saving heating technologies to the household with the use of an economic subsidy. Ex-post evaluations of this programme have precipitated a set of data in which households report on their satisfaction with this investment, together with data on savings and costs, technical issues and user experiences, attitudes and demographics, among other.

These households, the early adopters of pellet stove and heat pump heating technologies among Norwegian households, report overall high satisfaction with their investments. In spite of the fact that heat pumps showed a much better performance in terms of economic profitability than did pellet stoves, no difference can be detected in the reported investment satisfaction of the two household groups purchasing the respective technologies. The observed (calculated) return on investment is therefore not explaining the investment satisfaction among these households. This is not implying that economics does not matter. The analysis shows that the development of the electricity price is a significant explanatory variable for investment satisfaction, a higher market price for electricity tends to increase the satisfaction with the investment.

In addition to the market price, the analysis shows that other important variables in the households' assessment of an energy technology investment, are (i) the overall technical quality of the equipment, that is that it works as intended, (ii) availability of and good service by the supplier of the pellet stove/heat pump, and (iii) the improvement of indoor climate and heating comfort experienced after installation of the new equipment.

What this empirical analysis illustrates, is that the barriers to desired energy behaviours in the households are multidimensional, and that programmes such as this one must address all those barriers simultaneously. The monetary grant or subsidy lowers the economic barrier, increased knowledge on the technology's pros and cons can be achieved through an information programme, the availability of the technology and related services can be assured through a supply side programme. A broad portfolio of instruments thus seems to be necessary in order to achieve success of household energy behaviour change programmes.

Finally, if one is to take a step back, what are the main conclusions from this work? A fundamental premise seems to be that it is necessary to recognize that a better integration between natural and social systems must come about. Long term sustainability of society requires that the demands of the global economy better reflect and adjust to the limits represented by the ecological system. For the energy system this entails first of all a more efficient energy use, that is a society built to stimulate lower demands of energy in combination with diffusion of more efficient energy technologies. Conceptually simple, these needed innovations unfortunately seem to require radical changes in the complex economic, technological, political and cultural world views that have been the driving forces of the development of our modern society. Renewable energy sources, including bioenergy, is part of this solution. However, no energy-technological panacea seems to exist in this regard. Large-scale bioenergy systems in themselves represent both real and potential negative impacts on local and regional ecosystems. Further, biofuel raw materials that have alternative uses or compete for land and other resources with alternative productions, such as food, represent difficult ethical dilemmas that already have surfaced in the public debate. Other renewables, such as hydro-, solar- and wind power installations, also trigger opposition that is based on real arguments, not just NIMBYism. A general consensus seems to have developed, by which the current fossil-dependent global energy system must be replaced, both for reasons of climate change and long term resource availability, but the long term outcome of such a consensus is far from clear. The design of this future energy system seems to be characterised by a scaling down and increased degree of distribution of the production capacities, increased degree of communication, manageability and flexibility of the demand side, based on locally adapted renewable energy technologies and in close integration with ecological and social systems. Significant efforts in R&D in areas of technological, environmental and social/behavioural innovations will be needed to reach that state.

In a Scandinavian context, forest resources are the primary source of biomass for energy use. Integrated with the existing strong forestry industry, important progress has been made in the area of harvesting, logistics and upgrading of forest fuels in the form of residues and thinnings. The primary use thus far has been, as indicated by this thesis, for heating purposes in district heating, local heating systems and in single houses. Technical innovations and cost reductions over time have made this a logical extension of the forestry value chain. The multiple role of forestry in the climate question was discussed in paper II, with particular focus on the role of the forest as carbon storage. A related important issue is how the forest biomass resources are best used. Technologies for production of second generation biofuel from forest biomass is under development, making use of forest biomass for transportation purposes a competitor for the current heating uses. This illustrates some issues related to the future energy system.

Above, the need for fundamental changes in the way society produces and uses energy in the future was briefly discussed. Examples exist that demonstrate that such changes are in fact obtainable. The case of the Swedish district heating sector is illustrative in this respect. A large scale transition from an almost entirely fuel-oil dependent heating system to the current system with a much more diversified fuel mix dominated by renewable fuels, demonstrates that such fundamental systems of a modern economy may be restructured towards sustainability, given the political and economic will and accompanied by a suitable mix of natural resources and knowledge. Jacobsson and Johnson (2000) use the increased utilization of biofuels in the Swedish district heating sector as a case in their discussion of the innovation system perspective as a necessary approach to understand such fundamental techno-economic changes. This perspective gives more attention to superindividual structures and contexts as prerequisites for understanding human action and social development, than what is implied in the methodological individualist model of social change. The ability to change perspectives between the micro level actors (firms and households) and their behavioural drivers and barriers, and the system level, including strategic political and institutional development, R&D, policy instruments, etc., is a key to this transformation. The dynamics between these two perspectives defines the strategic innovation system which, if successfully designed and developed, will induce micro-level innovations and behavioural changes that are in line with the long term goals of the larger social system. Understanding and designing such social processes is a research field where much remains to be explored.

The concept of energy behaviour is used to describe the actions of firms and households that affect the energy use at the micro level. In the Sweden district heating case we saw how the early adopting plants seemed to follow the relatively straight forward logic of choosing the most cost-efficient fuel mix in a situation where coal and forest fuel were the main alternatives. In households, the energy behaviour seems to be much more complex. To induce changes in energy use at the household level so as to reduce energy intensity and increase the share of renewables, will involve a broad range of end uses (lighting, heating/cooling, cooking, washing, entertainment and so on) and a wide range of behaviours (from big investments to small daily habits). The household sector is a significant sector in terms of energy use, thus substantial changes in energy behaviour must be obtained in this sector in order to reach sustainability goals. The statement saying that economics is not the only, or perhaps not even the most important, choice variable in an energy behavioural decision in households, is no longer controversial. In addition to economic variables, a range of psychological and social determinants affect such choices, in addition to contextual and institutional determinants. The analysis of the diffusion of pellet stoves in Norwegian households reveals only a small piece of this complex research area. The sluggishness of behavioural change in households is a source of frustration for policy makers, since this is a sector with large potential and where these energy potentials can be reached with more or less “off the shelf” technologies. For a current update on key issues in this field one could consult Owens and Driffill (2008), Steg (2008) and Uitdenbogerd et al. (2007). Improved understanding of household energy behaviour and how to better design and implement behavioural change programmes is thus expected to become an even more active research field in the coming years.

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