Doctoral theses at NTNU, 2010:220

Thomas Martinsen

Technology learning in a global – local perspective

- the interplay between technology diffusion, niche markets and experience curves

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Technology learning in a global – local perspective

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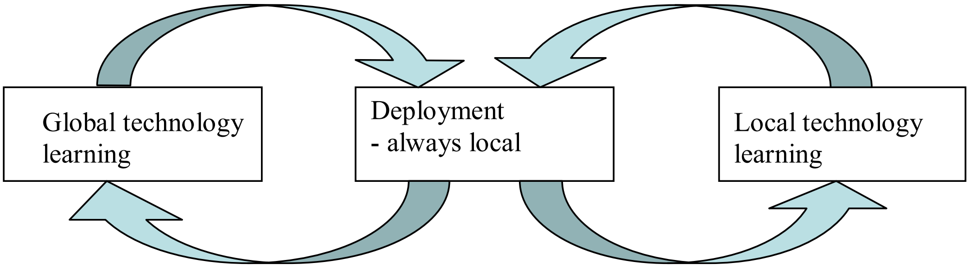
The price of new energy technologies in the Norwegian market, and thus the most cost efficient technology composition of the future Norwegian energy system, ultimately will be heavily influenced by the selections made in the international energy system and the corresponding development of the international energy technology market.


Global technology learning
Deployment
- always local
Local technology learning

Abstract

Preventing dangerous global climate change requires timely deployment of nascent energy technologies with zero or low CO_2 emissions. Managing the shift to a common sustainable technology path calls for insight about the influence of global technological change on the national energy system. Moreover, national policies are required to promote the shift to the new technology path. This calls for methods to analyse the national energy system within a global perspective. The objective of the work presented in this thesis was to investigate interplay between technology diffusion, niche markets and technology learning from the perspective of a small open economy like Norway. More specifically, develop methods to include the influence of technology learning manifested in experience and learning curves into *national* energy-economy-environment models. Moreover, apply the methods to investigate the potential influence and sensitivity to technology learning in a small open economy. In this thesis three such methods have been developed, applied and its importance assessed using Norway as an example.

In this work three models have been linked. They are the global Energy Technology Perspectives model operated by the International Energy Agency, the Norwegian Markal model at the Institute for Energy Technology and the macroeconomic model MSG6 at Statistics Norway. Method one and two has been developed to manage the interplay between the models. In a local perspective technology learning in the global market is perceived as spillover[1]. Based upon a review of the characteristics' of technological change and learning curves and its application to energy system modelling some criteria important for the parameterization and modelling of spillover in a small open economy are suggested. The first method incorporates spillover into the national Markal model. The second method establishes a soft-link between the national models. The soft-link served two purposes; to provide input on demand for energy services to the Markal model and to carry forward the influence of spillover into the MSG6 macroeconomic model. With the soft-link it is possible to investigate feedback on demand for energy service from the non-energy sectors of the economy at a sector level. Finally, a method to evaluate technology specific national policies to the realization of a global scenario is suggested.

The assessment shows that the national technology composition and CO_2 emissions exhibit sensitivity to spillover and thus the global scenario. Moreover, spillover may generate substantial benefit for a small open economy like Norway. Without the spillover from international deployment a domestic technology relies only on endogenous national learning. However, with high but realistic learning rates offshore floating wind power may become cost-efficient even if initially deployed only in Norwegian niche markets. The influence of spillover on the non-energy sectors, though modest, is most pronounced on the industrial chemicals production. Implementing a technology specific policy, e.g., a feed-in tariff in response to an EU directive in addition to spillover and the general CO_2 incentive, increases early deployment.

The elucidation of the application of spillover on the *national* energy system analysis in a globalized energy technology market and the combination of spillover and a *national* soft-linked hybrid model, exchanging information at a sector level, and adds new elements to national policy analysis. Moreover, the exertion to coordinate national efforts with a portfolio of globally desirable low-carbon technologies provides a new indicator for the national contribution to a shift in the global technology path.

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[1] Spillover in this work is the effect of technology learning embedded in the technologies purchased in the global technology market, i.e., cost reductions and efficiency improvements resulting from accumulated global production.

Preface

This thesis is in the interdisciplinary field of energy, economy and environmental modelling. The discussions centre around an effect named *technology learning*. The term covers all those processes contributing to the cost reduction and performance improvement of a technology in a competitive market. The study involves both a so called "top-down" macroeconomic model and the "bottom-up" systems engineering models. The thesis includes three papers submitted to scientific journals. The original papers, referred to by their Roman numerals I – III, are located at the end of the thesis.

Advisors

Principal advisor: Prof. Edgar Hertwich
Co-advisors: Prof. Emeritus Clas-Otto Wene and Adjunct Prof. Per Finden

Acknowledgement

In particular I would like to thank Professor emeritus Clas-Otto Wene for guiding me with a soft touch while offering his extensive knowledge in the field of energy systems analysis and technology learning, and my principal advisor Professor Edgar Hertwich for his encouragement and comments, overall guidance and making my study flow smoothly. My head of department at IFE, Adjunct professor Per Finden for making it possible and supporting the process from idea to completion. I thank my colleague Audun Fidje, for fruitful discussions and answering my many questions regarding the Norwegian Markal model, and my colleagues Mads Greaker, Marina Tsygankova and Geir H. Bjertnæs at Statistics Norway who provided data from- and insights about the MSG6 model. I have been fortunate to get detailed global data from the IEA Energy Perspectives Model, and without the generosity of Dr. Dolf Gielen this analysis could not have been done.

I would also like to extend my thanks to the systems analysis team at Kings College London, particularly Dr. Neil Strachen, for fruitful discussions during my stay as visiting researcher, and Niclas Mattsson always giving helpful answers about the ETP modelling. StatoilHydro, through a small grant, enabled me to include all the CCS technologies in the model. Moreover, thanks to Lew Fulton, Uwe Remme and the other ETP staff at the IEA, and Thomas Alfstad at BNL. Thanks also to my partner Birgitte for her understanding of my need to postpone everything but the thesis, and my friend Tore Brænd for enthusiastic listening and comments from a sociological perspective.

Trondheim December 2010

Thomas Martinsen

List of publications

This PhD thesis is based on the following articles:

I. Martinsen, T. 20xx Technology learning in a small open economy - The systems, modeling and exploiting the learning effect, submitted.

II. Martinsen, T. 20xx Introducing technology learning for energy technologies in a national CGE model through soft-links to global and national energy models, submitted.

III. Martinsen, T., 2010. Global technology learning and national policy--An incentive scheme for governments to assume the high cost of early deployment exemplified by Norway. Energy Policy 38, 4163-4172.

List of abbreviations

AEEI	Autonomous energy efficiency indicator
CCS	Carbon capture and storage
CES	Constant elasticity of substitution
CGE	Computable general equilibrium
DDF	Demand decoupling factor
ETP	Energy technology perspectives
GDP	Gross domestic product
IEA	International energy agency
IS	Investment support
LBD	Learning by doing
LBS	Learning by searching
LBU	Learning by using
LP	Linear programming
LR	Learning rate
OED	Royal Norwegian Ministry of oil and energy
OFW	Offshore floating wind power
TFP	Total factor productivity
TL	Technology learning
TLC	Technology learning curve
UNFCCC	United Nation Framework Convention for Climate Change
WEO	World energy outlook

1 Introduction

Preventing dangerous global climate change is the most important challenge today. The need to urgently shift away from the current continuous rise in global emissions of greenhouse gases is well documented. Emission from the use of fossil energy carriers is a major source of greenhouse gases. Furthermore, increased energy supply is a prerequisite to meet nearly all the UN millennium goals. The IEA (2008)[2] calls for a global revolution in the ways that energy is supplied and used. This will require massive diffusion of nascent energy technologies into the energy systems of both developed and developing countries. The investments required at the national level are very large and energy technologies generally have a long lifetime. Managing the shift to a common sustainable technology path involve insight about the influence of technological change.

The nascent energy technologies are at different stages within the early part of a typical technology life cycle. Some are at a research stage, e.g., wave power; others need up-scaling and demonstration, e.g., post combustion carbon capture, while solar PV and onshore wind power are available in the global market. Common for all the nascent energy technologies is that cost of the energy carrier they deliver can only compete with existing technologies in niche markets. Once in production and use, experience foster technology learning[3] and the cost will go down and performance improve (BCG et al. 1968; IEA 2000). While technology learning may be shared globally, deployment is always local. In order to minimize costs of policies as well as national technology investments improved knowledge of the influence of global technology learning on the *national* energy system is required. This thesis presents new approaches and methods to explore the effect, of technology learning in the global market and include the influence in national energy system analysis. Moreover, they are assessed through examples of its application on a small open economy like Norway.

Executive summary, page 37.

[3] The term *technology learning* is further defined in paper I.

1.1 Energy systems analysis and technology learning

Energy systems analysis using optimization models emerged in the 1970's when the sudden increase in the oil price made the "obvious development" of the energy system(s) much more uncertain. The diversity of supply side technologies and energy carriers that possibly could meet the growing demand increased. Moreover, more efficient demand side technologies could arguably reduce the need to expand the energy supply. Requirements external to the energy system, e.g., to reduce environmental impacts, further increased the complexity of energy system analysis. Policy makers, accepting the need for government measures to guide the development of the energy system on to a sustainable technological path, requested better understanding of the effectiveness of possible measures. Linear optimization (LP) techniques are well suited to handle the large array of possibilities and constraints characterizing the development of the energy system. Energy system models are often referred to as *bottom-up* models because they build up the energy system from a detailed description of the alternative technologies and chains of technologies that extracts, convert and transport energy from source to consumer. The Markal[4] LP model (Fishbone, L.G., Abilock, H., 1981) provided the analysts with such a tool. It was developed in a maulti-national co-operative project within the framework of the International Energy Agency (IEA). The IEA Secretariat recently used the MARKAL model as a basis for developing the global Energy Technology Perspectives LP model.More than 50 countries use a national Markal model today. The International Institute for Applied Systems Analysis (IIASA) developed its own global LP energy systems model "MESSAGE" in parallel with the development of the Markal model.

The Markal model captured the diversity of technological combinations and their gradual introduction into the energy system. It did not, however, initially include the influence of a competitive market where cost is reduced as accumulated production increases. That is, the non-linear experience curves representing the dynamic influence of technology learning. The use of experience curves to have an endogenous description of technology learning in optimising models causes computational difficulty due to their

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[4] Market allocation

non-linearity. This problem was resolved for the MESSAGE model (Messner 1997) and the GENIE model (Mattsson and Wene 1997) in parallel. Inclusion of technology learning has later become a standard option in Markal (Loulou et. al 2004) Many global models now include technology learning. Löschel (2002) provides a review of the various parameterizations of technology learning in global models. To evaluate the influence of technology learning on the development of the energy system the Innovation Modelling Comparison project included a cross section of global energy – economic – environment models. They provide a variety in their results with respect to future technology composition and total system cost, but concur that technology learning is an important factor affecting the cost of the transition to an energy system with low CO_2 emissions (Edenhofer et al. 2006). From the national viewpoint technology learning in the global market is perceived as spillover[5]. If technology learning is an important factor for the development of the global energy system, spillover may be equally or more important for the development of the national energy system. Discussion regarding the influence of technology learning at the *national* level is, however, hardly present in the international scientific literature discussing scenarios for a low-carbon future.

A criticism of the LP energy systems models was the lack of coupling to the other sectors of the economy. The macroeconomic models on the other hand include the entire economy, but do not have a detailed representation of the energy system. These models are often referred to as *top-down* models and may be used to estimate the demand for energy. The demand for energy services in the non-energy sectors of the economy is dynamically coupled to the energy system. That is, the cost of energy carriers is one of several factors influencing the demand for energy services. Models combining top-down and bottom-up are referred to as *hybrid models*.

In the Markal model package the Markal Macro option (Manne and Wene 1992) adds a top down module to the standard Markal bottom up model. Markal macro was included

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[5] Spillover is in this thesis limited to the cost reductions and efficiency improvements because of accumulated deployment in the global technology market, i.e., cost reductions and efficiency improvements resulting from accumulated global production. It is further discussed in Chapter 2.3.

in order to capture the feedback on demand from the non-energy sectors. In this hybrid model all the non-energy sectors of the economy is represented by a single production function. Because the different sectors may have very different sensitivity to the price of energy carriers, the sensitivity to the influence of technology learning is also expected to be variable. In order to analyze the influence of technology learning on the non-energy sectors, using a modeling framework based on a national Markal model, a more detailed approach is called for.

The global energy system is merely the sum of the national energy systems. Moreover, the decision to implement incentives for technological change firmly rests at the national level. Timely realisation of a global energy technology path, consistent with the recommendations of the IEA, thus depends on coordinated national policies to exploit the learning opportunities of a selected technology path. This calls for national energy system analysis capturing the influence of technology learning, both spillover and learning in national niche markets, and technology specific policies.

1.2 Objective

The objective of the work presented in this thesis was to investigate interplay between technology diffusion, niche markets and experience curves from the perspective of a small open economy like Norway. More specifically, the aim was to develop methods that can be used to include spillover of global technology learning into the national energy system analysis and assess its potential importance for the development of the Norwegian energy system up to 2050.

In Paper I the aim was to contribute to the understanding and modelling of technological change in the *national* energy system of a small open economy. The focus was on how spillover of technology learning may be included in a national bottom-up energy system analysis like Markal. The two following papers use the method developed to incorporate spillover in national analysis.

In Paper II the aim was to investigate the influence on demand for energy in the non-energy sectors from spillover of global technology learning using a *national* hybrid model linked to a global energy system model.

In Paper III the aim was to investigate the effect of national efforts to contribute to technology learning with spillover for a portfolio of globally desirable low-carbon technologies.

1.3 Scope and limitations

My starting point was the assumption that the price of new energy technologies in the Norwegian market, and thus the most cost efficient technology composition of the future Norwegian energy system, ultimately will be heavily influenced by the activities in the international energy system and in the international energy technology market. To obtain information about the influence I looked for global models. Obtaining usable data from global models was difficult, and the methods are exemplified using data from one global model. Moreover, a limited number of national policy scenarios are investigated. This is not sufficient to provide an affirmative conclusion with respect to the validity of the above assumption. While more scenarios generated by various models will map the uncertainty in the results for the Norwegian energy system, it will not change the methods developed. The scenarios have been selected to indicate the sensitivity of the Norwegian energy system to activities in the international energy system and in the international energy technology market. The focus of this work has been on the nascent energy technologies for electricity supply. The methods have been developed to suit the Markal model, but may be applicable to other models allowing input of technology specific data.

1.4 Specific research questions

The specific research questions in the three papers are followed by a statement about their contribution. I asked the questions:

Article 1

(1) How should spillover be handled when modelling the energy system of a small open economy? (2) What is the potential influence of spillover on the Norwegian energy system? (3) What is the sensitivity of the national system to spillover and will learning in the national market give a similar result? The elucidation of the application of spillover on the *national* energy system analysis in a globalized energy technology

market is novel. It contributes to the stock of knowledge on modelling TL with a focus on the national energy system.

Article 2

Can a national Markal model be used to carry the spillover of TL from the global model into a national macroeconomic model and what is the influence on demand for energy at the sector level? The combination of spillover of global technology learning and a *national* soft-linked hybrid model, exchanging information at a sector level, is a novel approach and adds a new element to national policy analysis.

Article 3

(1) What is the additional effect, of the national measures derived from EU directives, on deployment of nascent energy technologies when including spillover of global technology learning? (2) Specifically, do the selected policies and measures provide support to the high cost of early deployment? The exertion to coordinate national efforts to contribute to technology learning with a portfolio of globally desirable low-carbon technologies adds a new element to scenario analysis, not included in the earlier studies.

1.5 Outline of contents

The background section provides an overview of relevant aspects of technology change discussed in the literature. In chapter 3, the global perspective, an argument is presented for the selection of the global model. In chapter 4, the national perspective, a brief description of the Norwegian energy system, national circumstances and history of energy systems analysis in Norway is given. In chapter 5, arguments underpinning the need for the method development are presented together with an introduction to the papers. Finally, in chapter 6 the research questions are answered and the main contribution of the work presented.

2 Background

This chapter provides further background on the subject of technology change in energy systems analysis beyond what is included in the papers, though not comprehensive.

2.1 Characteristics of technological change

Technological change has been one of the main drivers of economic growth. It is not deterministic (Rophol 1983), even though it arises from within the economic system (Schumpeter, 1934, quoted in Grubler 1998, p 40). Development and diffusion of new technology has reduced costs of production and increased resource efficiency. There are two main drivers of technological change; research and development (R&D) and deployment. Formulating a general theory explaining the cause and effect have proven difficult. However, much insight has been gained.

Based on a large number of studies across industries and products the stylized life cycle of a technology has an S-shape, see Figure 1. Initially growth in market share is slow, followed by a period of constant growth corresponding to large market shares. During this period there are more or less continuous improvements in price and performance of a technology. Finally, further refinement and cost reductions are diminishing and a completely new technology may take over (Grubler et al. 1999; Grübler 1998). The stages invention, innovation and diffusion of technology development first used by J. A. Schumpeter (1934) refer to typical stages in technological development and deployment. Diffusion has later been further disaggregated into niche market commercialisation, pervasive diffusion and completed with the phase-out stages saturation and senescence. The commercial market share in the invention and innovation phases are zero and thus the technology development is only driven by R & D (Grübler 1998).

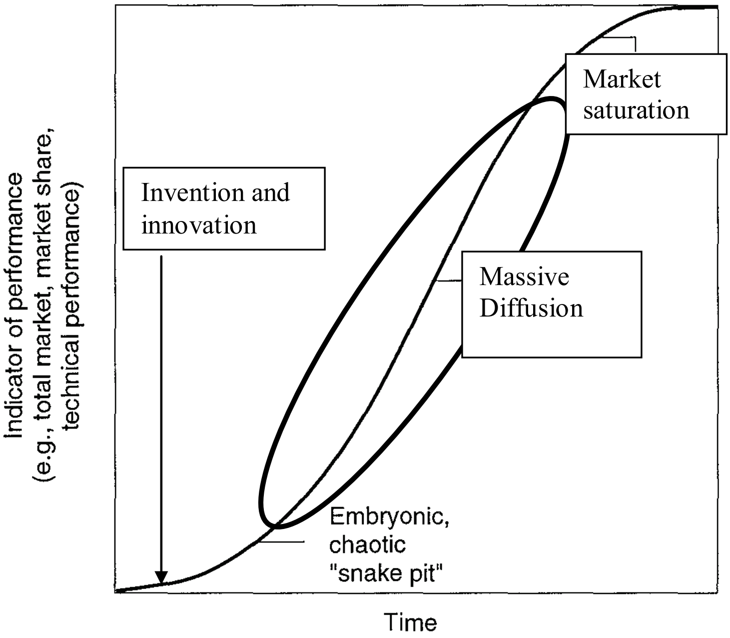

Figure 1 Typical technology life cycle with respect to total market share (Grubler, A. 1998 slightly modified).

The energy conversion technologies most relevant for this thesis are at different stages on the S-curve. Onshore wind power and solar technologies are in the early diffusion stage. Carbon capture and storage (CCS) as well as floating offshore wind power (OFW) are in the innovation stage. Parts used in both these technologies may, however, be situated well into the diffusion stage. Treating a technology as one homogenous piece will thus always be a simplification. Applying a systemic approach and evaluating the system boundary carefully, it may still provide insight.

Technological change can be in the form of small *incremental improvements*, *radical innovations* initiating a larger abrupt change, changes in the *technology system* affecting several branches of the economy and changes in the *techno-economic paradigm* where the change in the technology systems has a major influence on the entire economy (Freeman and Perez 1988). Small incremental improvements are occurring within most sectors while radical innovations are discontinuous and cannot emerge from incremental improvements. The engineering activities feeding the change are embedded in larger technological regimes where established practices, supplier-user relationships and consumption patterns constitute barriers towards technical change other than incremental improvements. Technological *regimes* are broader than technological paradigms in that they are socially embedded (Kemp et al. 1998).

2.2 Technological change in economic theory

Economic theory typically distinguishes between the micro level, for analysis of an individual company, e.g., performance and planning, and the macro level used for analysis of the economic system, e.g., influence of taxes and policies. The production function, describing in its simplest form the relationship between the output of products and the input of capital and labour, can be applied both at the micro and at a macro level. At the macro level it is referred to as the aggregate production function. The economic output is a function of labour, capital investment and the elasticity of substitution (α) between labour and capital. When α is constant over time it may be referred to as a constant elasticity of substitution (CES) production function.

R. M. Solow (1957) suggested an elementary way of segregating variations in output per unit labour due to technical change from those due to availability of capital. Assuming constant return to scale, and that both capital and labour is independent of technological change; he defines technical change as any shift in the production function. This includes building knowledge capital as well as substitution of production machinery. He shows that this approach fits reasonably well with the aggregate production, based on data from the USA. Finally he finds that the technological change was neutral, the case when there is no factor substitution, i.e. the relative magnitude of labour and capital is preserved over time (Solow 1957).

W. E. G. Salter and Reddaway (1966) in their discussion of productivity and technical change identified two main forces shaping the flow of new technologies into use: "improving technical knowledge expands the realm of the technically feasible, and changing factor prices alters the terms of choice between technical alternatives". The flow of new knowledge leads to a continuous change where the production function over time moves towards the origin. This corresponds to a neutral technological change that increases the efficiency.

In addition to the movement of the production function towards the origin, it may also rotate corresponding to a greater increase in efficiency of either capital or labour. Finally, the curvature of the production function may change corresponding to the elasticity of substitution. When the elasticity of substitution is zero there is a right angle between labour and capital and changes in factor prices have no effect. The other extreme is when the production function becomes a straight line and changes in factor prices have a very large effect on productivity. These characteristics represent the potential for technical advance. In addition one factor may be increased at the expense of the other (Salter and Reddaway 1966). While this representation of the economic effects of technological change are useful on a macro scale and for longer time periods, they are severely limited with respect to understanding the process of technological change (Nelson and Winter 1977). To influence technological change through policy requires understanding of the processes and the institutions involved. Particularly the assumptions in the Solow growth model that technological change is exogenous, firm's behaviour is fully rational and they have perfect foresight were disputed (Nelson and Winter 1977).

Alternative theories have been developed, e.g., evolutionary economics and optimal growth theory. Optimal growth theory allows investment in R&D to increase the knowledge stock, which in turn increases productivity (Köler et al. 2006). This way technological change is endogenous through the determination of the level of R&D investment. A high level of R&D, however, is no guarantee for a high rate of technological change. Moreover, without technology learning through deployment, it will be much harder to reach pervasion (Sagar and van der Zwaan 2006).

The technological change because of accumulated experience is acknowledged and has long been used in micro economics for the projection of future cost of production by manufacturing industries operating in a competitive market. A learning curve was first introduced for cost development of producing the same model airplane (Wright 1936).

Wright (1936) analysed the amount of labour required for the individual airplane in a series and found it was decreasing rapidly in the beginning and then tapering off. As the name implies, the cause of the reduced labour intensity was due to increased knowledge by the workers. He postulated that the relationship has the functional form $C = X^E$ where C is the resulting cost, X accumulated production and E a technology specific constant. The learning curve is generally described by the equation:

Equation 1 $C(X_{cum}) = C_0 (X_{cum})^{-E}$

The initial cost is denoted C_0, the learning parameter E, the accumulated production X_{cum} and the resulting cost $C(X_{cum})$. Later the concept of learning was extended to include all inputs affecting the cost of a product and renamed the *experience curve* (BCG et al. 1968). The cost development as a function of accumulated production of a number of products were analysed and the general equation found valid for the experience curve. The combined effects of experience and market share will thus generally show a continued decline in prices. Following the IEA terminology, this thesis uses the term *technology learning* to denote all those processes within a firm, group of firms or industries that lead to cost reductions in a *specific technology* as a result of actions in a competitive market (IEA 2000). A technology learning curve is most often presented in a log-log diagram where it becomes a straight line, see Figure 2. The relative cost reduction, or percentage, is thus constant for each doubling of production and equal to the learning rate (LR). The technology learning curve will capture incremental improvements from the diffusion stage and onwards.

R&D is crucial for the invention and innovation phase and thus may affect the cost of a technology when entering the market. Likewise, niche markets are decisive for starting the ride down the technology learning curve and may act as stepping-stones for the technology to reach the mass markets (IEA 2000, 2003). When entering the diffusion stage, both R&D and technology learning may contribute to the cost reduction and improved performance of a technology. In the two factor learning curve (2FLC) suggested by Kouvaritakis et al. (2000), accumulated R&D expenditure is assumed to be an independent variable affecting the cost of a technology. The validity of the 2FLC is disputed (Wene 2008b).

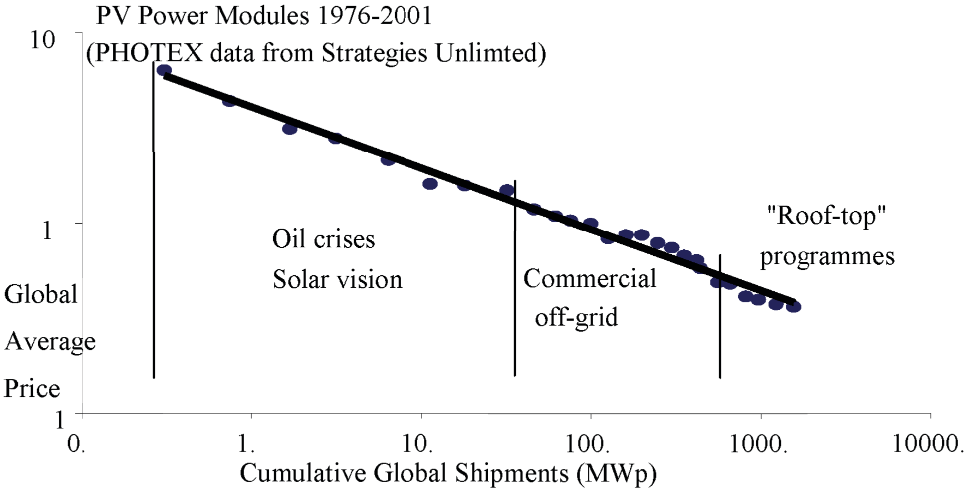

Figure 2 Technology learning curve for PV power modules. The three periods indicated by the vertical lines had very different deployment rate. The data still fits well with the technology learning curve. The learning rate is about 20 % (IEA 2000/Wene 2007b).

2.3 The learning mechanisms

In an effort to understand the underlying forces of technology change, several learning processes have been identified, see Figure 3. Learning processes may be viewed as feedback and feed forward loops. Learning by doing (LBD) (Arrow 1962) was defined as the embodied learning in production, much like the initial concept. Learning by searching (LBS) refers to the improvements because of private (industrial) R&D. Learning by using (LBU) refers to the learning taking place as the technology is used, outside the plant where it is produced. LBU is divided into two sub-categories, embodied and disembodied. Embodied LBU refers to the learning leading to improved design of the technology. Disembodied LBU (Rosenberg 1982) includes using the technology in a different way that increases the lifetime, reduces service intervals etc and thus reduce costs accrued to the user. While LBD and LBS are an integral part of the technology development and manufacturing system, LBU takes place in the energy system, see Figure 3. The different learning mechanisms may have different system boundary. The learning system boundary may be global, national or even local.

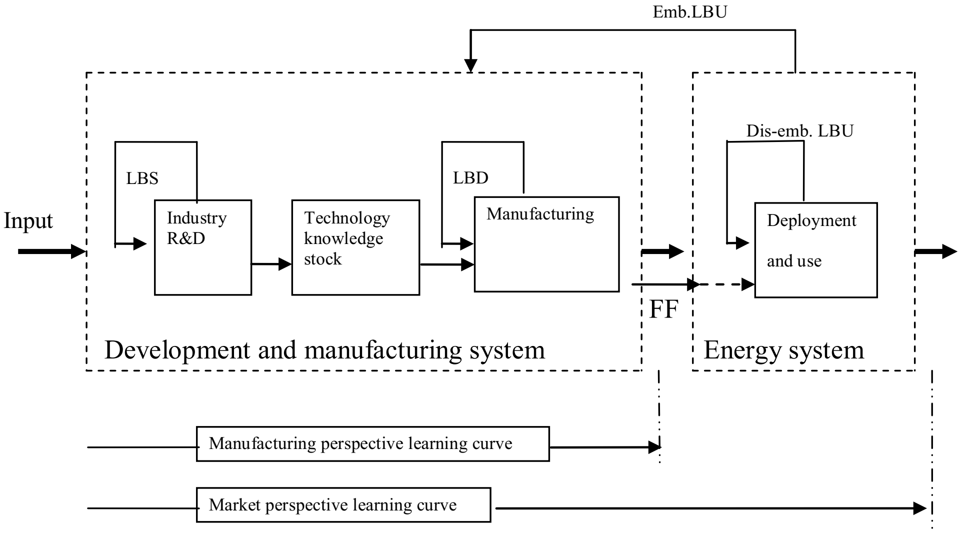

Figure 3 Simplified diagram showing the system boundaries and selected technology learning mechanisms. The broken lines indicate the system boundary of the development and manufacturing learning system and the energy learning system respectively. The two systems are linked through the learning by using (LBU) feedback loop and the feed forward (FF). Based on figure 2.2 and 2.9 in IEA (2000), figure 2.3 and 3.1 in Neij et al. (2003). Only the market perspective may capture the effect of local technology learning.

Embodied LBU is, in Paper I, identified as a potentially important source of learning to reduce manufacturers' need for adaptation of a technology to local circumstances. Disembodied LBU has by default a local system boundary and may remain as local learning unless specific organisational measures to share the experience are in place. Both global and local technology learning is a result of local deployment, see Figure 4.

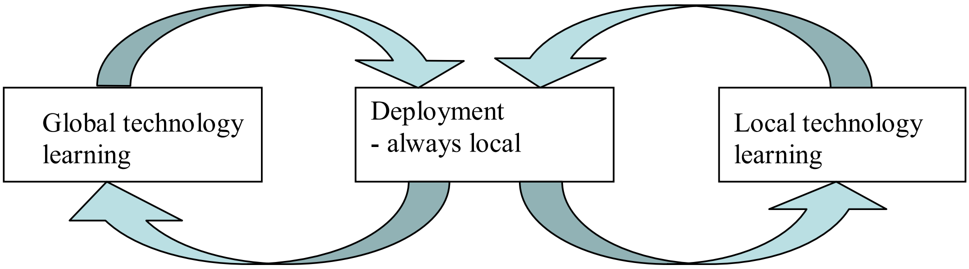

Figure 4 The technology learning system boundary may be global, national or even local, but deployment is always local.

Clearly the technology development taking place in most sectors of the economy may contribute with ideas and small bits and pieces that may or may not be included in the mechanisms mentioned above. An alternative approach emphasising this allocates the learning to the direct action relative to an energy technology, i.e., R&D, production and using, and spillover. Spillover refers to the fact that knowledge gained through investment in R&D and deployment will induce technological development outside the boundary where the investment is made. It may occur at different levels, e.g., between similar technologies and/or between producers in different regions. A simple, though limited, definition of spillover is: *"any positive externality that results from purposeful investment in technological development*" (Weyant and Olavson 1999)[6]. Direct spillover increases technology learning without any effort or action, while indirect spillover increases the pool of opportunity that might be exploited (Clarke et al. 2006a).

The term direct spillover is further confined to the result of a learning sub-system in industries producing parts used in the energy technology in question, but where the learning primarily is the result of R&D and use of the part in other industries. Direct spillover may be the result of grafting a technology into the energy technology in question where minimum modifications are required. Indirect spillover refers to the adoption of a technology requiring modification of the energy technology in order to be used. The utilisation of indirect spillover depends on the level of own-industry R&D (Cohen and Levinthal 1989). Pathways for spillover are shown in Figure 5.

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[6] Page 5, second paragraph

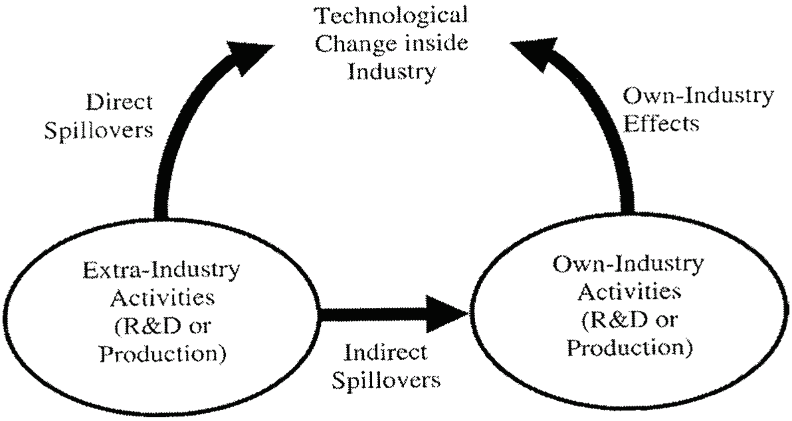

Figure 5 Pathways for spillover contributing to technological change (Clarke et al. 2006b).

2.4 Technology learning curves for energy technologies

A number of technology learning curves may be found in the literature. Kahouli-Brahmi (2008) presented a recent review of the TLC literature. In addition to energy policy assessment, technology learning curves are used for several purposes, notably to analyze future cost trends of individual technologies, identify possible market shifts and to integrate technology change into scenario planning (Neij 2004). Based upon bottom-up studies, e.g., of features, processes and events (Wene 2007a), a LR for technologies not yet in the market may be estimated. Because the technology learning curve is based upon trend analysis, increased difficulty with respect to data collection and conversion may incur for longer time scales. Technology learning curves for *specific technologies* (see Paper I) will in most cases have to rely on price data rather than cost. A technology learning curve based on price data is coupled to the curve based on cost data. It will also include the influence from sales and pricing strategies of the producers, investors bargaining power and market responses to public deployment policies (IEA 2000)[7]. The cost – price relationship will vary over time and is one cause of data points deviating from the technology learning curve. Typically, the initial manufacturer may maintain a price level through exerting market power for a limited time while the cost continues to

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[7] pp 35 - 40

fall. This is not a stable situation, however, and a shakeout phase follows forcing the price technology learning curve to again follow the cost (BCG et al. 1968).

Energy technologies are complex systems often containing a large number of commercially available parts. Each of these parts has their own learning system and may have a different LR, e.g., windmill blade, generator. Two distinct categories with different system boundary and cost parameters have emerged. The first system is classified as a manufacturing perspective using the capital investment as parameter, while a system using cost of generating electricity is classified as a market perspective (Neij et al. 2003). The market perspective has several sub-systems including the production perspective, see Figure 3. Only the market perspective may directly capture the effect of local technology learning i.e. disembodied LBU. The system boundary definition will thus affect the LR.

It is large variation in the LR available in the literature. One of the first studies of learning curves for an energy technology, estimating the LR at 4 % for wind turbines, applied a national learning system boundary (Neij 1997). Applying a global system boundary, the LR for wind farms using the market perspective was estimated at 19 % (Junginger et al. 2005). A survey of learning rates estimated for many different energy technologies indicate even larger extreme values and discusses the sources of variability (Kahouli-Brahmi 2008). Investigations into sub-sets of data also gave significant variation in the LR, indicating that it is sensitive to the time period of data selected (Nemet 2009). Moreover, when extrapolating the technology learning curve into a distant future it is questioned if all technologies must be viewed as a grafted, where the relative contribution to the overall LR changes over time and thus may change the overall LR (Ferioli et al. 2009). Both authors, however, find the LR for wind technology to exhibit reasonably stable behaviour.

Acknowledging the uncertainty, Neij (2008) confirms the LR-estimate at 15 % for onshore and 20 % for offshore wind based on a comparative bottom-up foresight study. Wene (2007) recommend a LR of 20 % for a virgin technology based upon a study of the eigenvalue of an operationally closed system. When operationally closed (Varela

1979, 1984; Wene 2008a) the system obtains optimal learning conditions from incremental technological change. Higher LR is interpreted by Wene (2008a) as a result of radical innovations, while the lower LR around 7 % corresponds to a grafted technology.

2.5 The role of policy

There is ample evidence of technological change taking place in our society. Most noticeable today is the cost development and improvement in performance of mobile phones and flat screen televisions. The efficiency of energy use has also continuously been increasing because of technological changes and may be expected to remain on the same path in the future. Technology learning reduces global energy system cost and lowers carbon emissions. It is not sufficient, however, to transform the energy system and stabilize GHG concentrations in the atmosphere consistent with the United Nation Framework Convention on Climate Change (Rao et al. 2006). Policies and measures are thus required. The influence of public policy may be allocated to two main groups, R&D and deployment. They provide a technology push and technology pull respectively. A schematic view of their influence on the technology learning system is given in Figure 6.

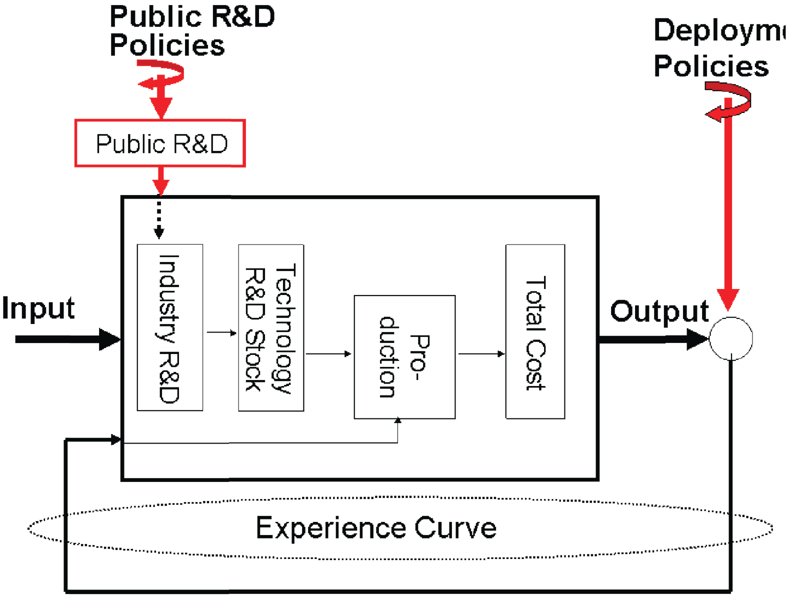

Figure 6 Influence of policy on the technology learning system (IEA 2000; Wene 2008b).

Deployment policies generating a market pull may be required to start the “ride down the technology learning curve” and may also reduce the time between a doubling of production. Policies may thus both introduce a nascent technology to the market and increases the speed of its cost reduction. Can policies also alter the LR? A study of LR for PV modules has shown an increase in the LR simultaneous with increased intensity of policy support measures (Schaeffer et al. 2004). However, the finding lacks theoretical underpinning and the uncertainty of the technology learning curves in the literature is much larger than the detected effect on the LR.

Technology learning represented by the technology learning (experience) curve may be viewed as a positive feedback loop reducing total cost (IEA 2000; Wene 2008b). A system with positive feedback and feed forward tends to have an increasing rate of return when measured in economic units and thus tend to reinforce itself. This is a typical feature of energy technology paths. The lock-in on existing technologies will be stronger if the new technology requires a change in the technological paradigm and even more so if a new technological regime must be established. In this case the challenge is not limited to support the deployment of a single technology but to manage a shift in the technological regime. This may be done through a policy for strategic niche market management. Such a policy also includes measures aiming to break down the barriers inherent to the existing technological regime (Kemp et al. 1998).

2.6 Modelling energy-economy-environment

Resource limitations, social demands and environmental requirements tend to raise costs while technological development reduces cost. Identifying the influence of technological change on the cost of policy and the optimal timing of investment has thus received increasing attention from economists and systems engineering modellers. There are two main approaches to energy - economic - environment (EEE) modelling, the “top-down” and the bottoms-up approach”.

The top-down macroeconomic models generally include all the major sectors of the national economy, e.g., energy sector, public sector, industry and the elements affecting economic development, e.g., labour force, wages as well as production and consumption of capital goods. They are represented by aggregate production and consumption functions that are expanded to include energy production or demand respectively. The macroeconomic models are particularly useful to study influence of various policies on welfare and economic development. The number of different technologies and energy carriers, however, is often limited. Moreover, technological change has [EH1]until recently tended to be an exogenous constant in the form of a total factor productivity factor (TFP). Following the development of evolutionary economics and optimal growth theory sub-categories of models called innovation models and endogenous growth models have emerged. The latter optimize welfare through maximising economic growth. Important features of these models are spillover, path dependence and crowding out. Spillover and path dependence is described in chapter 1.3 and 1.5 respectively. Crowding out is a term used to describe the effect of limited resource availability, particularly for R&D and deployment. Prioritising R&D and deployment resources implies that some technological options or sectors of the economy will get less. Environmental policies and policies to encourage technological change may contribute to reduced activity in other sectors and thus “crowding out”. As this affects the opportunity for cost reductions through learning it may contribute to path dependence or lock-in on selected technologies.

The bottom-up models, on the other hand, generally have a detailed representation of the energy system from energy sources, through conversion and transmission to end use, see Figure 7. Each of these categories includes a number of alternative technologies. All energy carriers are included as physical flows. The model is set up to satisfy a demand for energy service rather than a demand for energy carriers. The term *energy service* was most likely introduced by Thomas Edison (Mills 1993) when he in 1878 established his energy service company Edison Electric Light Company. An example of an energy service demand is 20 degrees in a room or vehicle kilometre. The energy service may thus also be met through the selection of technologies that use the energy carriers more efficiently. The demand for energy service must be obtained from an exogenous source, e.g., a top-down macroeconomic model. The bottom-up models also are economic models minimizing the cost of the future energy system given various constraints, e.g., environmental policies. However, they do not capture the rebound effect from interaction with other sectors of the economy, including changes in energy demand due to changes in relative prices.

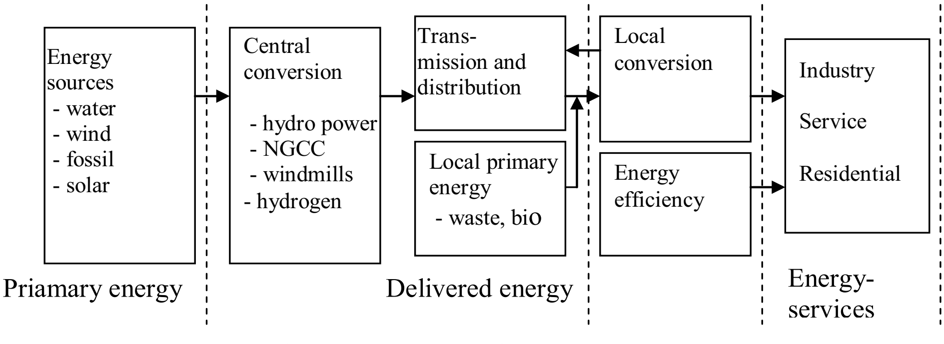

Figure 7 Schematic view of the energy system from sources to energy services.

Linking the bottom-up and top-down models to form a hybrid model has long been viewed as the optimal solution. They may be hard-linked where the data exchange is controlled by the equations defining the model or soft-linked where the data exchange is controlled by the user. With a hard-link the iteration process to reach the optimal solution is endogenous. While this may provide a more accurate result and facilitates analysis of many scenarios or sensitivity investigation, it also greatly increases the complexity and computational effort. More important, hard-linked hybrid models with equal amount of detail in both the top-down and the bottom-up models have proven difficult because of overlapping domains and differences in basic structure, e.g., linear versus non-linear representation. A soft-link, where the data is exchanged manually through a series of iterations the complexity of both models may easily be retained. Although a soft-link is more resource intensive during operation, it may provide valuable insight from the iteration process. The approaches used in hybrid models are briefly discussed in Paper II. A discussion of hybrid EEE models may be found in Bataille et al. (2006) who summarize a special issue of The Energy Journal on the topic.

2.7 Technological change in modelling

The increasing efficiency in the economy is in top-down models traditionally represented by a fixed parameter, the total factor productivity (TFP). It may include both structural changes in the energy system and energy efficiency improvement in demand side technologies, as well as increased efficiency in the use of other factors, e.g., capital and transport. When applying a less aggregated production function the TFP may be specified at the same level and vary between energy, capital, labour etc. Considering the energy system only, the autonomous energy efficiency parameter (AEEI) was defined as *"all non-price induced factors that could reduce energy demands per unit of gross output"* (Manne and Wene 1992). An aggregated TFP for the energy sector will also include electricity generation not included in the AEEI, see Figure 8. The value of the AEEI is usually determined on the basis of empirical data and will adjust the demand for energy services. If so it will not capture the effect of new policies and increased R&D and deployment increasing technological change. The adjustments to the TFP's in the Norwegian macroeconomic model, when soft-linked with the Markal model, is further discussed in Paper II. A slightly more sophisticated representation is developed for the Markal-Macro model. Utilizing the more detailed representation of the energy system, a demand decoupling factor (DDF) is used. The system components covered by the aggregate TFP, AEEI and the DDF is illustrated in Figure 8. All three factors capture the increasing efficiency in the energy system, but not a shift from one specific technology to another.

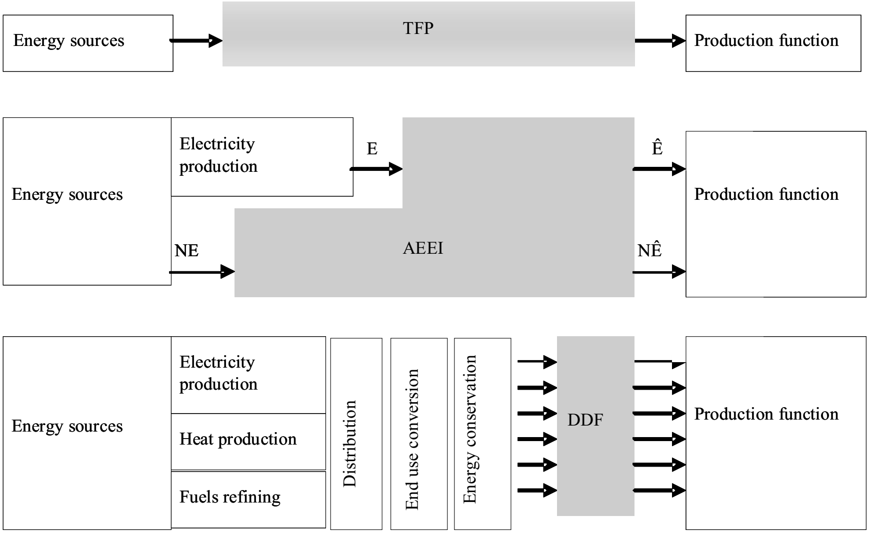

Figure 8 Illustration of the system components included in the aggregate total factor productivity (TFP),autonomous energy efficiency indicator (AEEI) and demand decoupling factor (DDF) respectively. From Nyström and Wene (1999) with the illustration of TFP added.

In addition to the factors described above a so called backstop technology may be introduced in top-down models. A backstop technology is a source of energy that is unlimited above a given price. The model may thus, because of policies, e.g., CO_2 incentive, displace baseline technologies and use the backstop technology to provide the same commodity, e.g., electricity. The price of electricity is thus capped by the price of the backstop technology. Typical backstop technologies include solar-PV and wind-mills and the price cap may vary through the use of technology learning curves. Models with endogenous representation of technological change the technology learning curves are seldom applied to all technologies simultaneously. The main reason for this may be the escalating processing power required. The approach may, however, not introduce unacceptable error because the effect of technology learning is also dependent accumulated production. If the historic accumulated production is large, the marginal effect of technology learning will be small. For technologies not yet in production, the initial accumulated production when technology learning starts must also be estimated. In the modelling for Norway presented in the papers, the author estimated it for offshore floating wind power. No estimates were found in the literature.

Several technologies may contain the same component, e.g., a turbine. In order to account for the contribution to technology learning by one common component included in several technologies Seebregts et al. (2000) introduced technology clusters. All the technologies within one cluster would then benefit from the technology learning contributed by the component. The direct spillover may thus be modelled as endogenous through the use of the cluster concept. In this thesis the technology learning system boundary is assumed to be global. Spillover is thus internal to the system and not modelled explicitly.

4 The global perspective

The global energy system is dominated by fossil fuel covering 85 % of energy demand in 2003 (IEA 2006a). Coal power is the dominating source of electricity followed by natural gas. Together with a relatively small contribution from oil fired power plants, fossil fuels provide about two thirds of global electricity production. Hydro power and nuclear power currently provide most of the remaining electricity production while a small fraction is produced by renewable energy technologies. Future global primary energy demand is uncertain, and scenarios range from six times the current level and down to about a doubling. Scenarios with high energy use imply a different energy technology portfolio than the scenarios with emphasis on end-use energy savings (Nakicenovic and Riahi 2002). The level of long term stabilisation of atmospheric CO_2 heavily influences the amount of renewable energy in the future global energy system. Analyses of the energy system from a global perspective have provided insight and fed the discussion about the cost and timing of a shift to a technology path consistent with the UN framework Convention for Climate Change[8] (UNFCCC).

Several studies have included the effect of endogenous technological learning on the global and regional, e.g., European, energy system using systems engineering models including MESSAGE, TIMES and MARKAL Europe. An assessment of the economic implications of stabilising GHG at 450 – 550 ppm with endogenous technological change in a selected cross-section of models has been done in the Innovation Modelling Comparison Project. The effect of endogenous technology learning is evaluated both with respect to energy intensity and carbon intensity (Edenhofer et al. 2006). There are thus several models available that could potentially be used to provide the global perspective for this study. However, extracting the appropriate data proved difficult. The approach used in the global Energy Technology Perspectives (ETP) model lends

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[8] Article 2, Objective and Article 4 c about technology

itself well to extracting data and includes most relevant scenarios with respect to global CO_2 emissions targets.

4.1 The global Energy Technology Perspective model

The ETP model is a global bottom up Markal energy systems model with 15 regions. It facilitates analysis of fuel and technology choices throughout the energy system from energy extraction, fuel conversion and electricity generation to end-use. It includes about 1000 technology options covering the energy system. Several policy scenarios with different CO_2 incentive and other constraints are analyzed. The ACT Map scenario stabilizes the CO_2 emissions at about the current level, while the BLUE Map scenario reduces the emissions of CO_2 by about 50 % compared to today's level by 2050. The results of the ETP study also include the effect of policies not primarily acting on price through the use of supplemental models of the demand-side in the industry, buildings and transport sectors (IEA 2006a)[9].

The model is set up to satisfy an exogenous demand for energy services. The global energy demand is driven by world population and economic growth measured as gross domestic product (GDP). While the global GDP in 2050 is about four times the 2005 GDP, the growth in Europe equals about a doubling of GDP. The ETP baseline scenario is calibrated to the World Energy Outlook (WEO) 2007 Reference Scenario up to 2030 and extended it to 2050 (IEA 2008)[10]. The WEO reference scenario includes all policies and measures enacted or adopted by mid 2007 (IEA 2007)[11]. The demand for primary energy almost doubles in the reference scenario (IEA 2006b).

In addition to meet the demand the installed capacity must have a reserve to account for peak load. Equally, each electricity generation technology must have assigned a contribution to the peak load. In the ETP model only 30 % of the installed wind power capacity may be used to meet peak load demand, while the full capacity of a gas power plant may be used. This "disadvantage", because of the intermittency of energy

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[9] ETP 2006 Report, box 2.2 page 45.

[10] ETP 2008 Report, Annex B, page 570 and 574.

[11] WEO 2007, page 53.

production, may affect the technology composition of the energy system, particularly as the share of wind and solar energy becomes significant.

Energy carrier prices are estimated endogenously in the ETP model. In the REF scenario the oil price is capped at US $ 65/barrel because of the availability of unconventional oil reserves above this price. Oil prices in the policy scenarios ACT and BLUE are lower than in the baseline scenario because demand is reduced as the share of new renewable energy technologies in the global energy system increases (IEA 2008)[12]. Electricity prices are calculated by the ETP model for each of the six time slices (winter, intermediate, summer - day, night) for each region.

The present and future characteristics of technology options, e.g., costs and potentials in the ETP model database are based on expert information from the IEA implementing agreements and other sources (Gielen et al. 2004; IEA 2008)[13]. In the ETP model the effect of technology learning is included for the new technologies where it may have significant influence on the cost and technology composition of the energy system. A cost curve is calculated for each technology applying learning rates available in the literature. An iterative approach between the ETP model and the external routine is applied to adjust and verify the data. For CCS technologies several vintages are included where the later vintages are introduced at a lower cost. Existing policies to introduce renewable energy is parameterized through a minimum energy conversion constraint for these technologies (Gielen 2006; Gielen et al. 2004; IEA 2008)[14]. That is, the model have to include in the solution an amount of energy from renewable technologies equal to what is assumed to be generated as a result of the policies.

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[12] ETP 2008 Report, Annex B, page 573.

[13] ETP 2008 Report, Annex B, page 574.

[14] ETP 2008 Report, chapter 5, page 207-208.

6 The national perspective

The Norwegian energy system is dominated by hydropower, covering almost all-domestic electricity consumption. Electricity is the main energy carrier used for space heating and industrial processes. Fossil fuels are mainly used in mobile sources, as feedstock in industrial processes, and some for space heating and industrial thermal energy use. Some consumers have flexibility with respect to choice of electricity or fossil fuel as their energy carrier. New renewable energy sources currently provide only a small fraction of the energy demand. Thermal energy generation systems are mostly small closed units in individual houses or apartment buildings. Typically they apply technologies using heating oil, wood and pellets but also and heat pumps. District heating networks, particularly using waste as primary fuel are introduced in the cities. Air to air heat pumps and night saving systems are installed in many apartments and single family houses.

The system boundary of the Norwegian energy system follows the national boundary including the offshore oil producing installations. The average annual electricity generation in the start period (2005) is about 120 TWh. All of this is generated by hydroelectric power. The first fossil fuel power plant Kårstø using natural gas was completed in 2006. It has not been in regular operation as the export value of natural gas has been higher than the value of the electricity.

The energy system may be characterised on a Nordic, European and global level with respect to the market for energy carriers. The Norwegian energy system is physically coupled to the Nordic and the European energy system through export/import cables. Norway is an integral part of the Nordic electricity marked and all electric energy is traded at the Nordic Power Exchange (Nor Pool). The market is fully competitive. Currently the potential for exchange of energy with the surrounding countries however, has been limited to 18 % of total power capacity (Statnett 2006). With the new Norway

– Netherland cable included in this work the capacity for export and import of electricity increases to 48 TWh annually. The increasing import and export capacity, together with the establishment of a fully competitive market for electricity have increased the "import" of European electricity prices. Electricity prices, though traded on the Nordic electricity exchange (Nor-Pool) are in Norway affected by the limitations in transmission capacity and thus generally lower than the price in Sweden and Denmark. The national market for fossil fuels is fully competitive and prices follow the global market despite large national production.

The average domestic CO_2 emissions in the period 2003 - 2007 were 43.6 Mton[15]. The use of fossil fuel and thus the national emissions of CO_2 are dominated by the oil production contributing about 30 % and transport sector at about 40 %. The remaining 30 % of the emissions are mostly from direct use of fossil fuel in refinery, industrial chemicals, other manufacturing industry, residential and agricultural and commercial sector and metal industry contributing from about 7 % and down to about 1 %. Light duty vehicles predominantly run on gasoline, trucks on diesel and oil boilers are the dominant technology causing CO_2 emissions from the onshore industry.

Both electricity consumption and CO_2 emissions are increasing. The Kyoto protocol requires a reduction in the CO_2 emissions. The remaining hydropower potential is limited. The national short-term target is 10 TWh to be provided by new renewable energy sources and/or through increased energy efficiency by 2010 (OED 1999). In the longer term there is a need for new technology to balance supply and demand, taking into account all international energy and environmental commitments. Such technology development and adoption will also try to accommodate specific Norwegian environmental considerations as well as development of Norwegian technology. Norwegian research and development are advanced in several energy technologies, e.g., wind power in cold climate, silicon solar cell and hydrogen storage.

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[15] The figure is consistent with the UNFCCC reporting instructions and does not include emissions from international aviation and shipping.

The future potential for electricity production includes fossil power plants, small-, mini- and micro hydro power, wind power, salt wedge power and wave and tidal power. Norway has a relatively large wind power potential both onshore and offshore and a niche market for onshore power is established. Technically the Norwegian energy system thus has a large degree of autonomy. However, because of the deregulation of the electricity market and trading of all consumer electricity delivered at Nor-Pool, all the Nordic countries increasingly face the same price signal.
Technological challenges with respect to increasing the electricity production are quite similar on a Nordic, European and global level. The similarity between Norway, Sweden and Finland is also true for the biomass energy market. The market for fossil fuels is fully competitive on a global scale, despite large national production.

6.1 Energy system modelling in Norway

Energy system modelling in Norway dates back to the seventies when IFE participated in the development of the Markal model. The development of energy and environmental accounting, preceding the inclusion of it in a macroeconomic model, were conducted by Statistics Norway in the same period. Both the Markal Norway model and the Multisectoral growth model version 6 (MSG6) models used in this project have emerged from this early development work. The two “schools of thought”: the top-down macroeconomic modelling group dominated by economists and the bottom-up energy systems modelling group dominated by the engineers, are very much a global phenomenon. While there has been much debate, most agree today that both approaches have its comparative advantages.

In response to the world Commission on Environment and Development (Brundtland 1987), a study of energy, industry and environment was conducted for Norway. A number of national scenarios were investigated. Detailed studies using the macroeconomic model MODAG preceding MSG were conducted. The aim of the study was to investigate the possibility of combining growth in industrial production with various emission limitations and constraints on energy supply. While it was deemed possible to stabilise the CO_2 emissions in the short term, it was concluded that new technology was required to obtain permanent long term reductions (SIMEN 1989).

In the early nineties, as the current version of the Markal Norway model was developed, the differences between the models were exposed. A study investigating the differences in estimates of demand for energy carriers in the household sector were conducted. The results revealed differences in the demand for energy service and adjustments were made in the respective models. While consistent demand was obtained, the impact on the general economy was small (Johnsen and Unander 1996).

Ten years after the SIMEN study, a white paper on “balancing energy and power demand until 2020” was issued by the Norwegian government. Three models were used, where output from one were used as input to other(s). A model of the Nordic electric power system and electricity market, NORMOD-T (Johnsen 1998) operated by Statistics Norway estimated the electricity prices. The version of MSG at the time was then used to estimate the demand for energy carriers. The latter formed the basis for estimates of input to the Markal model. The potential overlap between the TFP in MSG and energy efficiency measures in the Markal model were estimated as a percentage of demand. The input to Markal was adjusted accordingly. In a scenario with a relatively strong emission reduction incentive – “green brainpower” – the demand reduction factor was increased from 0.5 % to 1 % (Alm 1998). The national scenarios assumed two different levels in economic growth and an increase in a national CO_2 incentive from about 40 US $/ton in 2010 to about 80 US $/ton in 2020. Stabilisation of the national energy consumption by 2020 was deemed possible with the high CO_2 incentive (NOU-98:11 1998). In 2005 yet another study, with input on technological possibilities from Markal, concluded that reducing emissions of CO_2 by about 70 % by 2050 was feasible and at an acceptable cost by introducing new technology into the energy system (Randers et al. 2006). The study has been criticized, both regarding the large increase in electricity demand by 55 % from 2000 to 2050 and the low cost estimated to meet the target. In Paper II, the increase in demand for electricity is estimated at about 27 % with the hybrid model.

6.1.1 The Norwegian Markal model

The Markal Norway model is part of a family of models with various geographic scales. Within the systems analysis modelling group at IFE, a Nordic model as well as county models are developed. The MARKAL model of the Norwegian energy system is focused on electricity generation and demand side. The Norwegian MARKAL model database contains more than 400 technologies with energy sources (38), processes (76), electricity- and heat conversion technologies (78) and demand technologies (229). They are allocated to the sectors residential, industry, transport, and agriculture, service and commercial. Most of the demand technologies are in the industry and residential sector while transport has 29 technologies and agriculture 1. A schematic overview of the Norwegian Markal model is given in Figure 9.

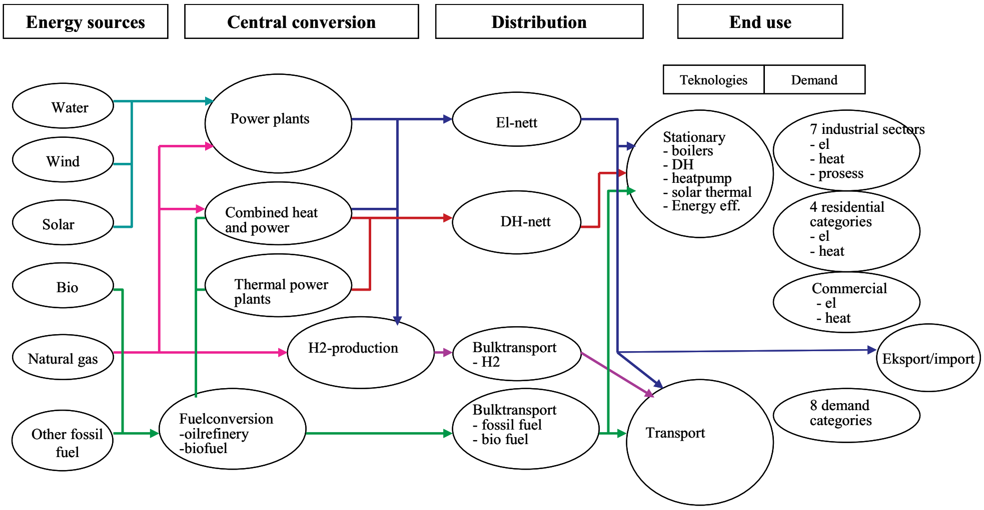

Figure 9 Simplified overview of the Markal Norway model reference energy system (Finden 2007, translated and slightly modified).

6.1.2 The MSG6 model

The macroeconomic model of the Norwegian economy is a computable general equilibrium (CGE) multi-sector growth model version 6 (MSG6). The MSG6 model is not one model, but rather a family of macroeconomic models developed for evaluation of policy, demographic changes and economic growth (SSB 2009). It has a detailed description of the structures in the Norwegian economy, e.g., production and consumption, see Figure 10.

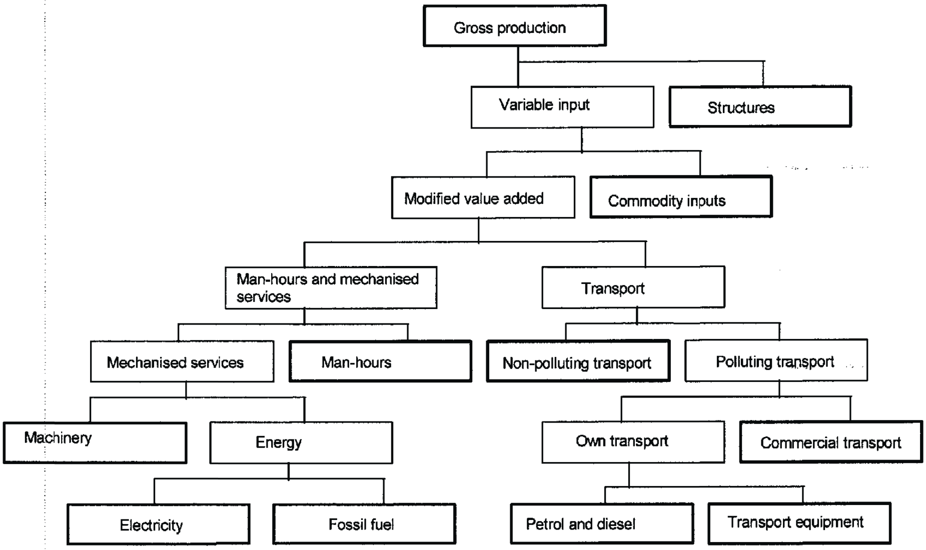

Figure 10 Schematic view of the production structure of the MSG mode (Heide et al. 2004).

The markets for energy and resources are linked making it a genuine equilibrium model. It is used for long term analysis of economic policy and its influence on economic growth and welfare. It also has an energy and emission module in order to analyse the influence of environmental taxes. The model has 41 private and 8 governmental production activities. TFP is exogenous and grows by 1.3 % per year in the private business sector. The TFP is equal for all production factors, e.g., labour, energy, capital, transport. There is however, decreasing returns to scale. The combined effect is a growth in productivity of about 1.1 %. In the household sector the TFP is zero. Together with the development of the model, a strong research group has also emerged. The active use of the model by the Ministry of Finance and the National Bank of Norway has also contributed to the strong standing of the model in national policy development.

7 Technology learning in a global – local perspective

Climate change and the need for increased energy generation in developing countries are both acknowledged as global challenges. Moreover, they are linked through the large emissions of greenhouse gases from fossil fuels. The emphasis on global co-operation to achieve a sustainable technology path laid out in the UNFCCC is unprecedented. Together with increasing globalization it moves the markets for energy technologies towards a common global market and technology path. It is highly uncertain though which technologies may become winners in this market and thus will dominate the technology path. Energy system modelling at the global level (see chapter 3) has provided insight. The global energy system, however, is merely the sum of the national energy systems. The question "what is in it for me" was directed to the IEA from the G7 meeting at Gleneagles in response to the ETP report Scenarios and Strategies to 2050. The IEA workshop "Towards country level granulation" was initiated in response to this request. Disaggregating the results of a global model to the individual countries, however, is difficult. Moreover, the question posed is universal and more than 50 countries use a national Markal model searching for insights to assist in the development of national policy.

National energy system analysis consistent with the global analysis will provide insights with respect to the national consequences of the global scenarios. The consistency requirement between the global and national level, however, is not obvious. Several studies including Seebregts et al. (1999), Edenhofer et al. (2006) and Grubler et al. (1999) find that incorporating technology learning makes an important difference in the global analysis. Capturing the influence of technology learning at the local level may be an important consistency criterion. This uncertainty calls for further investigation to determine how important the influence of technology learning at the local level is. Moreover, a method to include spillover while maintaining consistency with the global scenario is required.

The influence of technology learning is not limited to the energy sector. The energy system in a liberalized energy market is dynamically coupled to the other sectors of the economy. Demand for energy is elastic and dependent on the cost, particularly in the energy intensive industry. Technology learning in the global market may thus also influence the national demand for energy. Demand for energy is an exogenous parameter in an energy systems model like Markal. It may be provided by a macroeconomic model like the MSG6. A hybrid model capturing the feedback on total demand from the non-energy sectors is available as a standard option in the Markal model, i.e., Markal-Macro (Manne and Wene 1992). In order to investigate the influence of technology learning on the sector level, however, a hybrid model coupling demand for energy and energy cost at the sector level is required.

Technology learning may be global, national or even local, but deployment is always local. There is thus a dynamic coupling between national deployment and global learning. The feedback to the global development and manufacturing system from national deployment in a small economy like Norway is assumed negligible. Nevertheless, the decision to implement policies promoting technological change firmly rests at the national level. Commitments[16] under the UNFCCC and the EU renewable energy directive in particular, aim to promote deployment of nascent energy technologies. Development of indicators for monitoring the contribution by Parties to technology development, deployment and transfer under the UNFCCC has only just begun. The EU is applying an indicator[17] to allocate the commitment based on the relative share of renewable energy and energy efficiency in the national energy system (European Commission 2008). The EU approach may, however, not promote adequate support for the least developed technologies, e.g., offshore floating wind power, because the subsidies required per MW are higher than those needed for the technologies close to commercialisation, e.g., onshore wind power. Nevertheless, national governments may differentiate the policies and measures to encourage

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[16] Article 4.1c of the UNFCCC and article 2.1.a.iv of the Kyoto Protocol.

[17] The indicator measures the relative change in ΔQ = (renewable elect. + renewable heat/cooling + direct use of renewable energy carriers) / gross energy use

investment in the least developed technologies even though this indicator does not promote it. In addition to the lack of differentiation by the EU the need for financial support for technology deployment may vary depending on the global scenario and the corresponding spillover of technology learning from the global energy technology market (se chapter 2.3). An alternative method to measure the national contribution to a shift in the global technology path is therefore called for.

Spillover provides a boundary condition for all the modelling results presented in this thesis. In Paper I the sensitivity of the Norwegian energy system with different levels of spillover is investigated. It is compared with a special case where spillover for one technology is replaced by endogenous technology learning in the national niche market. In Paper II the method developed is exemplified by investigating the influence of spillover on the non-energy sectors of the Norwegian economy. The different steps in the soft-linking of the Norwegian Markal model and the macroeconomic model of the Norwegian economy MSG6 are described. Finally, in Paper III the method developed to measure the influence of technology specific measures over and above the general CO_2 tax and spillover is investigated. Each of the methods developed and the modelling performed are further introduced and discussed below.

7.1 Technology learning in a small open economy

The most common approach to include learning in energy system analysis is through technology learning curves. Learning curves (see chapter 2.2 and 2.4) represents well our current understanding of the influence of technology learning. Applying technology learning curves endogenously in a national model for technologies deployed in several countries, however, will yield distorted cost. This follows from Junginger (2005) who found that developing technology learning curves on the basis of national deployment data when there is multinational market, will give distorted progress ratio. Technology learning in the global market is perceived as spillover (see chapter 2.3) from a local perspective. To be consistent with the global analysis, spillover of technology learning should be included when the technologies are deployed in several countries.
Technology learning may be viewed applying a systems perspective. A system is “a set of elements connected together which form a whole, this showing property of the whole rather than the properties of the individual parts” (Checkland 1981). In order to

investigate the properties of the system we must draw the system boundary. The advantage of a systems perspective is that we do not need to follow the multitude of processes contributing to technology learning, but merely those that cross the selected system boundary. The technology learning curve is a property of a system. That is, a property of the elements within the system boundary. Elements which cross the system boundary must be treated explicitly in the analysis. The treatment of spillover in the analysis thus depends on the technology learning system boundary.

In general, the technology learning system boundary may change as the number of manufacturers' increases and technology deployment spreads through the global energy system. An illustration is developed in order to visualize the system view and my understanding of the technology development process, see Figure 11. It is showing three stylistic views of the learning system boundary. They are marked A, B and C. In A the learning system may initially have only one manufacturer and then expand to several manufacturers within a niche market. Because the same energy source, e.g., wind is available in many locations, technology development and manufacturing may initiate in completely separate niche market(s). The spillover between the niche markets 1 and 2 is negligible and the technologies are different specific technologies. They each have their learning system with a corresponding technology learning curve as indicated by the circle in view A in Figure 11. Several niche markets with knowledge spillover and export/import of parts may follow. This is indicated by view B. For example, wind mills manufactured in Denmark and Spain may include the same parts, e.g., the gear box. Finally, manufacturing are typically transferred to specialized sub-contractors as the market is expanding and the energy technology industry changes from manufacturing to assembling the final product. The knowledge spillover and trade then become extensive and includes complete technologies, e.g., wind mills. All contributions to cost reductions and efficiency improvements are then within the learning system boundary. The spillover crossing the system boundary of the national energy system is then limited to the cost reductions and efficiency improvements because of accumulated global production. In this work most technologies are assumed to have a global market and thus correspond to view C. For comparison, it is also investigated a special case where offshore floating wind is only deployed in a national niche market corresponding to view A.

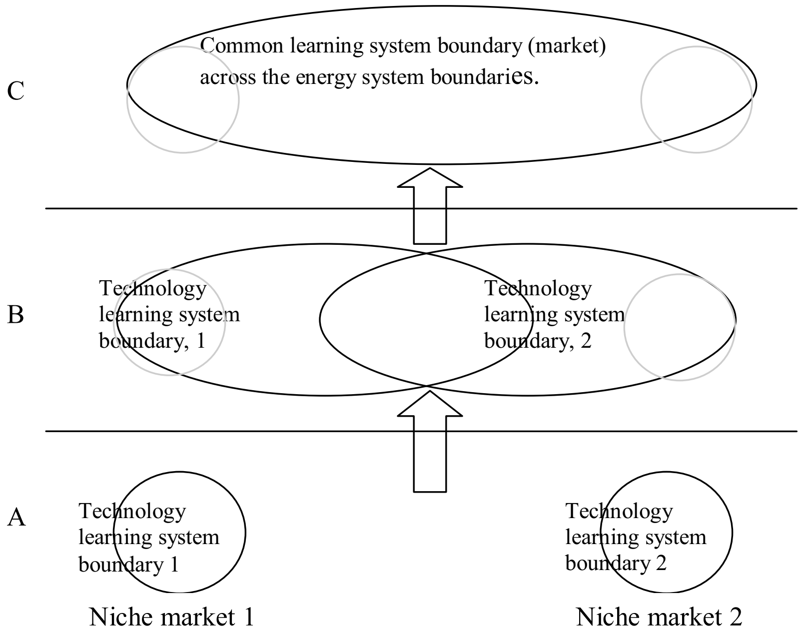

Figure 11 Three stylistic views of the technology learning system boundary within the technology diffusion stage (paper I).

In Paper I, I review the characteristics of technology learning important to determine spillover and discuss its application to energy system modelling in a global – local perspective. The dynamic nature of the learning system boundary and the feed forward and feedback between the *national* energy system and the *global* development and manufacturing system is elaborated. From the discussion some criteria important for the parameterization and modelling of spillover in a small open economy are suggested.

Applying view C I argue in Paper I that path dependence in the global energy system development calls for scenario specific spillover for the national analysis. Moreover, I argue that adaptation of a technology to national circumstances may increase or reduce cost and require adjustment compared. I also argue that embodied learning by using may serve as an important feedback from the energy system to the development and manufacturing system, see Figure 3. In the work presented in this thesis the ‘embodied learning by using’ loop is active, but only for adopting the technologies to local circumstances, e.g., icing on wind mill blades in northern Norway.

Finally, the element of local learning, ‘disembodied learning by using’, will only be captured when applying the market perspective system boundary for the technology learning curve. Applying a market perspective for one technology while the manufacturing perspective is applied to other technologies within the same analysis may cause double counting. In bottom-up models efficiency of a technology is an exogenous parameter. I argue that if using the market perspective LR, the efficiency should be constant for those technologies.

7.2 Introducing technology learning for energy technologies in a national CGE model through soft-links to global and national energy models

In a small open economy spillover of TL from the global market will in most cases be more important for the price of new energy technologies than experience gained in the national market. The cost of electricity in the national market will thus be heavily influenced by the cost of energy technologies in the international market. In Norway, where electricity is the dominant energy carrier and there is a significant energy intensive industry, changes in electricity cost also affect the demand for energy in the non-energy sectors of the economy. In the bottom-up energy system analysis demand for energy service (see chapter 2.6) is an important input parameter. While the MSG6 model does not capture technology learning and the dynamics of the energy system, the Markal model does not capture the interaction with the non-energy sectors of the economy. In the hybrid model developed Markal is given full control of the energy system, while the MSG6 handles all the remaining sectors of the economy; see Figure 12.

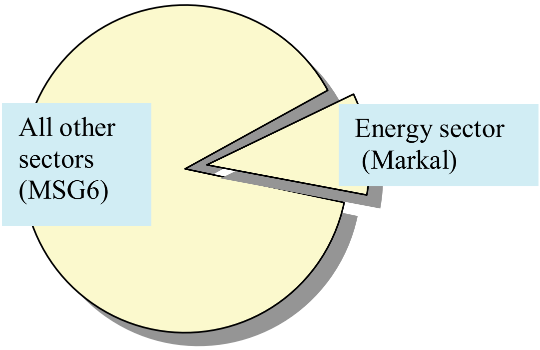

Figure 12 The division of tasks between the Markal Norway model and the macroeconomic model MSG6.

The models are soft-linked and communicate using a common protocol; the *demand transformer*. The protocol developed as part of this thesis is a core element in the establishment of the hybrid model. The basis for the demand transformer is the demand categories of the MSG6 and the Markal models. The MSG and Markal models have a relatively detailed description of energy carrier and energy service demand respectively; see Annex 1 to Paper II. In Paper II, I argue that the national Markal model seems well suited to carry forward the influence of technology learning in the global market to a macroeconomic model of the national economy.

The hybrid model may be used to provide insight beyond improved estimates of energy demand including spillover. In the macroeconomic model MSG 6, demand for energy is an indicator of economic activity. A hybrid model at the sector level may provide additional insight about the sensitivity of the sectors to technology learning. Comparison of energy efficiency measures implemented by Markal with the TFP or AEEI (see chapter 2.7) may provide insight about the level and the physical measures they represent. Moreover, the hybrid model may also be used to evaluate the effect on welfare of other policy measures when technology learning is present, e.g., country specific national taxation above a global CO_2 incentive. Building on the demand transformer a *result transformer* is developed. Markal is there used to estimate the CO_2 emission reductions and changes in energy system cost by sector. This information, together with information about the changes in technological composition of the energy system, is given back to MSG6. The result transformer and use of the hybrid model [EH2]to estimate the effect on welfare are not part of this thesis and are therefore not described further.

7.3 The demand transformer

The demand transformer is programmed in Excel. Data from MSG6 is received in a standardized format and transformed to match the demand categories of the Markal model. For most categories the following equation is used:

Equation 1 $\mathrm{DM}_i\,(\mathrm{t}) = \sum_{k=1}^{n} MSG_{k,i} \bullet \sum_{j=1}^{m} E_{j,k}(t) \bullet \eta_{i,j}$

DM_i is the demand for *energy service* input to the Markal Norway model where the index *i* denotes the demand category in Markal. $\mathrm{MSG}_{\mathrm{k,\,i}}$ is a constant linking MSG and Markal demand categories. When there is a one-to-one correspondence between categories $\mathrm{MSG}_{\mathrm{k,\,i}}$ equals zero for all k except for the single corresponding MSG category where it equals 1; when the Markal category corresponds to more than one MSG category each corresponding $\mathrm{MSG}_{\mathrm{k,\,i}}$ equals 1; see also Annex 1 to Paper II. The number of MSG6 categories, n, equals 41. In a few cases more than one MSG6 category is mapped into one Markal category *i*. This is typical for the less energy intensive sectors, e.g., the Markal category “other manufacturing industry”. $\mathrm{E}_{\mathrm{j,k}}$ is energy delivered by energy carrier *j* to MSG6 category *k*. $\eta_{i,j}$ is the conversion efficiency of the demand technology serving Markal category *i* and using energy carrier *j* as input. The technology efficiency is uniquely defined by the combination of Markal demand category and energy carrier. The number of different energy carriers in MSG6, m, is equal to 10. For the categories where Markal Norway has a more disaggregated categorisation than MSG the demand is first calculated using equation 1. It is then split and the fraction allocated to the Markal categories based on individual assumptions. Some details beyond what is included in Paper II are given below.

The category which is most aggregated in MSG6 compared to Markal is buildings. Several assumptions have to be made in order to allocate the energy service demand. The assumptions are not important for the results presented in this thesis. The share of thermal versus electricity specific energy service demand for buildings is assumed to remain about constant. The increase in electricity specific energy use thus follows the increase in total energy service demand. The demand for thermal energy service in existing buildings is assumed to increase an amount equivalent to the reduction potential in the energy efficiency measures included in the Markal Norway model. The remaining increase is allocated to new buildings. For commercial buildings it is assumed a linear replacement rate where all buildings are replaced by the end of the analysis period or refurbished to meet the prevailing building code. For residential housing 16 % is assumed replaced by the end of the analysis period. Finally, the demand for thermal energy in new buildings is divided into three demand categories; those build in the period 2006 – 2020, 2020 – 2035, and 2035 – 2050 respectively. The latter division is to facilitate analysis of a scenario with stricter national building code.

The standard MSG6 demand for energy carriers includes only electricity, gasoline, heating oil and auto diesel. Markal requires a complete energy budget. The demand for other energy carriers, e.g., natural gas, coal, coke, heavy oil, district heat and bio fuel in industry and trade and for residential use must therefore be added. The demand is extrapolated applying the economic growth rate for the respective demand categories. For the residential sector the gross amount of these energy carriers are assumed constant. An example of demand for energy service is shown in Figure 13. The visualization of total energy service demand including all energy carriers, long term cost of electricity and share of demand for specific energy carriers, e.g., share of electricity versus non-electric energy in industry, initiated discussions and revisions of the demand during the calibration of the models. When summed across all energy carriers the energy demand growth estimated by MSG6 for the energy intensive sectors refinery, metal production, pulp and paper and petrochemical industry was deemed unrealistically high by the researcher at Statistics Norway. These were therefore adjusted down consistent with historic development (Bjertnæs 2008). Bringing the two modelling approaches together, as is done in this work, is not just linking models but also bringing together two strong “schools of thought”.

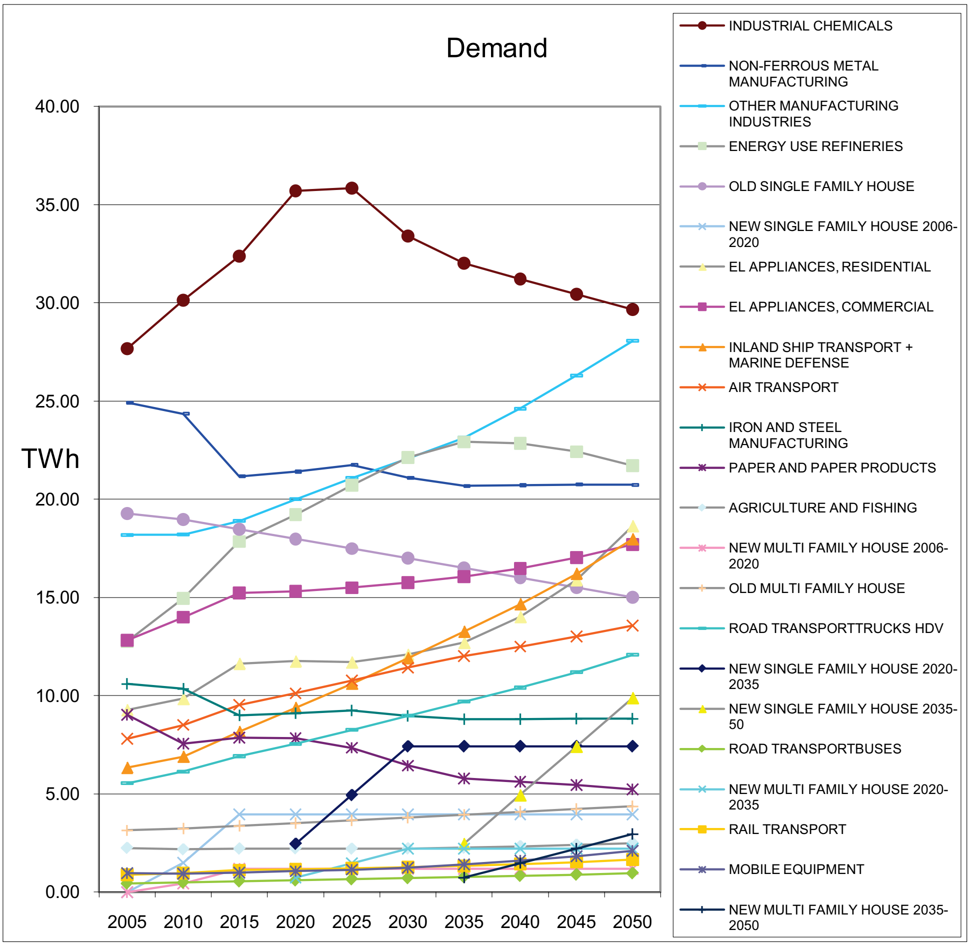

Figure 13. Example showing the demand for energy service in the reference scenario including all energy carriers.

7.4 Modeling spillover in a small open economy

The influence of spillover on the energy economy, CO_2 emissions and optimal technology composition from selected IEA scenarios is exemplified by Norway in Paper I. Moreover, the sensitivity of the Norwegian energy system to spillover is investigated. Learning in a national niche market is investigated for offshore floating wind power and compared with the influence of spillover. In this work three models are used. The global Energy Technology Perspectives (ETP) model, the national Markal model and the national macroeconomic model MSG6 are linked, see Figure 14. The link with the ETP model is a one way input of data to the national Markal model and the MSG6 model. These data constitute a national boundary condition for the analysis. The two national models are fully soft-linked. The MSG6 model provides demand for energy to Markal Norway. In this first part of the work the influence of spillover on the energy system demand is fixed at the reference scenario.

A step-by step approach is used to investigate the scenario specific influence of spillover (Paper I). The first step is to assure that the macro parameters, e.g., economic growth in both models is coherent. The second step is to estimate spillover from each of the selected global scenarios. The third step is to evaluate the dataset with respect to national circumstances. The steps are further elaborated below.

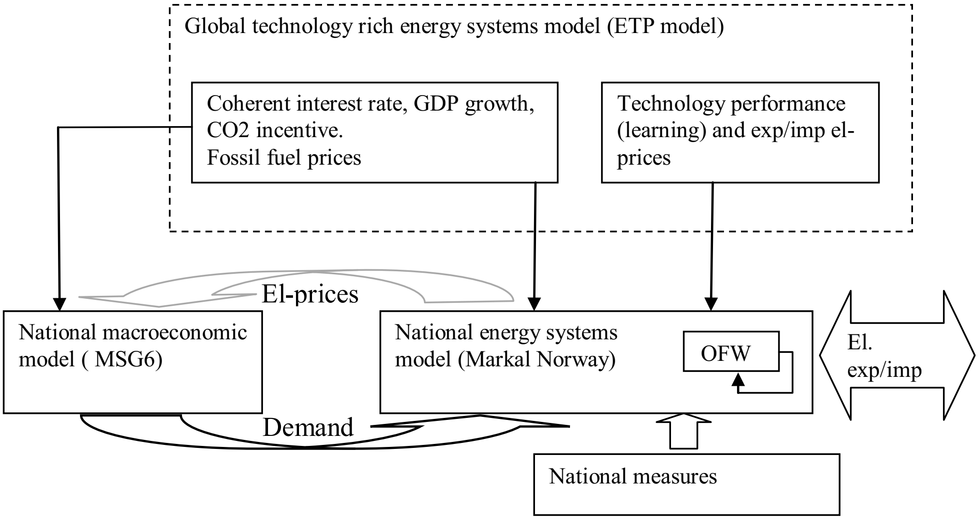

Figure 14. The model set-up consists of three models where the link with the global model provides a boundary condition for both the national models. The Markal Norway model handles the energy system, while feedback from the non-energy sectors of the Norwegian economy is provided by the macroeconomic model MSG6. The special case, where there is assumed a national niche market for offshore floating wind (OFW) is indicated by the feedback loop within the national model box (Martinsen 2010).

Economic growth may significantly influence the demand for energy. Because the global and national energy system models are set up to satisfy an exogenous demand for energy economic growth will also affect the total amount of technologies deployed globally and thus determines the learning potential. The estimated growth in the national economy and the interest rates used (Finansdepartementet 2000) are consistent with the assumptions for the western European region in the global model. This underpins the relevance of the global scenario(s). In step 2 spillover is incorporated in Markal Norway. Spillover tends to reduce investment and maintenance cost and may also improve the efficiency. Technology cost trajectories are determined by the Energy Technology Perspectives model (ETP) (Fulton 2008; Gielen 2006; Gielen and Alfstad 2008) on the basis of the accumulated global deployment and technology specific learning rates (IEA 2008)[18]. Efficiency improvements in the ETP model use the same basis. Because there are no learning curves available in the literature there is an element of expert judgement. An example of cost trajectories for the technologies offshore floating wind power and onshore wind power is given in Figure 15.

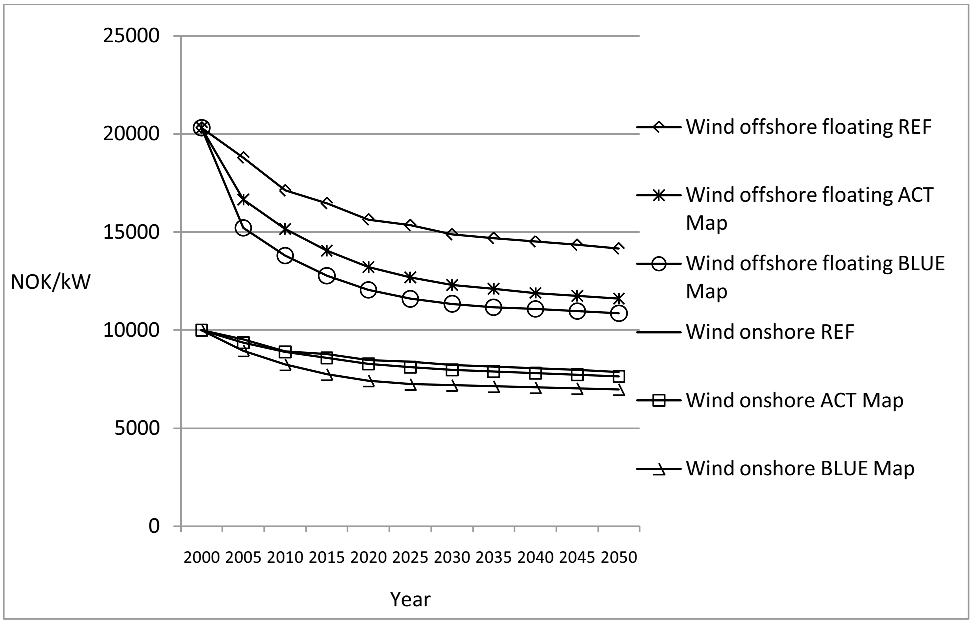

Figure 15 Investment cost trajectories for offshore floating wind power and the least costly onshore wind power category under the global scenarios REF, ACT Map and BLUE Map. These trajectories represent the resulting cost with spillover in the Norwegian Markal model.

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[18] Chapter 5, page 207.

Because the feedback from the Norwegian energy system to the global development and manufacturing system is assumed to be negligible the costs become time dependent input parameters. These trajectories provide the net cost for each 5-year time period in the Markal Norway model.

The cost trajectories are scenario specific. The starting cost of offshore floating wind is higher but the initial reductions in investment cost are greater. This is because the starting capacity is less and thus deployed capacity may double within a shorter time. In the global policy scenarios ACT Map and BLUE Map deployment increases and the costs are further reduced compared with the global REF scenario. Feedback to the global model because of changes in demand and thus technology deployment in Norway is assumed to be negligible. Net cost trajectories versus time may thus well represent the national boundary condition including spillover.

In the third step the onshore wind power categories are adjusted because of national circumstances, e.g., complex terrain. An example of the adjustment is shown in Figure 16. The trajectories for investment cost, fixed operating and maintenance cost and efficiency for each of the technologies with spillover (see appendix 1 to Paper I) are programmed as time series in excel. The scenario specific time series containing the technology and energy carrier data is imported to Markal Norway in order to run the different scenarios.

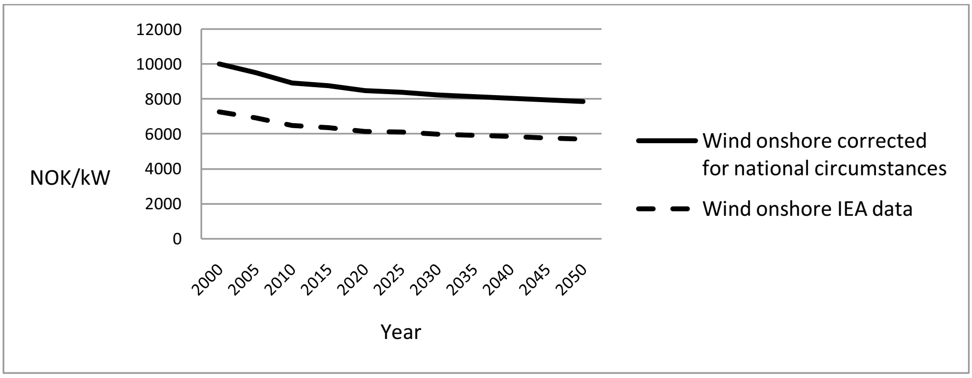

Figure 16. The investment cost trajectory for the least costly onshore wind power category under the global REF scenario with and without adjustment for national circumstances.

A set of scenarios have been selected to investigate the influence of, and sensitivity to, spillover (Paper I). In addition to the reference scenario, two scenarios representing a moderate and ambitious global CO_2 emission reduction illustrate the combined influence of spillover and the global CO_2 tax. To investigate the sensitivity to spillover only, three supplementary scenarios are investigated. One has no spillover, e.g., constant technology cost, and in two the CO_2 tax only is increased while the spillover is retained at the reference level. Finally, in two of the scenarios one selected technology does not benefit from spillover. In this case the endogenous technology learning option in the Markal model is used. That is, the developed framework for spillover is applied for the other technologies while a technology learning curve is specified for offshore floating wind. Comparing the scenario result with the corresponding spillover scenario may provide further insight with respect to the relevance of the developed framework for spillover. More interesting perhaps, it may indicate if OFW may become competitive in the national niche market alone.

The analysis shows that spillover from different global scenarios significantly affects the system cost, CO_2 emissions and technology composition of the energy system of a small open economy like Norway up to 2050. Moreover, the technology composition exhibits sensitivity to variations in the level of spillover within a scenario. The CO_2 emissions are less sensitive when the CO_2 tax is high. Offshore floating wind power

(OFW) shows particular sensitivity to technology learning. The national energy system development only includes OFW when spillover is present or when a high learning rate is assumed in the national niche market. The CO_2 tax alone does not provide sufficient support for this technology. The results indicate substantial benefit for Norway from spillover under the global policy scenarios. Contra-intuitive, global technology learning may reduce both national CO_2 emissions and total system cost. That is, if the industrial and electricity export opportunities, provided by the large offshore wind resources, are exploited.

While technology learning is important for the development of the energy system, it will also interact dynamically with the other sectors of the economy, e.g., through change in prices of the energy carriers (Paper II). The influence of spillover on the non-energy sectors of the Norwegian economy is most pronounced on the industrial chemicals, i.e., production level and electricity for residential energy service demand. The influence is modest, however, because all existing electricity generating capacity is hydroelectric and thus compatible with the low emission policy scenario. In countries where most of the existing generating capacity must be replaced by nascent energy technologies or power plants with carbon capture and storage the influence on demand is expected to be more significant. The development of a soft-linked hybrid model, Markal Norway – MSG6 (Paper II), has also given some insight about the content of the "black box" represented by the total factor productivity in MSG6 (see chapter 2.8). The increase in demand for energy carriers are reduced because of the energy efficiency measures and new technologies identified by Markal.

Without the framework and the criterion developed in this work, scenario specific spillover may not be accounted for. However, the approach using time dependent cost trajectories is not dependent on the developed criterion. Cost trajectories based on individual assessment of the deployment potential of each technology may overestimate the influence of spillover because the sum of energy carrier generation is larger than the demand. Moreover, the relative share of each technology is then determined by the analyst. Analyzing various technology paths, assuring consistent energy carrier supply and demand, may provide insight, e.g., through mapping the uncertainty in systems cost and technology cost estimates. Such an approach, however, does not capture the dynamic coupling between the global development and the manufacturing system and the national energy systems.

While both the input data to, and the results from, the global model have been quality assured through the IEA and its underlying network of experts, other global models and scenarios will generate other results. Further analysis using data from other models and scenarios are recommended. The uncertainty in the LR applied is emphasized in chapter 2.3. There are other assumptions as well. The uncertainties introduced may be grouped into three categories, (1) underlying assumptions, (2) different approaches for simplifying the models and (3) different assumptions concerning model parameters (van der Zwaan and Seebregts 2004). Only a few of the parameters affected by these categories are directly related to technology learning, but as it is endogenous in the global models the resulting technology path may be sensitive to all the parameters.

7.5 An incentive scheme for governments to assume the high cost of early deployment

The high cost of early deployment of the nascent energy technologies is a barrier for the investors. Moreover, a price on carbon, e.g. a CO_2 tax may not be adequate to reduce emissions at a sufficient pace and scale (Stern 2006). Because of the urgency of the climate change problem and large risks connected to investment in nascent energy technologies the Stern review (2006) calls for policies to support the development and deployment of a portfolio of low carbon technology options. The decision to implement policies promoting technological change firmly rests at the national level. Timely realisation of a global energy technology path, consistent with the recommendations of the IEA, thus depends on coordinated national policies to exploit the learning opportunities of the selected technology path. Incentives and indicators of concerted action is therefore of interest.

In Paper III a new indicator called investment support (IS) for the national contribution to global technology development is suggested. It builds on the concept of learning investments but deducts the influence of the global scenario. That is, the benefit Norway has from spillover in the analysis is not credited. In Paper III it is argued that technology learning may be both a barrier and an incentive for technology change in the national energy system. The indicator does credit the high cost of the early movers. Moreover, the possibility to realize an ambitious global emission reduction scenario is enhanced by coordinated action between countries in national policy implementation.

IS captures two important aspects of national support for technology learning. It measures support over and above what is generally required by an agreed international CO_2 –incentive, administrated, e.g., through internationally tradable emission certificates. It focuses on the high cost of early deployment because it measures the economic contribution rather than the increased deployment in physical units, e.g., MWh and thus serves as a complement to the EU indicator. Because early deployment has higher cost I argue that investment support before a technology becomes commercially viable, with the CO_2 incentive, is a preferred indicator of alignment. The analysis shows that the CO_2 incentive alone will initiate Norwegian deployment supporting the realization of the global ACT Map policy scenario. The additional feed-in tariff for wind power initiates earlier deployment and increases IS.

From a policy perspective, recognizing the urgency in the need for action to reduce emissions of CO_2, further development of incentives and indicators for concerted action should be top priority. A study of the interaction between the Norwegian and United Kingdom with respect to niche market deployment of offshore floating wind was initiated but not completed. Identifying such potential niche markets, across national boundaries, where selected technologies have the best opportunities to become cost efficient is recommended. Moreover, further analysis of the need for policy incentives, under uncertainty or using a game theoretical approach may provide additional insight.

8 Final remarks

In this thesis the interplay between technology diffusion, niche markets and experience curves are investigated in a national perspective. Three methods to include technology change in national energy system analysis are developed, applied and used to assess the influence of technology learning on a small open economy. A modelling framework consisting of a global energy systems model, a national energy systems model and a national macroeconomic model is used. The first method facilitates input from the global model to the national energy system models consistent with our knowledge of technology learning curves and is the basis for all the work in this thesis. The second method soft-links the two national models and the third method is a means to measure the national contribution to diffusion of nascent energy technologies. The methods are applied to Norway.

The review of the technology learning systems points at the importance of the feed forward and feedback between the global energy technology development and manufacturing system and the national energy system(s). It concludes that that spillover should be estimated by a global model and should emanate from the same scenario and technology path. This is to assure consistency with characteristics of the technology learning curve, i.e., that the energy balance and technology path dependence in the global energy system is taken into account. Adaptation to national circumstances may be required and is implemented for one technology. The modelling framework provides boundary conditions not only for the investigation of spillover on the energy system but also on the non-energy sectors and the indicator for national contribution to global change. These boundary conditions also influence the demand for energy service, an important parameter in energy systems analysis. The soft-link with the macroeconomic model is therefore an integrated element of the modelling framework facilitating consistency with the overall economic development and the behaviour of the non-energy sectors.

The modelling results underpin the starting point for the work; that spillover may significantly influence the development of the national energy system of a small open economy. The analysis shows that the Norwegian energy system up to 2050 is sensitive to the level of spillover and thus the global scenario. Spillover significantly affects the system cost, CO_2 emissions and technology composition. The influence of spillover on the non-energy sectors is discernable, though modest, as would be expected for an energy system where electricity is the main energy carrier and 99.5 % of existing electricity production is hydro electric power. However, linking the two modelling "schools of thought" and replacing the total factor productivity for technology with physical energy efficiency measures had substantial influence. Introducing a targeted national subsidy for the nascent energy technologies onshore-, near shore- and floating offshore wind power and NGCC with CCS significantly increases Norway's contribution to early deployment of the nascent energy technologies. Both onshore wind power and offshore floating wind power is under the global policy scenarios deployed earlier with the subsidy than with spillover and the global CO_2 tax only.

The results indicate substantial benefits for Norway from spillover under the global policy scenarios. Contra-intuitive, spillover of global technology learning may reduce both CO_2 emissions and total system cost. That is, if the industrial and electricity export opportunities, provided by the large offshore wind resources, are exploited. Assuming no spillover for offshore floating wind power but learning in the national niche market at the same learning rate as the global scenario yield, as expected, a very different result. However, offshore floating wind power may become competitive with a high learning rate and a CO_2 incentive above 300 NOK/ton[19]. In this case the contribution to the indicator for investment support (IS) is larger than with spillover. The contribution by a country that takes on the role of "first mover" may then be acknowledged through crediting the high value of the national investment support compared to the case with spillover.

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[19] About 50 US $/ton

The results illustrate the capacity of the methodologies to highlight the interconnectedness between the national energy system(s) as well as the non energy sectors and the technology development and manufacturing system. The framework developed thus facilitates inclusion of spillover in national energy system analysis consistently across technologies and energy carriers. Moreover, soft-linking a detailed national macroeconomic model and an equally detailed energy systems model with scenario specific input on spillover indicate that the energy systems model is suitable to carry forward the influence of spillover to the non-energy sectors of the economy. The framework facilitates transparency from the assumptions in the global model through the national energy systems model to the non-energy sectors in the national macroeconomic model. The indicator suggested, IS, facilitates support for the high cost of early deployment and increases transparency in the national contribution the realization of a sustainable global technology path.

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Paper I

Paper I

Technology learning in a small open economy

- The systems, modeling and exploiting the learning effect

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Abstract

This paper reviews the characteristics' of technology learning and discusses its application to energy system modelling in a global – local perspective. Its influence on the *national* energy system, exemplified by Norway, is investigated using a global and national Markal model. The dynamic nature of the learning system boundary and coupling between the *national* energy system and the *global* development and manufacturing system is elaborated. Some criteria important for modelling of spillover[1] are suggested. Particularly, to ensure balance in global energy demand and supply and that alternative global technology pathways are accurately reflected spillover for all technologies as well as energy carrier cost/prices should be estimated under the same global scenario. The technology composition, CO_2 emissions and system cost in Norway up to 2050 exhibit sensitivity to spillover. Moreover, spillover may reduce both CO_2 emissions and total system cost. National energy system analysis of low carbon society should therefore consider technology development paths in global policy scenarios. Without the spillover from international deployment a domestic technology relies only on endogenous national learning. However, with high but realistic learning rates off-shore floating wind may become cost-efficient even if initially deployed only in Norwegian niche markets.

Key words: National energy systems analysis, technology learning, niche market, CO_2 emissions, wind power

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[1] Spillover in this paper includes the effect of technology learning embedded in the technologies purchased in the global technology market, i.e., cost reductions and efficiency improvements resulting from accumulated global production.

1 Introduction

The development of the national energy system depends on a large number of factors external to the system but strongly influencing choice of technology and energy carriers. A taxonomy of such factors used by Wene and Rydén (1988) is: availability of domestic energy sources, cost of imported energy carriers, development of the energy technology, environmental constraints and energy demand. The taxonomy includes global, regional and national factors. A corresponding global-local perspective is thus called for in national energy planning and analysis. For example, there may be a choice between local-renewable energy and fossil energy from the global market. While the price of fossil fuel is mainly determined by the balance of regional supply and demand, the exploitation of local renewable energy requires energy conversion technologies whose costs and technical performances are largely determined in the global technology markets. From the national perspective the cost reductions of the nascent energy technologies is seen as spillover of technology learning from the global technology market.

Understanding the forces of technological change and incorporating them in energy – economic – environmental (EEE) models have received increasing attention during the last decade. Different global EEE models provide a variety in their results with respect to future technology composition and total system cost, but concur that experience foster technology learning (TL) and is an important factor affecting the cost of the transition to a sustainable energy system (Edenhofer et al. 2006). The starting point of the analysis presented is the assumption that in a small open economy spillover from the global market will in most cases be more important for the price of new energy technologies than experience gained in the national market. However, in the very early stages of technology development learning in the national market may dominate. While TL reduces costs, national circumstances may require adaptation of a technology and thereby increasing costs. In the long run, though, it is also a source of learning and thus indirectly contributes to cost reductions. The aim of this paper is to contribute to the understanding and modelling of the effect of technological change on the *national* energy system of a small open economy. It is exemplified by Norway.

In Norway, primary energy sources are abundant; particularly wind offshore and natural gas. There is also potential for storage of CO_2 underneath the sea bed. There is thus ample potential for electricity generation with low or zero CO2 emissions. The development of the Norwegian energy system towards low emissions of CO_2 may thus follow a variety of technology paths, depending on the cost development and performance of the nascent energy technologies available in the global market. Moreover, Norway's energy resources and engineering capacity offer possibilities as a cradle for offshore floating wind power, thus influencing the technology path through TL in a national niche market.

We ask three questions: (1) How should spillover be included when modelling the energy system of a small open economy? (2) What is the potential influence of spillover on the Norwegian energy system? (3) What is the sensitivity of the *national* system to spillover and will learning in the national market give a similar result? The elucidation of the application of spillover on the *national* energy system analysis in a globalized energy technology market is novel. It contributes to the stock of knowledge on modelling TL with a focus on the national energy system.

The first part of this paper reviews the properties of TL relevant to a small open economy and discusses it in a global – local perspective. From the discussion some criteria important for the parameterization and modelling are suggested. The criteria are subsequently applied to evaluate the influence of spillover on the Norwegian energy system up to 2050. Two national cases are analysed: (1) Spillover of TL dominates and the local TL is assumed negligible, and (2) a special case where learning for offshore floating wind power (OFW) is dominated by the national niche market. While the other technologies benefit from spillover, TL for OFW is modelled endogenously and thus dependent on national deployment only. The results presented focus on the overall system performance and technology composition of electricity conversion and light duty vehicle (LDV). Finally, some conclusions are drawn and suggestions for future work offered.

2 Theory and application

Though stochastic at the micro level the influence on cost from learning may be approximated by a simple mathematical relation (Argote and Epple 1990; Wright 1936) using a systems approach[2]. The properties of this system is the initial cost C_0, the learning parameter E, the accumulated production and the resulting cost $C(X_{cum})$, see Equation 1. Rather than using the learning parameter E directly, a progress rate (PR) or the learning rate (LR) is used. Its relationship to E is defined in equation 2. A technology learning curve is a graph of cost vs. accumulated production most often presented in a log-log diagram where it becomes a straight line. The relative cost reduction or percentage is thus constant for each doubling of production and equal to the learning rate.

Equation 1 $C(X_{cum}) = C_0\,(X_{cum})^{-E}$

Equation 2 $LR = 1 - PR = 1 - [C_0\,(2X_{cum})^{-E} / C_0\,(X_{cum})^{-E}] = 1 - 2^{-E}$

Experience and learning curves provide a quantitative measure of TL, exhibiting a continuous reduction in cost with cumulative production of the technology. While the mathematical relationship is simple, sensible use of equation 1 requires careful evaluation of the system boundary (Schaeffer et al. 2004)[3]. The choice of system boundary defines the technology with a cost C and thus what may contribute to cost reductions through learning. Moreover, only production within the system boundary may contribute to X_{cum}. Finally, the learning parameter E will vary depending on what learning processes are included within the system boundary. Each of these issues is elaborated further in section 2.1 below. Another issue important for the inclusion of learning in *national* modelling is the non-linearity of Equation 1. This causes path dependency enhancing the coupling between the global, regional and local energy systems and is discussed in section 2.2.

2.1 The system boundary

The system boundary of learning by doing (Arrow 1962) was confined to the increased labour productivity in a production process while the term *experience* was introduced covering all aspects influencing the cost development of an industrial product (BCG et al. 1968). BCG et al.

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[2] A system is a set of elements connected together which form a whole, this showing properties of the whole rather than the properties of the individual parts" (Checkland 1981).

[3] Page 86.

(1968) included more elements affecting the cost reduction within the system boundary and found the system characteristic valid i.e. equation 1 and 2. The importance of experience was generally accepted and the concept used, e.g., to assist investments decisions within corporations. Utilizing this concept to determine cost development for an energy technology across producers expands the system boundary further. Following the IEA terminology, this paper uses the term *technology learning* to denote all those processes within a firm, group of firms or industries that lead to cost reductions in a *specific technology*, e.g., onshore wind power, as a result of actions in a competitive market (IEA 2000).

A study comparing experience curves with technology bottom-up assessment find support for treating wind turbines as a *specific technology* (Neij 2008). While there may be more technological variety within other generic conversion technologies, e.g., solar PV, Neij (2008) concludes there is reasonable support in bottom-up technology analysis treat the major types of electricity generation technologies as specific technologies. The conclusion is useful with respect to modelling TL on a global scale. However, the approach may conceal the introduction of a new technology or the specialization an existing one until it should be viewed as separate specific technology. This process typically takes place within a smaller system boundary, e.g., the national energy system. For example, offshore floating wind mills may initially use a turbine developed for onshore wind mills and thus be very similar but with a floating base. Because floating wind mills demand much lighter turbines the number of common parts and construction may diverge so much that the turbine for offshore floating wind should be considered a separate specific technology with a non-overlapping technology learning system with onshore wind. In general, the system boundary may change as the number of manufacturers' increases and technology deployment spread through the global energy system, see Figure 1. Three stylistic views of the learning system boundary are extracted and described. They are marked A, B and C in Figure 1. In A the learning system may initially have only one manufacturer and then expand to several manufacturers within a niche market. Because the same energy source, e.g., wind is available in many locations, technology development and manufacturing may initiate in completely separate niche market(s). The spillover between the niche markets 1 and 2 is negligible and the technologies are different specific technologies. They each have their learning system with a corresponding technology learning curve as indicated by the circle in view A in

Figure 1. Several niche markets with knowledge spillover and export/import of parts may follow. This is indicated by view B. For example, wind mills manufactured in Denmark and Spain may include the same parts, e.g., the gear box. The learning system boundaries are now overlapping while the technologies may still viewed as separate specific technologies. The spillover between the two learning systems is crossing the system boundaries and consequently becomes a property of the system that must be treated as an exogenous variable in the analysis. This view will not be further discussed in this paper.

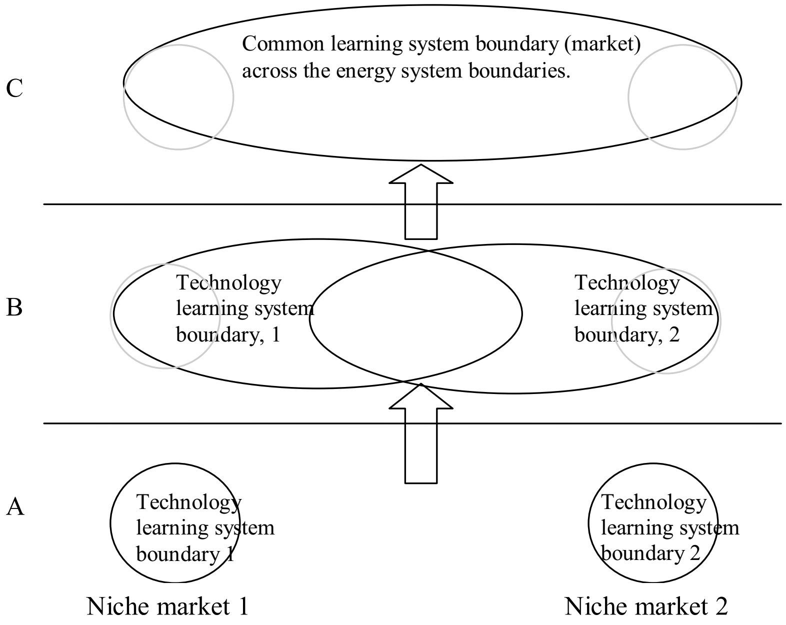

Figure 1 Three stylistic views of the technology learning system boundary.

Finally, manufacturing are typically transferred to specialized sub-contractors as the market is expanding and the energy technology industry changes from manufacturing to assembling the final product. The knowledge spillover and trade then become extensive and includes complete technologies, e.g., wind mills. This is not merely an internationalizing process where the same technology spreads geographically but a globalizing process including also a functional integration. In the globalizing process the functional integration increases, e.g., the production chains and production networks become more harmonised (Dicken 2003). The energy system(s) then “sees” only one specific technology as is illustrated by view C. “*When a global market exists for a technology, constructing a learning curve based on national deployment data will yield distorted progress ratios*” (Junginger 2005) [4]. View C thus calls for a global model to determine TL and its spillover to the national energy system. In view A TL may be endogenous in the optimizing routine because the deployment within the national niche market dominates the contribution the TL. View C is applied in this paper exempt for the special case where view A is applied for offshore floating wind, see Section 4.

2.2 Global and national learning

The deliberation above has focused on assumptions affecting the development of accumulated production (X_{cum}) in Equation 1. This section elaborates on the coupling between the national and global systems and the national learning processes affecting the learning rate E. A simplified diagram showing the learning system boundaries of the development and manufacturing system and the energy system, and selected technology learning mechanisms based on IEA (2000)[5] and Neij et al. (2003)[6] is shown in Figure 2. Following the cybernetic approach in IEA (2000) and Wene (2008) learning by (re)searching (LBS) and learning by doing (LBD) (Arrow 1962) may be viewed as feedback loops within the development and manufacturing industry. These learning mechanisms will not be discussed further.

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[4] Page 58.

[5] figure 2.2 and 2.9. As the driving forces for technology learning are not discussed here, the external feed-back loops in IEA (2000) are left out of figure 2 above.

[6] figure 2.3 and 3.1

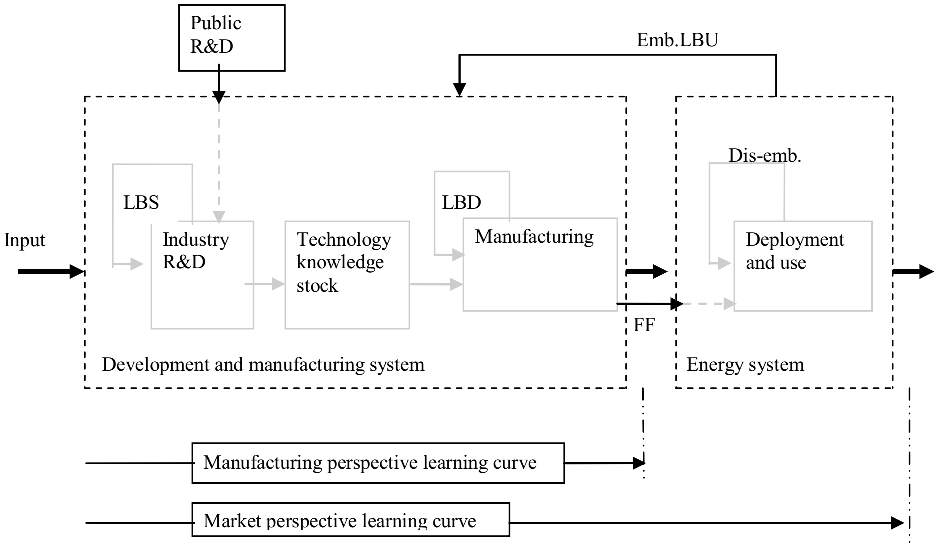

Figure 2 Simplified diagram showing the system boundaries and selected technology learning mechanisms. The broken lines indicate the system boundary of the development and manufacturing learning system and the energy learning system respectively. The two systems are linked through the learning by using (LBU) feedback loop and the feed forward (FF). Based on figure 2.2 and 2.9 in IEA (2000), figure 2.3 and 3.1 in Neij et al. (2003).

The development and manufacturing system is closely linked to the users of the technologies in the national energy systems. The performance, e.g., cost development, of the specific technologies is input from the global development and manufacturing system to the national energy system. The actors in the manufacturing system and the energy system are separated by a market. There is, however, a systemic interdependence between the systems where both the producer and the user have an interest in sharing information (Lundvall 1992). In this context learning by using (LBU) and the feed forward (FF) are of special interest. The feed forward (FF) coupling enables the actors in the development and manufacturing system to optimize the initial performance of a specific technology within the national energy system. It is thus an important source of spillover. LBU takes place in the national energy system. It may be split in embodied and disembodied (Rosenberg 1982). While embodied LBU refer to changes in the product delivered by the development and manufacturing system, disembodied LBU refers to changes in the operation and maintenance. Disembodied LBU may be viewed as an internal feedback loop within the national or even local energy system while the embodied LBU is a feedback from the national energy system to the development and manufacturing system. Adaptation of a technology because of national circumstances is a source of feedback and is critical for continuous development of a technology. Adaptation may be required, particularly when used in a harsh environment, e.g., cold climate with potential for icing on wind mill blades. The adaptation of a technology tends to increase the cost. Real time monitoring of turbine performance and annual consumer surveys is among the tools used to assure that LBU is fed back to the wind mill producer (Vestas 2009). The combined effect of the feed forward and feedback of embodied LBU will reduce the need for adaptation in the long term.

Disembodied LBU primarily affects the operation, but may also improve the process or routine of deployment and reduce the cost of electricity produced. Disembodied LBU thus includes an additional learning component; "*modifications in the product itself giving a better product, e.g., more efficient, more durable and better suited to our needs*" (Rosenberg 1982). Examples include more efficient equipment to erect the wind mill towers and better forecasting of production that increases the sales value of near term electricity production. Disembodied LBU may hence contribute to learning through increasing the efficiency in use and reduce the investment cost of a complete technology, e.g., of the wind mill or a wind mill park rather than the turbine only. Two distinct perspectives have been suggested, the development and manufacturing perspective and the market perspective (Neij et al. 2003), see Figure 2. Disembodied LBU will only be captured in the market perspective. The market perspective often uses amount- vs. cost of electricity generated while the manufacturing perspective uses the number of units produced or shipped vs. production cost/price as variables. Neij (2008) recommends applying the LR determined using the market perspective in policy analysis. However, Markal models have investment cost as input variable, while the cost development of the electricity is endogenous. Furthermore, technology learning curves for efficiency improvement, complementary to the cost development is not available in the literature. This raises the question; Can we apply a LR calculated using a market perspective to estimate the investment cost, i.e., manufacturing perspective? For wind power where the energy source is free and the cost reductions and efficiency gain because of disembodied LBU directly affects the cost of electricity my answer is yes. However, the efficiency of a technology is an exogenous parameter in the Markal model and should be constant to avoid double counting if applying the market perspective LR. In the case where the efficiency increase is measured as reduced use of an energy carrier, including it in the LR will cause errors, e.g., in the mass balance constraint for the energy carrier and in the CO_2 emission calculation. The market perspective LR can therefore not be used when modelling.

Using experience curves to have an endogenous description of technology learning in EEE optimising models cause computational difficulty due to their non-linearity. It was resolved for the MESSAGE model (Messner 1997) and the GENIE model (Mattsson and Wene 1997) in parallel. The approaches and thus the model behaviours are slightly different. The non-linear approach with the GENIE model revealed the existence of several optima at almost the same system cost but with very different technological composition. A path dependency with respect to the technological composition because of endogenous technological change has also been observed in later work with the MESSAGE model (Rao et al. 2006). Path dependency is an inherent feature of technology learning and should not be confused with effects of alternative scenarios. Wene (2008) interprets the existence of optima with different technological compositions as the result of the *structural coupling* (Varela, 1979) between the energy system and the technology developing and manufacturing system, meaning that the two systems select each other's trajectories creating an interlocked history of transformations. Technology learning thus appears as one important source for the path dependency of technology development discussed in evolutionary economics and in analysis of national systems of innovation (Cimboli and Dosi 1995) (Cowan and Gunby, 1996; Kemp, 1997). The path dependency enhances the coupling between the global-regional-national energy systems. The national energy system actor must therefore in their strategy planning consider technology development paths in the global energy system. The important observation for this paper is that choices made in the *global energy* system will decide the future cost of technologies produced by the *developing and manufacturing* system. Analysis of the national energy system of a small open economy therefore requires evaluation of spillover and the importance of country specific circumstances. The discussion shows that two types of analytical instruments are required to analyse the impact of TL on a *national* energy system. Investigation of spillover needs a global model with a realistic representation of learning opportunities for different technologies in different regions of the world. The global model should assure consistency between exploited learning opportunities and balancing supply and demand in the global energy system. Furthermore, in order to have a consistent characterisation of technologies in a national model, the spillover for all technologies must refer to the same global scenario and selected global technology path.

3 Method

The impact of spillover on Norway's energy system is investigated with a Norwegian version of the Markal model (Fishbone and Abilock 1981). It includes the mainland energy system and offshore oil producing installations. Export and import of electricity is constrained by existing transmission capacity. The Norwegian energy system and Markal model is briefly described in Appendix A. A simplified overview of the Norwegian energy system indicating the technologies influenced by spillover is also included. In this study, demand for energy service is received from the macro-economic model of the Norwegian economy MSG6[7] (Heide et al. 2004) run by Statistics Norway. The Norwegian Markal model is fully soft-linked to the MSG6. The soft-link captures the feedback on demand for energy service from spillover. The variation in demand in Norway because of different levels of spillover between the global scenarios is modest (Martinsen 2010b). Demand is therefore retained at the level obtained in the reference scenario in the analysis presented in this paper. The national boundary conditions, e.g., spillover, are obtained from the Energy Technology Perspectives model (ETP) by the International Energy Agency (Fulton 2008; Gielen 2006; Gielen and Alfstad 2008). The modelling framework is shown in Figure 3. Two cases are analysed. In the first case it is assumed that Norway is a price taker and thus the technology cost reductions and efficiency improvement is given by the global model. That is, view C in Figure 1 is applied for all technologies. In the second case "learning in a domestic strategic niche market", view A is applied for offshore floating wind power (OFW) while view C is used for the other technologies.

A step-by step approach is used to estimate the scenario specific spillover from the global model to the national model. The first step is to assure that the macro parameters, e.g., economic growth in both models is coherent. The second step is to estimate spillover, e.g. technology costs and

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[7] Multisectoral growth model version 6

import/export prices for energy carriers for each of the selected global scenarios. The third step is to evaluate the influence of national circumstances. The steps are elaborated below.

3.1 The national boundary condition

The ETP model is a global bottom up Markal energy systems model (Fishbone and Abilock 1981) with 15 regions. In the scenarios the global GDP is assumed to grow four-fold while in Europe it nearly doubles (IEA 2008)[8]. This matches well with the expected growth used to determine the Norwegian national demand for energy services. The interest rate used in the ETP model varies between sectors but the average matches well with the 6.5 % used in the Norwegian model. This completes step one.

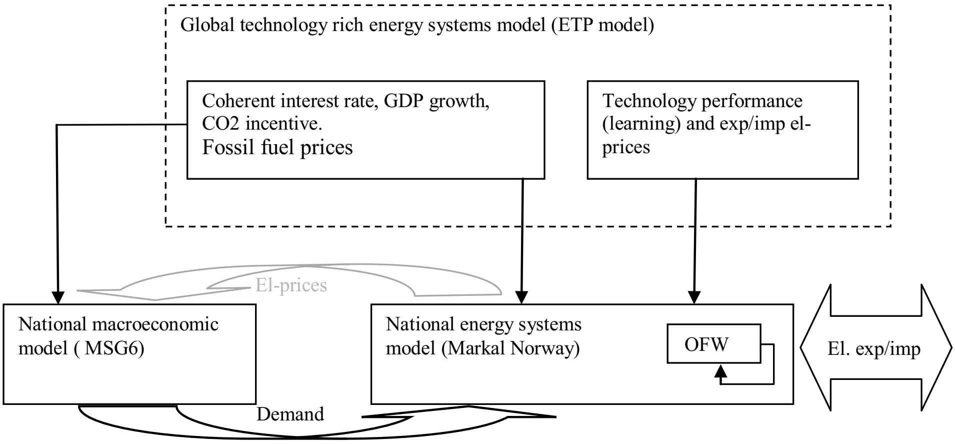

Figure 3 The model set-up consists of three models where the link with the global model provides a boundary condition for both the national models as well as spillover to Markal Norway. The soft-link with the MSG6 model is only active in the reference scenario in this paper. The special case, where there is assumed a national niche market for offshore floating wind (OFW) is indicated by the feedback loop within the national model box. Slightly modified from Martinsen (2010a).

In step two spillover is included in the national analysis by importing the scenario specific cost and efficiency trajectories from the global model. Moreover, the ETP model provides cost

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[8] ETP 2008 Report, Annex B, page 570.

trajectories versus time for oil, natural gas, coal, liquid bio fuel, electricity, technology investment cost and efficiency. The present and future characteristics of technology options, e.g., costs and potentials in the ETP model database are based on expert information from-, and the results a consensus of, the IEA and its implementing agreements and other sources (IEA 2008)[9]. The technology cost trajectories are determined on the basis of the accumulated global deployment and technology specific learning rates (IEA 2008)[10]. For large plant-like facilities with very long lifetime, e.g., gas power with CCS several vintages with improved efficiency and/or declining cost are used rather than applying the improvements in cost and efficiency from the technology learning analysis to the generic technology. The global preference of light duty vehicle (LDV) propulsion technology and fuel may be more path dependent than electricity generation, where local availability of energy resources is important for the choice of conversion technology. In the long run, cost reductions and efficiency gains are thus likely to be substantial in only a few technologies. Clearly, if one technology gains then others doesnot. Transport fuel and technologies are, however, not included in the ETP model but run on a separate model. Consistent with the ETP assumptions and estimated improvements in technology performance (Fulton 2008), we assembled scenario specific input to the Norwegian model. An overview of the relative efficiency and cost development assumed for the LDV technologies most important in the Norwegian model are given in Appendix B. The ETP model framework includes an oil price module providing the market prices of fossil fuel (IEA 2005)[11]. Electricity prices are calculated by the ETP model for each of the six time slices (winter, intermediate, summer - day, night) for each region. Results from the western European region are used as import price to the Norwegian market. The Norwegian export price is set slightly higher to avoid oscillation.

The ETP study evaluated three different scenarios: a reference scenario (REF), a moderate scenario (ACT) that stabilizes global emissions at today’s level and a stringent reduction scenario (BLUE) where the global emissions of CO_2 are reduced by about 50 % from today’s level by 2050. The REF scenario is consistent with the World Energy Outlook 2006 as extended to 2050 in the ETP model. Furthermore, the oil price is capped at US $ 65/barrel because of the

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[9] ETP 2008 Report, Annex B, page 574.

[10] Chapter 5, page 207.

[11] Annex 1, page 207

availability of unconventional oil reserves above this price. The ACT policy scenario has a CO_2 incentive of 50 US $ /ton and the BLUE scenario has an increasing CO_2 incentive up to 200 US $ / ton. The ETP study also includes the effect of policies not primarily acting on price through the use of supplemental models of the demand-side in the industry, buildings and transport sectors (IEA 2006)[12]. In the ACT and BLUE scenarios the market price of oil is expected to reach a maximum around 2035, because demand is reduced as the share of new renewable energy technologies in the global energy system increases (IEA 2008)[13], and then fall slightly up to 2050 (Gielen 2006; IEA 2008). Prices of bio fuels, bio diesel and ethanol fuel for cars are important for the choice of propulsion technology. In the global REF scenario the global market for these fuels are assumed to remain small and the prices are dominated by the national production cost. The Norwegian production capacity is limited but additional 1st generation bio fuel is available for import at a higher cost. In the ACT and BLUE scenario global use of bio fuels are substantial. The global market then consists mostly of 2nd generation bio fuels where the price of bio diesel and E85 is following the diesel and gasoline prices respectively. The cost of the bio fuels are assumed slightly higher than the fossil fuels. The difference is, however, reduced in the ACT and the BLUE scenarios because of technology learning (Fulton 2008). Emissions of CO_2 from use of bio fuel are assumed to be neutral and thus not influenced by the CO_2 incentive.

Within the ACT and the BLUE scenarios there are several technology paths. The ETP technology paths include ACT Map, ACT No-CCS[14], ACT Low renewables and ACT Low energy efficiency. Within the BLUE scenario the paths includes the BLUE Map and the BLUE electric vehicle (EV) success. The no-CCS, Low renewable and Low energy efficiency are pessimistic regarding the prospects for CCS, renewables and energy efficiency respectively. The Map technology paths are relatively optimistic with respect to technology development and were the most attractive starting point for the linking experiments. The REF, ACT Map, BLUE Map and the BLUE EV Success have been selected for the national analysis. In the BLUE EV Success the cost reductions are more pronounced for electric LDV. The EV success path was

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[12] ETP 2006 Report, box 2.2 page 45.

[13] ETP 2008 Report, Annex B, page 573.

[14] Carbon capture and storage

selected because the large potential for hydro and new renewable power makes this an attractive technology for de-carbonizing the transport sector in Norway.

3.2 Adaptation to national circumstances

In the third step the need for adaptation of the data set(s) is evaluated. In particular onshore wind power will experience increased deployment cost because of complex terrain along the Norwegian coast. In addition, turbine blades experience heavier strain compared to locations in central Europe because of icing. Hydroelectric power is another technology that may be influenced by national circumstances. Norway has a century of experience in building dams and other infrastructure for large hydro power and thus the effect of technology learning is assumed to be negligible. However, the turbine and electrical installations may benefit from global technology learning, particularly for small hydro power. The adjustment is done in two steps. First the cost reduction observed in the global data in each time period is calculated as a percentage compared to the cost in the initial period. This percentage reduction is then applied to the national cost estimates in the respective time periods. The same method is applied to the maintenance costs. Near shore wind mills mounted in shallow water and offshore floating wind mills is expected to be deployed from custom made ships and thus not as susceptible to the national circumstances.

Another important factor influencing the cost of electricity and thus the technology composition of the energy system, is the availability of energy resources, e.g., average wind speed and the fraction of the year this wind is assumed to be available. The availability factor for wind power is generally high in Norway. Particularly OFW has an annual average availability of 0.5 equal to 4200 hours. The national values are used for these parameters for all wind categories. Finally, the potential contribution to peak load from intermittent energy conversion technologies like wind and solar PV, depend on the regulating capacity of the energy system as a whole. The large amount of regulable hydro power reduces in Norwegian energy system more or less eliminates this constraint. Finally, there is substantial capacity for storage of CO_2 in depleted oil and gas fields, as well as under the sea bed, offshore the Norwegian coast. These typical site specific parameters follow the national data.

A number of national policies affecting the energy system are currently in place. These policies are replaced by a general CO_2 incentive of 25 US $/ton from 2015 in the national reference scenario (RT1). In the other scenarios the CO_2 incentive follows the global scenario. There is thus no purchase tax or fuel tax applied to LDV fuel. The long term electricity contracts, providing favourable prices for the energy intensive industries, are terminated in 2015. Nuclear power and coal fired power plants are currently not considered viable options by policy makers in Norway and thus not included as technological options in the national model.

3.3 Learning in a domestic strategic niche market

In this second case it is assumed that OFW is a separate specific technology with a national learning system boundary. This represents an extreme situation where no other country deploys this technology. Moreover, it exemplifies what may happen if disregarding spillover.

National circumstances including both natural resource availability and technical capacity may provide favourable circumstances to nurse technologies at the embryonic stage and prepare them for the global markets. In this case spillover is assumed negligible and learning in the national niche market dominates. That is, view A in Figure 1. Offshore floating wind (StatoilHydro 2009) is an example where both the wind resource and the technological capacity in Norway may be sufficient for it to become commercially viable within the national market alone. The wind conditions are particularly favourable in the North Sea, adjustable hydro power may be used to balance the system and we may draw on experience from the development of the offshore oil industry. The first prototype was deployed in 2009. The prototype was build with parts from existing technologies, e.g., the same turbine is used as in onshore wind mills. It is thus currently a grafted technology. However, to become commercially viable on a large scale the weight in the wind mill head must be reduced substantially (Bratland 2009). Development of lighter turbines and experiments with installation of turbine at sea level and hydraulic power transfer from wind mill head indicates that offshore floating wind power may evolve and become a separate specific technology through a specialisation process.

In the analysis the standard option in Markal where TL is endogenous in the optimizing routine (Loulou et al. 2004) is used for OFW. Determination of the cost and capacity when learning starts and of the LR is then required. An initial investment cost of 20 000 million NOK/GW and a starting capacity of 0.3 GW are assumed. A LR using the market perspective is selected because efficiency gains are included in the spillover for other technologies. For a virgin technology in an operationally closed system (Varela 1979, 1984; Wene 2007), a LR of 20 % is recommended based on the eigenvalue of the system (Wene 2008). Two peaks appear in measured distributions of LR for energy technologies, a major one at 20% and another one around 7% (McDonald and Schrattenholzer 2001). The second peak is consistent with eigenvalues for higher learning modes, applicable to grafted technologies (Wene 2007). In this paper, we experiment with 20% and 9 % LR for OFW. Choosing 9 % LR rather than 7 % is consistent with the LR used in the ETP model (IEA 2008) and thus enhances the comparability between the cases. Together with the 9 % LR the starting cost is set equal to the 2015 cost estimate by the ETP model and a high starting capacity.

4 Results

The emphasis in this paper is on the electricity supply side and light duty vehicle. A set of scenarios and technology paths are selected to illustrate the potential influence of, and sensitivity to, spillover. Moreover, two scenarios with learning in a national niche market are included. That is, the developed framework for spillover is not applied for OFW but rather the endogenous technology learning option in the Markal model. Comparing these scenario results with the AN3 scenario I expect it will underpin my assumption that the methodological framework to include spillover is important. More interesting perhaps, it may indicate if OFW may become competitive in the national niche market alone. The scenarios are summarized in Table 2. The scenarios RT1, AT3 and BT12 are the national response to the global scenarios REF, ACT Map and BLUE Map. They are analysed in the first case study. Moreover, while the RT1 is the national reference scenario, comparison with the AT3 and BT12 are more useful as reference when investigating the sensitivity of the national energy system to spillover. First the sensitivity to an increased CO_2 tax only is considered - to the level of the ACT Map and BLUE Map scenario respectively - while spillover is retained at REF level in the RT3 and RT12 scenarios. Second, the CO_2 tax is retained and spillover is forced to zero in the AN3 scenario. The reduction in fossil fuel import prices, because of increasing share of renewable energy technologies in the global energy system, is then less likely to happen and the fossil fuel prices are set at the REF level. In the second case study, with a national niche market for OFW and spillover according to the ACT Map scenario, a LR for OFW of 9 % and 20 % respectively is evaluated in the scenarios AE3-09 and AE3-20.

Table 1 Nomenclature of scenarios. The first letter in the national scenario indicates the selected global scenario (R, A, B), the second letter the technology learning mode (T is spillover, N no spillover, E endogenous learning for OFW), the first number the CO_2 incentive and those with a second number the learning rate for OFW.

Boundary condition			National scenario	Description
Electricity and fossil fuel price		Spillover/ Endog. TL		
Global REF scenario		REF	RT1	Reference scenario with 150 NOK/ton CO_2.
		REF	RT3	300 NOK/ton CO_2. Spillover and energy carrier prices at REF level.
		REF	RT12	Increasing CO_2 incentive 1200 NOK /ton CO_2. Spillover and energy carrier prices at REF level.
Global policy scenario	ACT Map	ACT	AT3	300 NOK/ton CO_2.
		None	AN3	300 NOK/ton CO_2. Technology cost and efficiency fixed at 2005 value.
		ACT / ETL (OFW)	AE3-20	300 Nok/ton CO_2. 20 % LR for OFW and global ACT Map 2000 starting cost.
		ACT / ETL (OFW)	AE3-09	300 Nok/ton CO_2. 9 % LR for OFW and global ACT Map 2015 starting cost.
	BLUE Map	BLUE	BT12	Increasing CO_2 incentive to 1200 Nok/ton CO_2.

In the national reference scenario, RT1, the CO_2 emissions are increasing about 37 % from 2005 to 2050. The increase is caused by about 20 TWh electricity generated by natural gas combined cycle (NGCC) power plant and increasing vehicle km using traditional gasoline engine. Electricity supplied by onshore wind power increases slightly up to 2020, but renewable energy remains as an insignificant contributor throughout the analysis period.

4.1 Spillover of technology learning

The national energy system response to spillover under the global policy scenarios, ACT Map and BLUE Map, is notable. Both CO_2 emissions and discounted total system cost net of taxes and subsidies (hereafter called system cost), are decreasing, see Table 2. The reason is two-fold: Spillover reduces the electricity generation cost to a level where increased export is optimal and the system cost includes the income from export of electricity. The shadow cost of the export constraint indicates potential for additional export. Spillover of global TL thus creates potential value for a small open economy with renewable energy sources.

Table 2 Key national parameters in 2050 for the scenario and paths REF, ACT Map, and BLUE Map. The difference in discounted system cost net of taxes and subsidies are given in brackets. The export of electricity shown is the net annual value.

	Key national parameters in 2050			
	RT1	AN3	AT3	BT12
CO_2 (Mton):	60	59	41	27
System cost (BNOK)	5,375	5,574 (+ 199)	5,043 (- 332)	5,011 (- 363)
El-produc. (TWh)	162.77	162.13	200.74	199.74
El-export (TWh)	16.21	17.4	48.55	38.11

The reduced system cost is not “a free lunch”. The investment in energy technologies increases in order to meet both the domestic demand for electricity and utilization of the cable capacity for export, see Figure 4. The undiscounted investments increase steadily from 2025 in BT12, while they are about level in RT1.

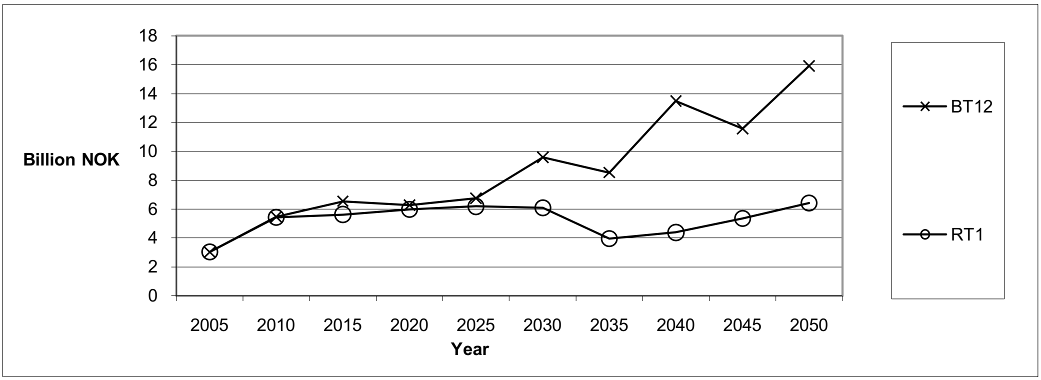

Figure 4 Undiscounted investment cost in supply technologies in the RT1 and the BT12 scenarios. The series are smoothed using a sliding average.

The CO2 emissions are slowly reduced until 2020 and 2030 respectively in the AT3- and BT12 scenarios, see Figure 5. In 2050 CO_2 emissions have increased slightly again but are still about 11 % and 25 % lower than the 2005 level. Compared to 1990[15] however, the emissions of CO_2 in the AT3 scenario are higher. Even the ambitious BT12 scenario exhibits a minimum merely 30 % less than 1990 around 2040, or about 40 % below today’s level. For industrial countries like

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[15] The emissions in 1990 are the reference values for Norway’s commitment to limit the increase in national greenhouse gas emissions, measured in CO_2 equivalent, to 1 % by 2012. The CO_2 emissions in 1990 were about 35 million tons.

Norway a long term agreement under the UNFCCC consistent with the BLUE Map scenario may imply a future commitment closer to 70 or 80 % reduction. While spillover creates potential value for a small open economy like Norway, the combined effect of spillover and CO_2 tax is not sufficient to meet such a commitment.

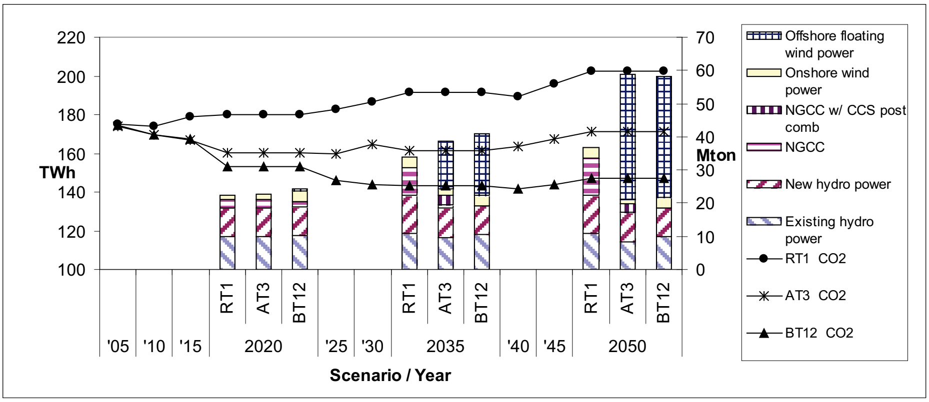

Figure 5 CO_2 emissions (lines) and technology composition of electricity production (stacks) in selected years.

Consistent with the reduced CO_2 emissions we can observe a shift in the technology composition from the RT1 to the AT3 scenario, where OFW and some NGCC with CCS are introduced into the national energy system. In the BT12 scenario, with higher global deployment of renewable energy technologies spillover reduces the investment cost for nascent technologies further. The small amount of NGCC with post combustion CCS is then displaced by onshore wind power. This is because the CCS benefitting from technology learning is only a small part of the investment compared with the NGCC power plant and the high CO_2 tax on the remaining emissions from NGCC with CCS. While electricity generation is more or less decarbonised in both the AT3 and BT12 scenarios, the substantial difference in CO_2 emissions is caused by the difference in LDV fuel, see Figure 6.

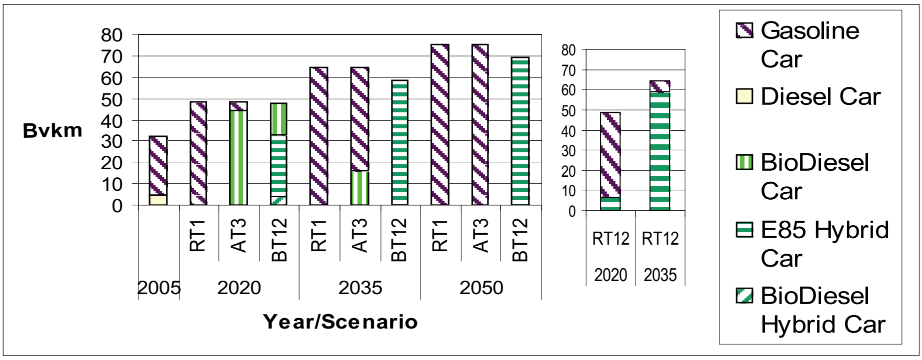

Figure 6 LDV propulsion technology compositions in the Norwegian car fleet in selected years. The RT1, AT3 and BT12 scenarios are the standard technology paths under the scenarios REF, ACT Map and BLUE Map respectively. For the RT3 and the RT12 scenarios the technology learning remains at the level of the REF scenario.

LDV temporarily use bio diesel in the AT3 scenario until the improvement in efficiency of the gasoline internal combustion engine (ICE) together with the shift towards lower fossil fuel prices after 2035 reinstates it. The reduced cost and improved performance of electric LDV under the global BLUE EV Success technology path is not sufficient to make electric LDV cost effective in the BT12 scenario. However, life cycle studies of bio fuel production indicate significant emissions of CO_2 and methane (Bright 2009). These emissions, as well as abatement of other environmental effects caused by growing fuel crops, could increase the price of bio fuel in the global market and thus influence these results.

To explore the sensitivity to the CO_2 incentive and spillover respectively, the scenario variants, RT3, RT12 and AN3 are investigated. Retaining spillover at the REF scenario level and merely increasing the CO_2 incentive, the RT3 scenario exhibit reduced CO_2 emissions from 2035 though above those in the AT3 scenario, see Figure 7. Increasing the CO_2 incentive further, in the RT12 scenario, the CO_2 emissions are above those in the BT12 scenario until 2035 where the two curves converge. In the RT12 scenario gasoline is used as fuel for LDV in the early periods causing higher CO_2 emissions. In the later periods the LDV exhibit a gradual shift to E85 hybrid, see Figure 6. The emission reduction, cost efficient at 1200 NOK/ton, is thus not very sensitive to spillover.

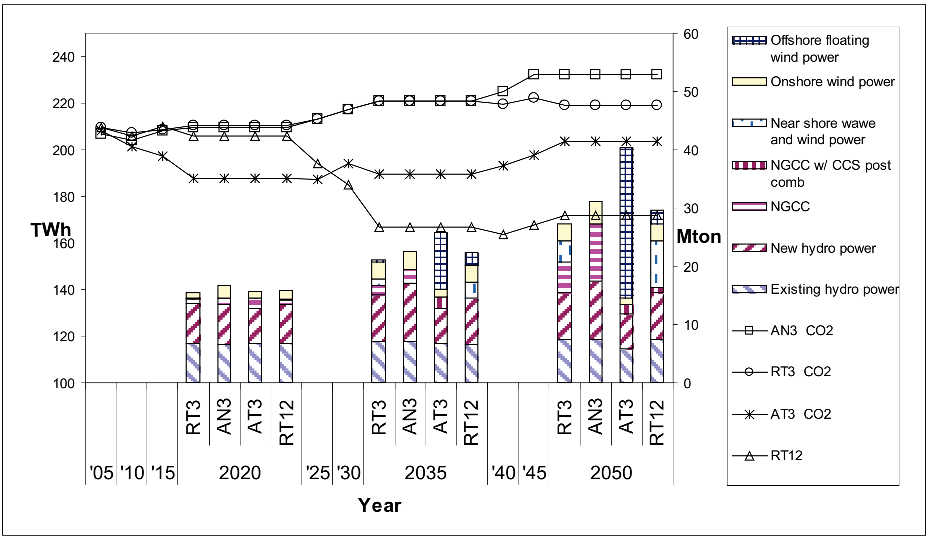

Figure 7 Exploring the sensitivity to TL and CO_2 incentive, the CO_2 emissions (curves) and the corresponding technology composition in selected years (stacks) are shown. The no-TL scenario AN3 has the highest CO_2 emissions of all the scenarios. The reference scenario with increased CO_2 incentive, RT3 exhibit reduced emissions but substantially less than the AT3 scenario with TL. There is also a shift in the technology portfolio from NGCC to OFW together with increased export of electricity in the AT3 scenario. With a high CO_2 incentive, in the RT12 scenario, the sensitivity to TL is reduced.

The technology composition in the RT3 and RT12 scenarios in the later periods is very different than the AT3 and BT12 scenarios. While the use of NGCC is reduced because of the CO_2 tax, the technologies selected for electricity generation are the most mature renewables rather than OFW, see Figure 7. Forcing spillover to zero, in the AN3 scenario, NGCC displace both the near shore wind power selected in the RT3 scenario and the OFW selected in the AT3 scenario. Spillover may thus significantly influence the optimal technology composition of a small open economy. Moreover, the system cost is significantly higher when spillover is eliminated and the CO_2 emissions remains at about the level as the RT1 scenario, see Table 3. With a moderate CO_2 tax the Norwegian energy system is sensitive to spillover, with respect to emission reduction, technology composition and system cost.

4.2 Strategic niche market for offshore floating wind

In this second case study the endogenous technology learning (ETL) modelling approach is applied for offshore floating wind power (OFW). Two distinct starting costs and LR's have been investigated. They are simulating a new specific technology and a grafted technology respectively. In the AE3-09 offshore floating wind is not introduced and near shore wind- and wave-technologies are selected. If OFW remains as a grafted technology it is thus not cost effective when deployed in the national niche market only. Comparing with the AT3 scenario, this also indicates that the national results may be very different if spillover simply is ignored in national analysis. In the AE3-20 scenario the OFW completely dominates and even displaces a small part of the new small hydro selected in AT3, see Figure 8.

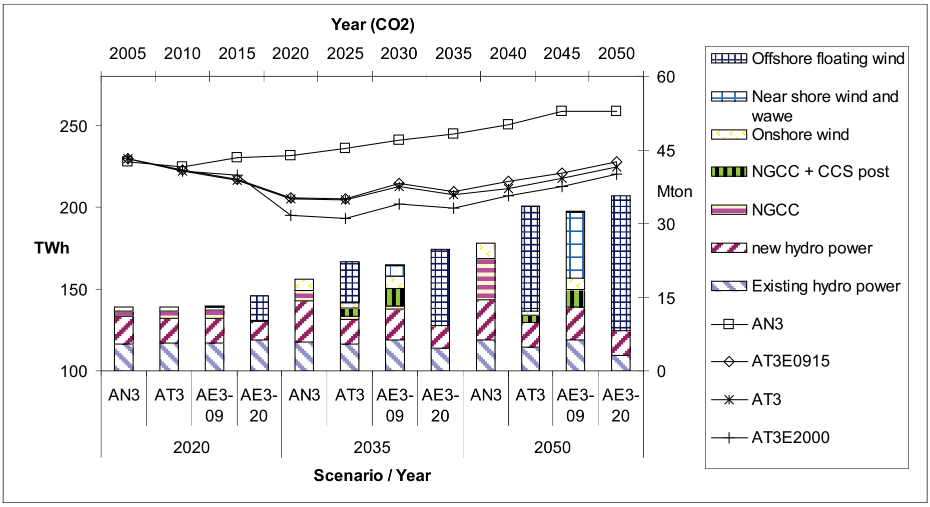

Figure 8 Electricity generation, CO_2 emissions and technology composition with two different LR for floating wind power while the other nascent energy technologies benefit from spillover under the global ACT Map scenario. The AN3 and AT3 scenarios are included for comparison.

The all-or-nothing behaviour of the model with ETL is an exaggeration of reality. Constraining the growth of OFW stretch the investment over a longer time period, but does not change the technology composition in 2050. Sensitivity tests with different LR close to 20 % reveal that this is close to a minimum value. The timing of both the investment and the fixed running and maintenance cost (O&M) are very different in the AE3-20 scenario compared with the AT3 scenario. In the AE3-20 scenario a large investment occurs early to initiate TL. The discounted total system cost over the whole analysis period is, however, about the same.

5 Conclusion

The review of the technology learning systems point at the importance of the feed forward and feedback link between the global energy technology development and manufacturing system and the national energy system. The review concludes that that spillover should be estimated by a global model and should emanate from the same scenario and technology path. Moreover, adaptation to national circumstances may be required.

The modelling results support the assumption that spillover may significantly influence the development of the national energy system of a small open economy. The analysis shows that spillover from different global scenarios, used as boundary condition for the national energy system analysis, significantly affects the system cost, CO_2 emissions and technology composition of the energy system in Norway up to 2050. The results indicate substantial benefit for a small open economy like Norway from spillover under IEA's Energy technology Perspectives global policy scenarios. Contra-intuitive, spillover of global technology learning may reduce both CO_2 emissions and total system cost. That is, if the industrial and electricity export opportunities, provided by the large offshore wind resources, are exploited. Assuming no spillover for offshore floating wind power but learning in the national niche market at the same learning rate as the global scenario yield, as expected, a very different result. However, offshore floating wind power may become competitive with a 20 % learning rate and a CO_2 incentive above 300 NOK/ton[16]. Repeating the analysis with other global scenarios as boundary condition will map the uncertainty. Development of a set of boundary conditions using a cross section of global models and making them available for national analysis is recommended.

The approach described in this paper provides a method to include spillover of technology learning consistently across technologies and energy carriers. The results illustrate the capacity

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[16] About 50 US $/ton

of the methodology to highlight the interconnectedness within the energy systems and the technology development and manufacturing systems.

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6 Appendix A The Norwegian energy system and the Markal model

The system boundary of the Norwegian energy system follows the national boundary including the offshore oil producing installations. It is physically coupled to the Nordic and the European energy system through export/import cables. It is embedded in a technological regime with hydroelectric power and where electricity is dominating as energy carrier outside the transport and oil producing sectors. The average annual electricity generation in the start period (2005) is about 120 TWh. All of this is generated by hydroelectric power. The first fossil fuel power plant Kårstø using natural gas was completed in 2006. It has not been in regular operation as the export value of natural gas has been higher than the value of the electricity.

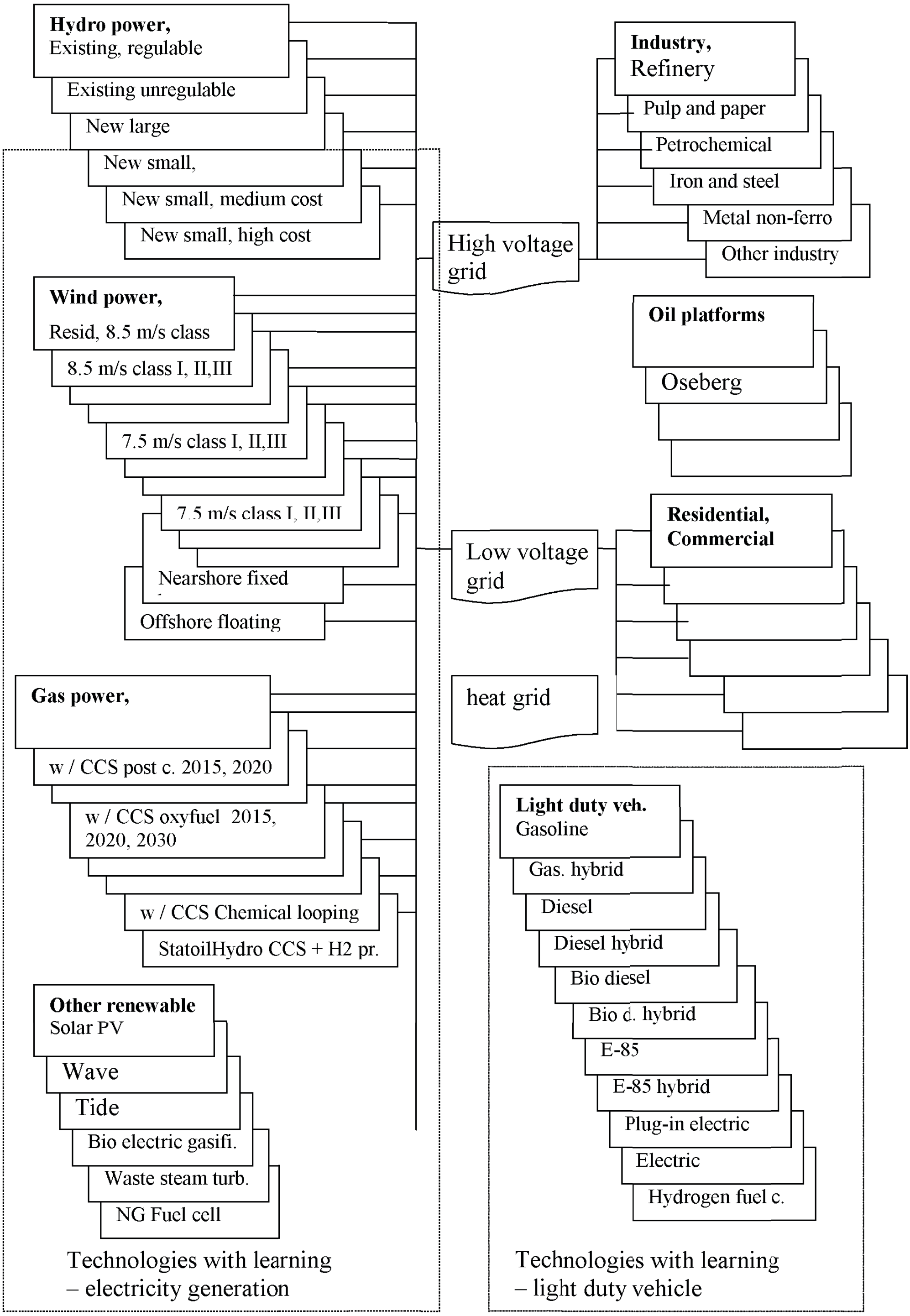
With the new Norway – Netherland cable the capacity for export and import of electricity has increased to 48 TWh annually. The increasing import and export capacity, together with the establishment of a fully competitive market for electricity have increased the “import” of European electricity prices. Electricity prices, though traded on the Nordic electricity exchange (Nor-Pool) are in Norway affected by the limitations in transmission capacity and thus generally lower than the price in Sweden and Denmark. The national market for fossil fuels is fully competitive and prices follow the global market despite large national production.

The future potential for electricity production in large hydroelectric plants is limited. Alternative conversion technologies includes fossil power plants, small-, mini- and micro hydro power, wind power, salt wedge power and wave and tidal power. Norway has a relatively large wind power potential both onshore and offshore. A significant potential for storage of CO_2 under the seabed off the coast of Norway is identified. Coal, oil and nuclear power plants are in the current political and public outlook not considered as technology options. The capacity to produce 1st generation bio fuel is limited.

The average CO_2 emissions in the period 2003 - 2007 were 43.6 Mton. The use of fossil fuel and thus the national emissions of CO_2 are dominated by the oil production contributing about 30 % and the transport sector at about 40 %. The remaining 30 % of the emissions are mostly from direct use of fossil fuel in refinery, industrial chemical production and other manufacturing industry. Residential, agricultural, the commercial sector and the metal industry contributes from about 7 % and down to about 1 %. Light duty vehicles predominantly run on gasoline, trucks on diesel and oil boilers are the dominant technology causing CO_2 emissions from the onshore industry.

The MARKAL model of the Norwegian energy system is focused on electricity generation and demand side. The Norwegian MARKAL model database contains more than 400 technologies with energy sources (38), processes (76), electricity- and heat conversion technologies (78) and demand technologies (229). They are allocated to the sectors residential, industry, transport, and agriculture, service and commercial. Most of the demand technologies are in the industry and residential sector while transport has 29 technologies and agriculture 1. A simplified overview of the Norwegian Markal model, indicating the technologies with TL is given in Figure 8. The model is set up to satisfy an exogenous demand for energy services.

Figure A1 (Next page) Simplified overview of the Norwegian reference energy system (RES) indicating technologies with learning.


Hydro power,
Existing, regulable
Existing unregulable
New large
New small,
New small, medium cost
New small, high cost
Wind power,
Resid, 8.5 m/s class
8.5 m/s class I, II,III
7.5 m/s class I, II,III
7.5 m/s class I, II,III
Nearshore fixed
Offshore floating
Gas power,
w / CCS post c. 2015, 2020
w / CCS oxyfuel 2015, 2020, 2030
w / CCS Chemical looping
StatoilHydro CCS + H2 pr.
Other renewable
Solar PV
Wave
Tide
Bio electric gasifi.
Waste steam turb.
NG Fuel cell
Technologies with learning – electricity generation
High voltage grid
Low voltage grid
heat grid
Industry,
Refinery
Pulp and paper
Petrochemical
Iron and steel
Metal non-ferro
Other industry
Oil platforms
Oseberg
Residential, Commercial
Light duty veh.
Gasoline
Gas. hybrid
Diesel
Diesel hybrid
Bio diesel
Bio d. hybrid
E-85
E-85 hybrid
Plug-in electric
Electric
Hydrogen fuel c.
Technologies with learning – light duty vehicle

7 Appendix B

Table B1 Changes in cost and efficiency because of global technology learning in ACT Map, BLUE Map and BLUE EV Success compared to the REF scenario. A "0" means no change while "+" means improved when related to efficiency and lower when related to investment cost.

Technology		ACT Map	BLUE Map	BLUE EV Success
Gasoline Car	- cost	0	0	0
	- efficiency	+	0	0
Gasoline Hybrid Car (ICE[1]+battery)	- cost	0	0	0
	- efficiency	+	+ +	+
E85 Hybrid Car (ICE[1]+battery)	- cost	0	0	0
	- efficiency	+ +	+	+
BioDiesel	- cost	0	0	0
	- efficiency	++	0	0
BioDiesel Hybrid Car	- cost	0	0	0
	- efficiency	++	+	+
Plug-in hybrid Car	- cost	+	+ +	+ +
	- efficiency	+	+ +	+ +
Electric Car	- cost	0	+	+ +
	- efficiency	0	+	+

[1] Internal combustion engine

Paper II

Paper II

Introducing technology learning for energy technologies in a national CGE model through soft links to global and national energy models

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Abstract

This paper describes a method to model the influence by global policy scenarios, particularly spillover of technology learning, on the energy service demand of the non-energy sectors of the national economy. It is exemplified by Norway. Spillover is obtained from the technology rich global Energy Technology Perspective model operated by the International Energy Agency. It is provided to a national hybrid model where a national bottom-up Markal model carries forward spillover into a national top-down CGE[1] model at a disaggregated demand category level. Spillover of technology learning from the *global* energy technology market will reduce *national* generation costs of energy carriers. This may in turn increase demand in the non-energy sectors of the economy because of the rebound effect. The influence of spillover on the Norwegian economy is most pronounced on the industrial chemicals, i.e., production level and electricity for residential energy service demand. The influence is modest, however, because all existing electricity generating capacity is hydroelectric and thus compatible with the low emission policy scenario. In countries where most of the existing generating capacity must be replaced by nascent energy technologies or carbon captured and storage the influence on demand is expected to be more significant.

Key words: national energy system modelling, soft-linking, hybrid model, technology learning

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[1] Computable general equilibrium

1 Introduction

Reduced cost of energy technologies because of technology learning (experience) in the global market has received increasing attention during the last decade. Different global energy – economic – environmental (EEE) models provide a variety in their results with respect to future technology composition and total system cost, but concur that technology learning (TL) and is an important factor affecting the cost of the transition to an energy system with low CO_2 emissions (Edenhofer et al. 2006). In a small open economy spillover[2] of TL from the global market will in most cases be more important for the price of new energy technologies than experience gained in the national market. The cost of electricity in the national market will thus be heavily influenced by the cost of energy technologies in the international market. In a small open economy like Norway, with energy intensive industry and where electricity is the dominant energy carrier, changes in electricity cost also affect the demand for energy in the non-energy sectors of the economy.

Endogenous handling of TL in models may be implemented using an experience- or technology learning curve, exhibiting the cost reduction of the nascent energy technologies as a result of cumulative deployment. Assuming there is – or will be within the analysis period - a global market for the nascent energy technologies, total global deployment should be the basis for estimating the future cost using the technology learning curves (Junginger 2005). Moreover, the future global deployment of any particular technology is scenario dependent (IEA 2008). To determine the spillover of TL a global model is thus required. The global model estimates the net investment cost with TL and provides scenario specific, time dependent cost trajectories for each of the nascent energy technologies as a boundary condition for the national analysis. Moreover, the global model also provides scenario specific input on other parameters sensitive to technological change in the

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[2] Spillover in this paper includes the effect of technology learning embedded in the technologies purchased in the global technology market, i.e., cost reductions and efficiency improvements resulting from accumulated global production.

energy system, e.g., the price of fossil fuel and the import end export price of electricity. All of these boundary conditions influence the national demand for energy. In this paper we analyse the influence of these boundary conditions, i.e., spillover, on the *national* demand for energy under two different *global* emission reduction scenarios.

There are two main approaches to EEE modelling. The top-down tradition, using macroeconomic models, emphasizes a consistent description of the whole economy. The bottom-up tradition, using energy system models, is rich in technological detail but includes the energy system only. They do, however, lend them selves well to model technological change in the energy system including TL. Demand for energy in the bottom-up models is an exogenous input and is often obtained from a macroeconomic model. Models that link the bottom-up with top-down are referred to as hybrid models. Hybrid models may capture both the feedback on demand from the non-energy sectors and the influence of technological change. In this paper a *national* hybrid model is linked to a global energy system model to investigate the influence on demand for energy in the non-energy sectors from spillover of global technology learning. We use a soft-linked, hybrid model of the Norwegian economy consisting of the national computable general equilibrium model MSG6[3] and a Markal model. We ask the question: Can a national Markal model be used to carry the spillover of TL from the global model into a national macroeconomic model and what is the influence on demand for energy at the sector level? The combination of spillover of global technology learning and a *national* soft-linked hybrid model, exchanging information at a sector level, is a novel approach and adds a new element to national policy analysis.

The paper is organised as follows: Initially we depict previous work on the subject of the paper. A short description of the models is provided. The emphasis of the paper is on the description of the method using a 3-step procedure. Some insights

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[3] Multisectoral growth model version 6

gained from the calibration and simulations are presented. Finally, a conclusion is drawn and some suggestions for future work offered.

1.1 Top-down, bottom-up or hybrid model – soft-link or hard-link?

This section briefly discusses the two lines of development important for the study; the linking of top-down and bottom-up models and representation of technology change in EEE models. Technological change has been included in both top-down, bottom-up and hybrid models using various approaches. An overview of the representation of technological change in many of the models still used today may be found in (Löschel 2002). Only those directly relevant for this study are mentioned here.

Bottom-up linear optimization models are well suited to capture the influence from balancing the energy system and to study shifts in technology in response to a number of factors external to the system. Moreover, internal dynamics of technological progress, e.g., investment cost reductions because of technology learning, may be explicitly modelled using experience curves (hereafter called technology learning curves, TLC). Endogenous handling of TL was first solved by (Mattsson and Wene 1997; Messner 1997) and is now a standard option in Markal modelling (Loulou et al. 2004). Use of TLC also lends itself to study spillover using various assumptions influencing accumulated deployment. Modelling the global energy system, the importance of spillover between regions for the technology composition of the energy system was investigated by (Barreto and Kypreos 2004).

In top-down models the increasing economic efficiency because of technology change has often been modelled using the autonomous energy efficiency indicators (AEEI). The AEEI was defined as *"all non-price induced factors that could reduce energy demands per unit of gross output"* (Manne and Wene 1992). This includes technological shifts increasing the efficiency within the energy supply system and the demand side, as well as structural change of the economy and autonomous (not price induced) change in behaviour affecting energy demand. Technological shifts have also been included in top-down models through the use of a “backstop” technology. A backstop technology is defined as one that may provide unlimited supply of energy above a given cost. A more sophisticated approach is to add technology specific production functions (Böhringer 1998). The latter approach may lend itself to include the influence of spillover. Many of the technology paths we foresee today, however, include significant increase in use of renewable energy sources with intermittent availability. Balancing the energy system is thus becoming more important and also influences the electricity prices. This effect may not be captured by the top-down model.

Jaccard et al. (1996) suggested adding behavioural realism to a top-down model through mapping a range of AEEI and elasticity’s of substitution (ESUB). The mapping of AEEI and ESUB has also been extended to include spillover of TL and was applied in linking a bottom-up technology module with a top-down macroeconomic model and solving it iteratively (Bataille et al. 2006). Further investigation using this approach and comparison with the results reported here would be interesting, but is beyond the scope of this study.

Despite the progress made in both top-down and bottom-up models it is still argued that the hybrid model is the most complete choice (Hourcade et al. 2006). Combining bottom-up and top-down EEE models into a hybrid model started in the early 70s using a soft-link approach (Hoffman and Jorgenson 1974). Soft-linking or informal linking means that the models are run iteratively and the information transfer between the models is carried out by the user. The soft-link facilitates the use of comprehensive models, as the complexity and running time generally is manageable. Moreover, user control also facilitates transparency and learning with respect to the linking procedure.

The development of EEE models and the increase in computational power facilitated use of a hard-link where data transfer is automatic. As the one proceeds from learning to multiple routine model runs the hard-link increases efficiency and consistency across users (Wene 1996). For the bottom-up Markal model the Markal-

Macro (Manne and Wene 1992) hard-linked a growth module with a single economy wide production function to account for price induced feedback on demand for the energy. The MESSAGE-MACRO builds on Markal-Macro, but rather than using a hard-link it retains the complexity of each model and uses a soft-link. The MESSAGE module has seven demand categories and provides an aggregate value of cost for electricity and non-electricity respectively to the MACRO module in return for useful energy demand (Messner and Schrattenholzer 2000).

In this study a global model is used to estimate spillover input to a soft linked national hybrid model. The bottom-up Markal Norway model is given control of the energy system and balances the supply side while the top-down macroeconomic model provides demand for energy service. In a globalized world the functional integration increases, e.g., the production chains and production networks become more harmonised (Dicken 2003). Applying the endogenous TLC function in the national Markal model and only include the deployment within the country is meaningless when there is a globalised energy technology market. A global model is required to determine the influence of TL on investment cost and thus the spillover to the national model. Moreover, this work differs from Wene (1996) and Messner and Schrattenholzer (2000) in that the top-down model represents the national economy in great detail through a nested set of production functions. In this study more than twenty demand categories are used, see Annex 1. The choice of soft-link is, beside the advantages mentioned above, very much a practical choice because the models reside at different institutions. Behaviourally realistic is satisfied for the industrial actor's by the detailed description of their behaviour in the MSG6 model. These are also the sectors of main interest in this study.

The link to the global model providing spillover of technology learning, facilitate transparency from the global scenarios and technology paths to the effects on the energy service demand in the national non-energy sectors. It provides a possibility to evaluate the influence of global policy, from the global technology preferences to the effect on the non-energy sectors of the national economy.

2 Method

This section initially presents briefly national circumstances, the three models and scenarios used with emphasis on the features and parameters important for this paper. The three-step approach starting from coherence through calibration to simulation is subsequently described.

2.1 National circumstances and the models

The Norwegian energy system is embedded in a technological regime with hydroelectric power and where electricity is dominating as energy carrier outside the transport and oil producing sectors. Even though the Nordic electricity market is fully competitive and electricity is traded on the Nordic electricity exchange (Nor-Pool), electricity prices in Norway are affected by the limitations in transmission capacity and thus lower on the annual average than the price in Sweden and Denmark. The national market for fossil fuels is fully competitive and prices follow the global market. A constant exchange rate at 6 NOK per US $ is applied. The existing national policies, e.g., sector specific CO_2 taxes are in the model replaced by a general CO_2 tax of 150 NOK/ton CO_2 (25 US $) in the national reference scenario. In this study the favourable electricity contracts held by energy intensive industry are terminated in 2015. While the demand for energy service (useful energy) is projected to increase, the future potential for electricity production in large hydroelectric plants is limited. Alternative conversion technologies include fossil power plants, small-, mini- and micro hydro power, wind power, salt wedge power and wave and tidal power. The cost and conversion efficiency of these technologies will be significantly influenced by technology learning in the global market. Spillover may thus be important for the future national energy economy. The global scenarios selected in this study are those described in the Energy Technology Perspectives (ETP) – Scenarios & Strategies to 2050 (IEA 2008). There are two reasons for this choice of global scenarios. Firstly, the IEA scenarios outline alternative technology paths to 2050 consistent with global energy demand scenarios. Secondly, they have been extensively reviewed by a large number of policy analysts and experts from IEA government agencies, industries and research organisations.

The Energy Technology Perspectives (ETP) model is a global bottom up energy systems model with 15 regions operated by the International Energy Agency (IEA). Norway is part of the western European region and it is this data that is used in this study. The model applies 5-year intervals and optimizes the global energy system up to 2050 (IEA 2005)[4]. This is thus also the time resolution for the data, e.g., spillover, from the ETP model and the time perspective used in this study. The ETP scenarios relevant for this paper are the reference scenario (REF), the ACT Map scenario and the BLUE Map scenario (IEA 2008). Up to 2030 the REF scenario is calibrated to the World Energy Outlook (WEO) 2007 (IEA 2007). The WEO assumptions are extrapolated for the period 2030-2050. The ACT Map scenario applies a CO_2 tax [5]of 50 US $/ton sufficient to stabilize the global emissions by 2050. In the BLUE Map scenario the CO_2 tax is gradually increased up to 200 US $/ton and the global CO_2 emissions are then reduced by about 50 % by 2050 compared to today's level. The performance, e.g., cost of the new renewable energy technologies are affected by technology learning (Fulton 2008; Gielen 2006; Gielen et al. 2004). The cost trajectories of the nascent renewable conversion technologies are determined on the basis of the accumulated global deployment and technology specific learning rates (IEA 2008)[6]. For large plant like facilities with very long lifetime, e.g., gas power with CCS, the ETP model uses several vintages with declining cost. The cost trajectory for these technologies input to the national model use only the existing technologies for the REF scenario while the ACT Map and BLUE Map progressively include the more technologically advanced vintages. The ETP model framework includes an oil price module estimating the market prices of fossil fuel

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[4] Annex 1 page 202-203.

[5] The IEA applies the term "incentive" rather than a tax. In the models it is a tax but it could be any combination of policies and measures at equivalent cost.

[6] Chapter 5, page 207.

endogenously (IEA 2005)[7]. In the ACT Map and BLUE Map global scenarios the market price of oil is expected to reach a maximum around 2035 and then fall slightly up to 2050 (Gielen 2006; IEA 2008).

The Markal (Fishbone and Abilock 1981) **Norway** model includes the entire energy system and applies a system boundary for the Norwegian energy system following the national boundary including the offshore oil producing installations. The Markal Norway model has about 400 technologies and including the nascent renewable electricity generating technologies and demand side technologies. Coal fired power plants and nuclear power is not included in the national database because they are politically not acceptable. The cost trajectories and increasing efficiency of the advanced vintages input from the ETP model reflects spillover of technology learning from the global market. Six time slices are used when balancing the energy system; summer, intermediate and winter season in addition to night and day. There are no price elasticises in the Markal Norway model. The model is set up to satisfy an exogenous demand for *energy services* in 29 demand categories, see Annex 1. Demand for electricity may also be met through import, and surplus electricity is exported. The cost of electricity estimated by Markal may thus not be equal to the marginal cost of electricity generation. The marginal cost of electricity production in the western European region in the ETP model is used as import cost while the export price is set 5 % higher to avoid oscillation. In the evaluation of demand side measures by Markal, e.g., energy efficiency, transmission cost and taxes are added to the electricity cost.

The macroeconomic model of the Norwegian economy is a CGE multi-sector growth model version 6 (MSG6) operated by Statistics Norway. It estimates the demand for *delivered energy*. Demand for energy is sensitive to several factors. Most important for this study are global economic growth, interest rate and national productivity. Moreover, the petroleum production generates considerable

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[7] Annex 1, page 207

government revenues from taxes and export. While the revenue is allocated to a fund a fiscal rule adopted allows a deficit on the annual structural central government budget equal to the real rate of return from the fund. An interest rate of 6.9 % is applied uniformly. Historically, the increase in productivity has varied between sectors and industries. To reproduce the historical trend a constant total factor productivity (TFP) is applied across all sectors exempt the residential sector. TFP was exogenous and set at 1.3 % per year in the private business sector. The TFP is equal for all production factors, e.g., labor, energy, capital, transport. Because of decreasing returns to scale the combined effect is an annual growth in productivity of about 1.1 %. The combined effect including all assumptions is a GDP growth of 1.7 % per year up to 2050 (Heide et al. 2004).

The MSG6 has a detailed description of the structures in the Norwegian economy, e.g., production and consumption. It has a nested system of constant elasticity of substitution (CES) production functions. The model has 41 private and 8 governmental production activities. It has 41 demand categories, see Annex 1. The standard MSG6 demand for energy carriers include only electricity, gasoline, heating oil and auto diesel. As Markal requires a complete energy budget, the demand for *other* energy carriers, e.g., natural gas, coal, coke, heavy oil, district heat and bio fuel in industry and trade are extrapolated applying the same growth rate as the respective demand categories. For the residential sector the gross amount of *other* energy carriers are assumed constant. The oil producing sector is handled exogenously in the MSG6 model. Its energy demand is therefore estimated from the oil and gas production projection (Oljedirektoratet 2007). The cost of electricity generation measured at the *power plant wall* is input exogenously to the MSG6 model. The price of electricity for the MSG6 demand categories is calculated by MSG6. It includes transmission and taxes and varies between the different consumers. The income from the CO_2 tax is recycled back to the national economy through reduced payroll tax for employers. Finally, world market prices of products typically exported from Norway, e.g., aluminum, are increased consistent with the scenario specific global CO_2 incentives (Bjertnæs 2008).

Besides existing and new hydropower at a given cost MSG6 is normally set up with a backstop technology[8]. Gas power with carbon capture and storage (CCS) is used as a backstop technology. To account for increased economic efficiency total factor productivity (TFP) including the AEEI is used. This will not capture the technology specific cost trajectories for the nascent energy technologies. The aggregate CGE framework used in the MSG6 model is not well suited to account for the radical system changes, e.g., shift between gas power and wind mills, likely to occur in the energy system by 2050 (Bjertnæs et al. 2009). Moreover, the availability of equally detailed bottom-up and top-down models, with respect to demand categories, facilitates analysis of the combination of technology preference and demand for energy together in a hybrid model.

The hybrid model requires transfer of data. In order to use the data from MSG6 it must be transformed to match the demand categories constituting the information entry points (IEP) in the Markal model. The basis for the demand transformer is the minimum common denominator of the demand categories of the MSG6 and the Markal model. This key element of the soft-link maps the output from the MSG6 into the respective IEPs of the Markal model, see annex 1. The level of disaggregation of the demand categories varies between the models. For example, the energy intensive industry maps one-to-one exempt for metal industry where Markal models iron and steel separate from other metals, e.g., aluminium. Moreover, Markal separates between electricity specific demand and heating. To transform the demand for the energy carriers provided by MSG6 is summed and/or split consistent with the mapping. The energy service demand is the sum across all energy carriers' recalculated to useful energy using the efficiencies of the technologies in the Markal residual energy system. The demand *DM* for each Markal category, *i*, is given by equation 1 where Ej is delivered energy of energy carrier j and η is the technology

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[8] The backstop technology provides unlimited electricity above a given cost.

efficiency. When there is more than one demand category, *k*, in MSG6 mapped into a Markal demand category *i* we must also sum across *k*, see Annex 1.

Equation 1 $\mathrm{DM}_i\,(\mathrm{t}) = \sum_{k=1}^{n} MSG_{k,i} \bullet \sum_{j=1}^{m} E_{j,k}(t) \bullet \eta_{i,j}$

The split is subsequently done based on individual assumptions. Markal Norway has a more disaggregated demand for energy in buildings than MSG6, e.g., electricity specific demand and new and old single and multi household houses. The following assumptions have been used in the allocation: It is assumed that the relative share of electricity specific demand is unchanged over the analysis period. For commercial buildings it is assumed a linear replacement of buildings so that all are replaced by the end of the analysis period. Only 16 % of existing residential buildings are replaced by the end of the analysis period.

The data transferred from Markal Norway to MSG6 is cost of electricity generation at power plant wall. The marginal cost of electricity for each time slice estimated by Markal Norway is converted to an annual average cost by weighting it with the electricity generation in the respective time slices.

2.2 Approach

In this study three models are linked. The ETP model provides boundary conditions for both the national models, though most important for this study is spillover of TL input to the Markal model. We have assumed that Norway is a price taker and thus not consider feedback to the global model. In the hybrid model Markal Norway is given control of the energy system including export and import of electricity. The national models are solved iteratively using a disaggregated demand configuration. The models and the principal set-up are shown in Figure 1.

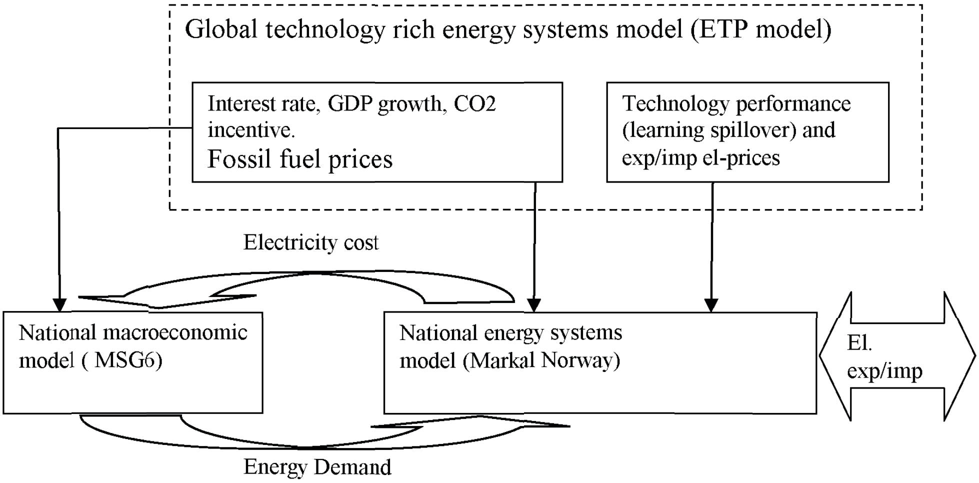

Figure 1. Initial set-up of the hybrid model consisting of the national macroeconomic model MSG6 and the national energy system model Markal with the global energy system model Energy Technology Perspectives providing boundary conditions. Coherence is assured for interest rate and GDP growth important for energy carrier demand calculation (Martinsen, 2010 slightly modified).

Inspired by the work of Johnsen and Unander (1996), and the approach used by Schäfer and Jacoby (2006), a step-by step method emphasizing consistency between the models is developed. In step 1, coherence is sought in parameters included in all three models. In step 2, calibration, we seek Markal Norway to reproduce the electricity trajectory estimated by MSG6. In step 3, simulation, the hybrid model is ready for policy analysis. The steps are described in more detail below.

2.3 Coherence

All three models are run independently and coherent scenario assumptions across the models are therefore required. In step 1, exogenous input to the models is reviewed and adjusted. Interest rate and GDP growth are adjusted in the national models to match the western European region in the ETP model. Between the national models, data on production capacity and cost of existing and new hydro power is compared and found to be equal. Finally, the fraction of non-substitutable energy carrier demand was compared between the models and MSG6 was adjusted according to Markal Norway.

2.4 Calibration

Step 2, calibration, the influence of overlapping domains in the hybrid model is evaluated using common measuring points (CMP) where the models should produce coherent results (Wene 1996). In this step the export and import of electricity is forced to zero in both models to eliminate this source of inconsistency. This will not influence the results because Markal Norway during simulation will control export and import and include its influence in the data transfer to MSG6. The option to export and import electricity in MSG6 remains blocked. Adjustments in MSG6 and constraints implemented in Markal are made in order to have Markal reproduce the electricity production estimated by MSG6. That is, the domains of potential overlap are eliminated from both models. Nyström and Wene (1999) identified 3 different phenomena with potential overlap:

- Technical efficiency improvements within the energy supply system.
- Technical efficiency improvements on the demand side (energy conservation).
- Structural change of the economy and autonomous (not price induced) change in behaviour, affecting energy demand.

All three were contributing to a change in energy productivity, parameterised in MSG6 by total factor productivity (TFP). Evaluation and adjustments of the TFP to avoid overlap in the hybrid model is thus the core task of the calibration procedure. A schematic view MSG6 energy flow and corresponding TFPs are shown in Figure 2.

Following the above taxonomy the TFP_{Ef} for electricity production was assumed to be dominated by technological changes. Consequently, the TFP_{Eh} was set to zero. The TFP_{Eb} for the back stop technology modelled in MSG6 as gas power was adjusted down until the marginal electricity price from gas power in the long term exhibit coherent growth with the price of natural gas. This eliminates the influence of technical change from TFP_{Eb}. The TFP_D applied to distribution was retained because there are no energy efficiency measures for distribution in Markal Norway. The loss (demand) in transmission and distribution (T&D) in Markal Norway follow the use of electricity. The TFP_P and TFP_C for private industry and commercial services were retained to account for structural changes. The overlap with the energy technology specific efficiency measures in Markal was assumed to be small. For the residential sector the TFP in MSG6 is retained at zero. The TFP_R for refinery was retained as there is no energy efficiency technologies specified for this industry in Markal Norway. The TFP_o for energy carriers *other* including district heat and bio fuel is set to zero because efficiency gains are assumed dominated by technological change included in Markal Norway.

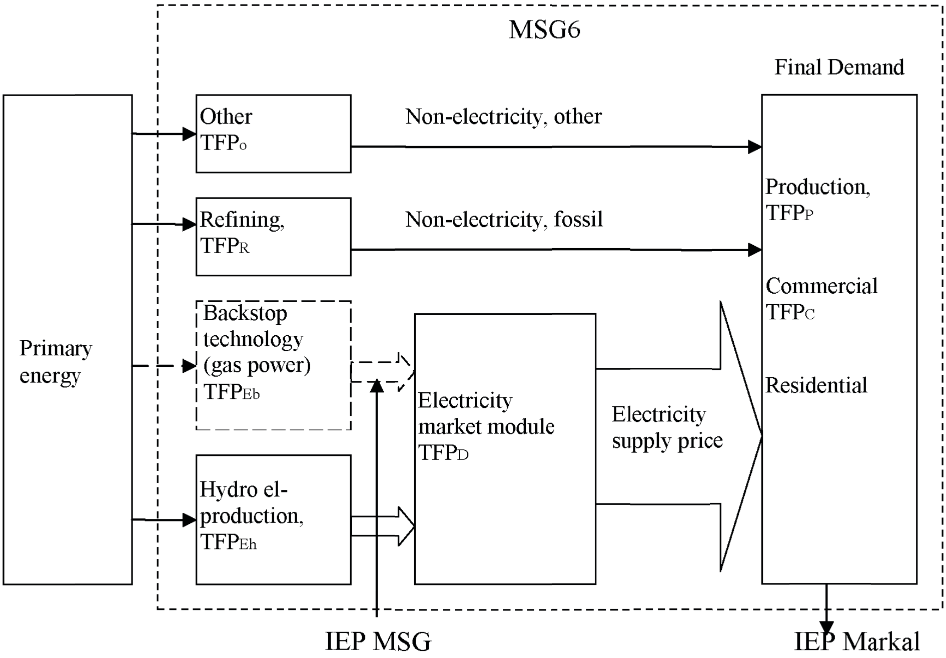

Figure 2. A schematic view of the energy flow through the MSG6 model indicating the location of the total factor productivity (TFP) factors. The location of the information entry points (IEP) during the simulation step is also indicated. The input to IEP MSG from Markal Norway replaces the backstop technology in the simulation step.

To match the set-up in the adjusted MSG6 model all new technologies in Markal Norway not included in the residual energy system and all energy efficiency measures were blocked out. Moreover, the spillover of technology learning was set to zero by fixing the technology cost and efficiencies at the value of the starting year.

The calibration procedure is initiated by MSG6 calculating the gross energy carrier demand and transferring it to Markal. The models are not yet linked; we are merely testing for consistency. Electricity generation is endogenously determined by both models and therefore used as CMP. That is, to have Markal Norway to reproduce the electricity generation estimated by MSG6. Several model runs were made with both models. The electricity generation calculated by the MSG6 and Markal in the initial runs and in the final run is shown in Figure 3.

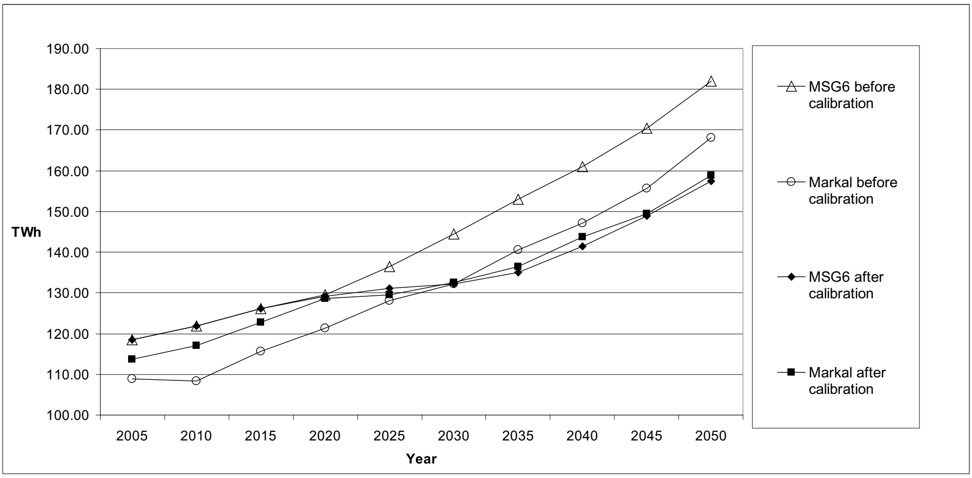

Figure 3. The open markers are the electricity generation estimated by MSG6 and Markal respectively in the initial baseline model run. The filled markers are the electricity generation after adjustments in MSG6 and constraints eliminating technology learning and technologies not included in the Markal 2005 residual energy system.

The electricity generation level is shifted down after the calibration. In previous analysis with MSG6 only four energy carriers were included. When summed across all energy carriers the energy demand growth estimated by MSG6 for the energy intensive sectors refinery, metal production, pulp and paper and petrochemical industry was deemed unrealistically high by the researcher at Statistics Norway. These were therefore adjusted down consistent with historic development (Bjertnæs 2008). This is not a result of the calibration per se, nor does it affect it or the results presented.

The CO_2 incentive, oil price, electricity import cost and technology cost and efficiency are dependent on the global scenario selected. While this potentially could influence productivity, only the nascent energy technologies may directly, and export and import of electricity indirectly, cause a change in productivity in the hybrid model. The technologies not included in residual energy system and export and import of electricity, however, are blocked. Repeating the calibration procedure for the other scenarios are thus considered, but not implemented.

2.5 Simulation

In the third step the constraints on new technologies are removed, the spillover of technology learning and energy efficiency measures in Markal Norway are included and the model is opened for export and import of electricity. An iterative procedure is activated where Markal Norway receives demand for energy and provides electricity cost, see Figure 4. The marginal cost of electricity generation, over and above the cost of existing and new hydropower, input to MSG6 replaces the cost of electricity from the backstop technology. Markal Norway is then run with the different boundary conditions, e.g., spillover. The consistency clearing house (Wene 1996) is a conceptual element and the control centre during set-up and operation of the hybrid model. Its function is to assure coherence in all parameters affecting the data transferred. The market price of fossil fuel in the western European region is assumed independent of Norwegian demand. It is therefore not part of the iteration procedure between the national models. The data flow in the calibration mode is also shown in Figure 4.

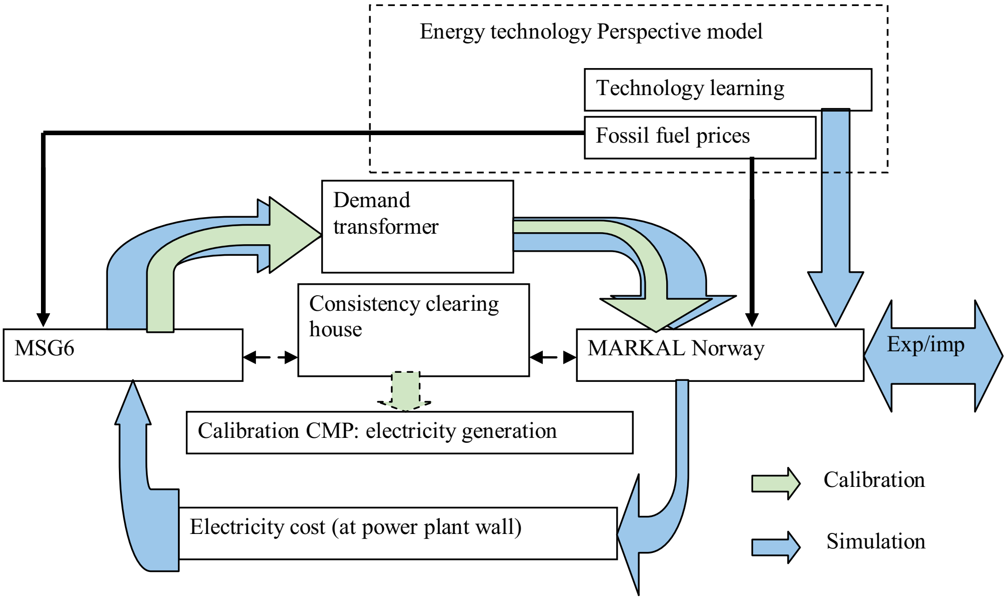

Figure 4. The hybrid model in the calibration and simulation step indicated by light green (transparent) block arrows and blue (grey) block arrows respectively. As Markal is given control of the energy system in the simulation step, the electricity production cost is transferred to MSG6 and the demand for energy carriers recalculated by MSG6 in an iterative procedure.

To check that the models are linked the value of a common measurement point (CMP) is compared. The long term marginal electricity price estimated by MSG6 is compared with the annual average electricity cost from Markal Norway. Before iteration the cost of electricity estimated by Markal Norway is higher, see Figure 5. Markal is now given control of electricity generation in the hybrid model. While the electricity cost and generating capacity of existing and new hydropower is equal in the two models, the electricity production cost of the backstop technology in MSG6 is replaced by a time series generated by Markal. A new demand is then estimated by MSG 6. The iteration procedure is repeated until the value of the CMP converges, see Figure 6. The hybrid model is now calibrated for the ETP REF scenario. The electricity price peaks around 2035 and is subsequently slightly reduced. This is mainly because domestic demand increases and thus the influence of import are reduced. The electricity price consequently moves towards the marginal production cost.

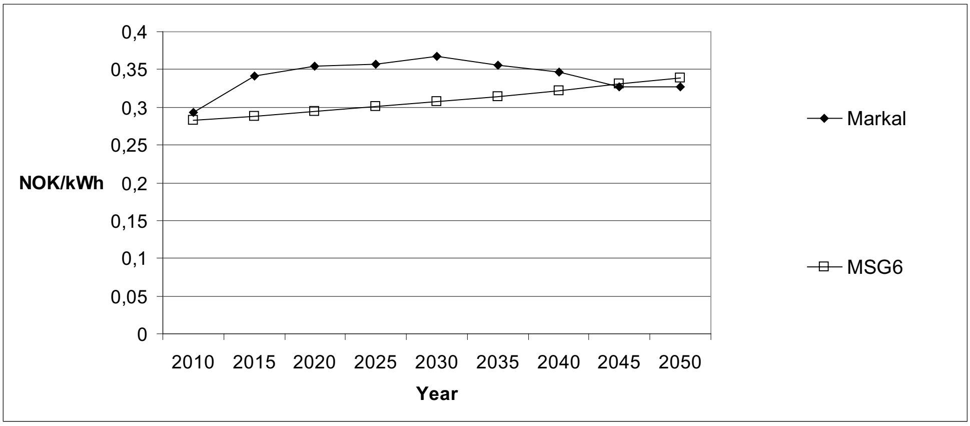

Figure 5. Cost of electricity estimated as annual average from Markal REF scenario and long term marginal cost by MSG6 before the link is established (before simulation step).

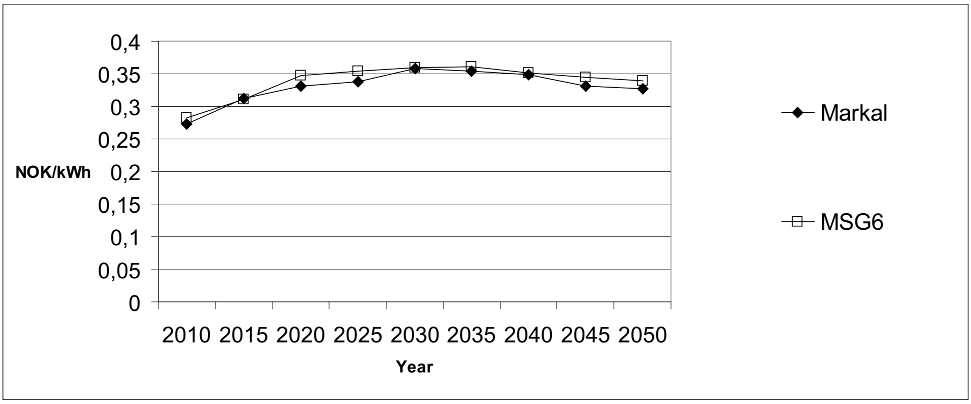

Figure 6. Cost of electricity estimated as annual average from Markal REF scenario and long term marginal cost by MSG6 after the link is established (in simulation step).

Performing step 3 for the global scenarios ACT Map and BLUE Map exhibits similar converging. The electricity price under those scenarios is lower because spillover reduces the investment cost while the technologies selected largely remains the same, see Figure 7. As export is constrained the effect of spillover dominates over the effect of “importing” regional electricity prices. The lower cost of electricity under the global policy scenario BLUE Map increase the demand for energy services in the residential sector, where the dominant energy carrier is electricity.

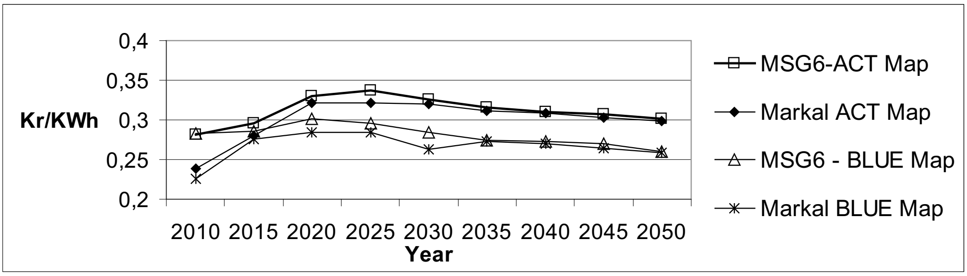

Figure 7. Electricity prices in the global scenarios ACT Map and BLUE Map respectively. The slightly reduced price in 2010 in BLUE Map compared to ACT Map is because of the assumption that a higher global CO_2 incentive reduces the starting cost through increased R&D. The generally lower electricity price in BLUE Map is because the reduced cost of the technologies from spillover while the national technology composition remains largely the same.

Consistency is thus obtained with respect to total demand, electricity specific demand and electricity price at the level of demand category mapping given in Annex 1.Still, there is a potential inconsistency in the use of non-electric energy carriers. However, the substitution elasticity’s in MSG6 are small. Moreover, there is no spillover for technologies outside the electricity producing sector, and thus the demand side technology costs in Markal Norway are equal across the global scenarios. The error introduced is therefore considered small with respect to the influence of spillover investigated in this paper.

3 Insights from calibration and simulation

We investigate influence of spillover on the demand for energy and thus level of activity of the non-energy sectors in Norway. Spillover of technology learning is given by the global policy scenarios ACT Map and BLUE Map. Applying the method described, using Norway as example, has revealed three issues where insight may be gained; consistency of electricity supply and energy demand, sector response to supply price curves and the effect of spillover on the activity of non-energy sectors. The three issues are further elaborated below.

3.1 Consistency in electricity supply and demand

As noted in the calibration section, the initial demand shown in was adjusted down because conversion of energy demand into energy service demand, summarised across all energy carriers, exposed a growth that was inconsistent with historic development. During the subsequent calibration the hybrid model, the individual effect of new technologies and spillover is investigated by removing them consecutively. Allowing new technologies and energy efficiency measures in Markal, reduces the electricity demand projection by about 11 to 18 TWh over the analysis period, see Figure 8a. This is equal to an average decrease of about 11 % in addition to TFP_P and TFP_C while the energy service demand remains unchanged. The CO_2 emissions are also reduced, up to 3.5 Mton or about 10 % when allowing energy efficiency and new technologies, see Figure 8 b.

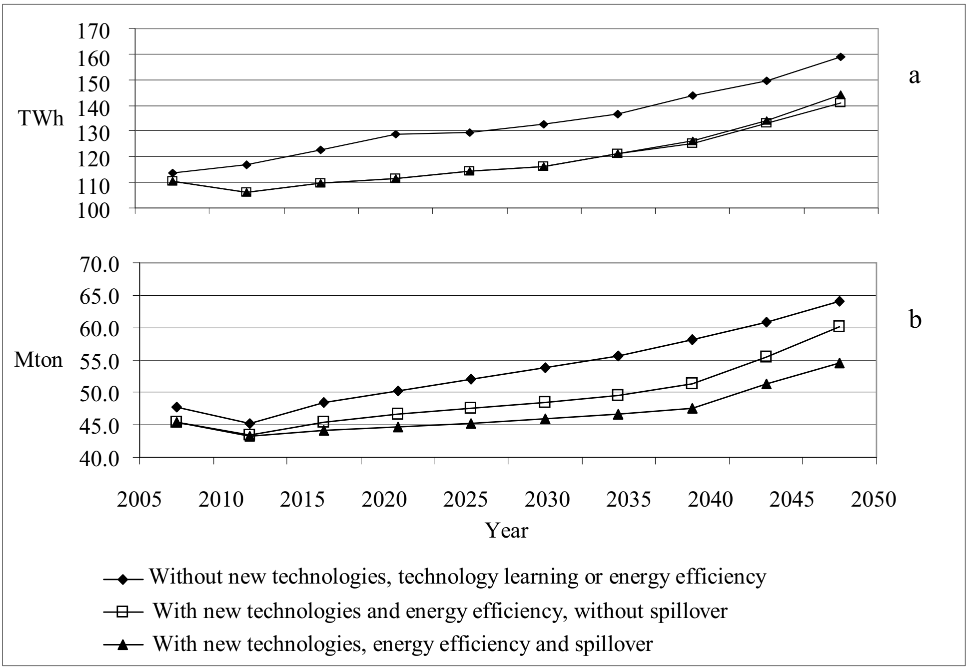

Figure 8. Electricity generation and CO_2 emissions for the reference scenario while removing the constraints in two steps as calculated by Markal. With no export of electricity or technology learning but removing the constraint on energy efficiency measures and new technologies the electricity generation is the lowest. Note that the scales start at 100 TWh and 40 Mton respectively.

3.2 Sector response to supply price curves

Linking the models and entering the simulation mode the price of electricity in MSG6 increases as seen by comparing Figure 5 and Figure 6. The corresponding change in energy service demand for selected sectors is shown in Figure 9. The industrial sector is found to be more sensitive to changes in the electricity price than other sectors. As the electricity price increases in the early periods the demand for energy and thus production is reduced in industrial chemicals, non ferrous metal and iron and steel production. While the production of industrial chemicals is maintained at a stable level, the metal production increases slightly towards 2050.

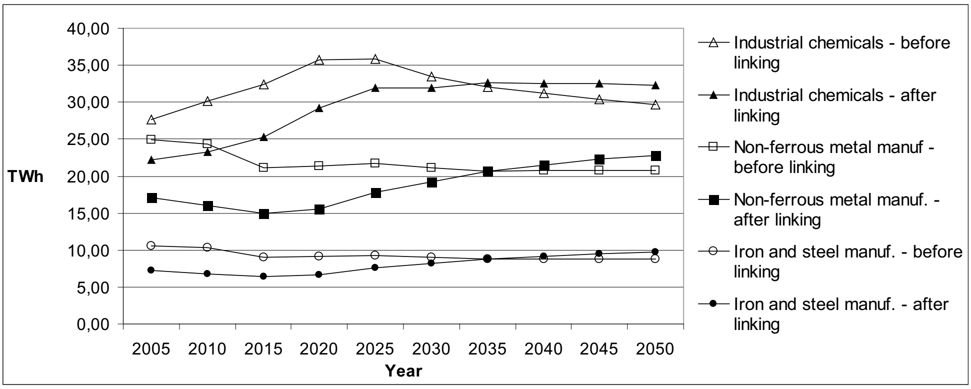

Figure 9. Energy service demand for selected sectors, before and after linking the models (simulation step) under the global REF scenario. The energy service demand reflects the reduced activity in the categories in the early periods as a result of the feedback effect because electricity prices have increased. In the latter periods the energy service demand increases because global technology learning reduces the investment cost and consequently the electricity prices estimated by the hybrid model.

3.2.1 Spillover of global technology learning

Including spillover under the global REF scenario has almost no influence on the total electricity generation and thus demand, see Figure 8 a. The CO_2 emissions, however, are reduced when including spillover because more renewable energy is selected instead of gas power, see Figure 8 b. To investigate the effect of spillover only at the sector level, the electricity cost without spillover is simulated by fixing the technology cost and efficiency at the starting value (2005). We selected the global ACT Map scenario to illustrate the effect of spillover on the sector level because the global deployment of renewable technologies is higher. The influence of spillover in terms of reduced investment cost and efficiency improvement increases and thus facilitates lower electricity prices. It may, however, in Norway partly be counteracted by the “import of electricity prices” because higher price is obtained for export of electricity. We find that industrial chemical production is reduced if we may not benefit from technology learning. The influence of spillover on *other* manufacturing industry and electric appliances in the commercial sector is less, but still discernable, see Figure 10.

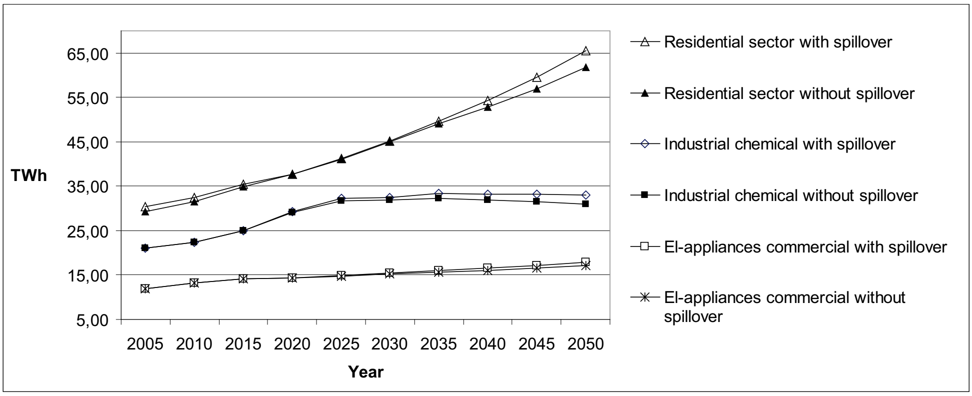

Figure 10. Energy service demand under the global ACT Map scenario in selected categories with and without spillover (TL).

The results show that the sector energy demand response by MSG6 to the electricity price signal from Markal Norway is consistent with the influence of technical change and spillover. In the short term demand for electricity in energy intensive industries is reduced because of higher prices. Technical changes and gradual reduction of the investment cost of nascent energy technologies because of global technology learning increase demand in the long term compared to a no-learning case. The rebound effect is in this case a response to the global development. The experiments thus indicate that a national energy systems model, linked to a global model, is suitable to carry forward spillover of technology learning into a macroeconomic model of the national economy.

Further work on several issues may improve the hybrid model. Firstly, the electricity prices, input to the MSG6, are the annual average price weighted with the electricity generation in the respective time slices. This removes the peaks in electricity prices, and the peak energy service demand response is thus not exhibited. Secondly, in the simulation mode the price of electricity from Markal replaces the cost of the back stop technology used in MSG6. Consequently, all energy conversion technologies are modelled in MSG6 as if it is was a natural gas power plant. Differences between the technologies, in the required labour and material input to add electricity generation capacity, are thus not accounted for. Thirdly, the marginal cost of electricity is a combination of the cost of expanding the electricity generation and import of prices through export of electricity. As Norway is a net exporter, there may thus be a net income from export of electricity not accounted for in this study. Likewise, the indirect cost of labour and materials required to build the electricity generation capacity used for export only, is not accounted for either. Finally, differentiating the TFP for the non-energy sectors, particularly for energy in the energy intensive industries, is recommended. This may avoid a potential double counting with energy efficiency measures in Markal that is assumed negligible in this study. Further investigations into the sensitivity to these issues, together with analysis of other scenarios and technology paths generated by a selection of global models, are recommended.

3.3 Conclusion

This paper describes a method of soft-linking a detailed national macroeconomic model and an equally detailed energy systems model with scenario specific input on spillover of global market effects. The experiments indicate that a national energy systems model, linked to a global model, is suitable to carry forward spillover of technology learning into a macroeconomic model of the national economy. The effect of spillover of technology learning on energy service demand in Norway is discernable, though modest, as would be expected for an energy system where electricity is the main energy carrier and 99.5 % of existing electricity production is hydro electric power. For countries where large amount of existing electricity generation capacity must be replaced, and thus affected by technology learning, the results are expected to be more significant. The soft-linked *national* Markal-MSG6 hybrid model exhibits significant differences in the electricity price in response to the influence of spillover between the different global scenarios. The approach facilitates transparency in the effect chain, from the assumptions in the global model through the national energy systems model to the national macroeconomic model.

3.4 Acknowledgement

This paper is funded by the Research Council of Norway and the Institute for Energy Technology and is part of my PhD thesis. I would like to thank my advisors, particularly Professor Emeritus Clas-Otto Wene and also Professor Edgar Hertwich for the many fruitful discussions and comments. Thanks also to my colleague Geir Bjertnæs, Marina Tsygankova, Mads Greaker, Birger Strøm and Knut Einar Rosendahl at Statistics Norway who provided data and insights about the MSG6 model. Thanks to Dolf Gielen at the IEA for providing the global data.

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Annex 1

MSG category	Markal category – Demand IEP
Agriculture	Agriculture and fishing
Forestry	
Fishing	
Breeding of Fish	
Production of Grain, Vegetables, Fruit, Oils, Beverages and Tobacco etc.	Other manufacturing industries
Manufacture of Fish Products	
Manufacture of Meat and Dairy Products	
Manufacture of Textiles, Apparel, and Footwear	
Manufacture of Furniture and Fixtures	
Production of Chemical and Mineral Products, incl. Mining and Quarrying	
Printing and Publishing	
Manufacture of Pulp and Paper Articles	Paper and paper products
Manufacture of Industrial Chemicals	Industrial chemicals – mtbe
Fossil fuel Refining	Energy use refineries
Manufacture of Metals	Iron and steel manufacturing
	Non-ferrous metal manufacturing
Manufacture of Metals	Other manufacturing industries
Building of Ships	
Manufacture and repair of oil drilling rigs and ships, oil production platforms etc.	
Construction, excl. Oil Well Drilling	Other manufacturing industries
Wholesale and Retail Trade	Commercial, buildings El appliances, commercial
Ocean Transport – Foreign	
Crude Oil and natural gas Exploration	Dsl to dsl engine offshore
	Nat.gas consumption gas+oil production

Servicing in Oil and Gas Exploration	Other manufacturing industries
Car and Other Land Transportation	Road transport cars l1,l2,l3 LDV Road transport trucks HDV Road transport buses Mobile equipment Fishing
Air Transport	Air transport
Railroads and Electrical Commuters	Rail transport
Ocean Transport – Domestic	Inland ship transport + marine defence
Post and Tele Communication	Commercial, buildings existing 2005 Commercial, buildings build after 2005 El appliances, commercial
Finance and Insurance Servicing	
Dwelling Servicing	
Other Private Servicing	
Large military purchases	
Defense Servicing	
Research and education	
Health care services	
Other governmental services	
Research and education	
Municipal health care services	
Other municipal services	
Fresh water supply	
Residential housing	El appliances, residential New single family house New multi family house Old single family house Old multi family house

Paper III

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Global technology learning and national policy—An incentive scheme for governments to assume the high cost of early deployment exemplified by Norway

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ABSTRACT

In this paper it is argued that technology learning may be both a barrier and an incentive for technology change in the national energy system. The possibility to realize an ambitious global emission reduction scenario is enhanced by coordinated action between countries in national policy implementation. An indicator for coordinated action is suggested. Targeted measures to increase deployment of nascent energy technologies and increasing energy efficiency in a small open economy like Norway are examined. The measures are evaluated against a set of baselines with different levels of spillover of technology learning from the global market. It is found that implementation of technology subsidies increase the national contribution to early deployment independent of the level of spillover. In a special case with no spillover for offshore floating wind power and endogenous technology learning substantial subsidy or a learning rate of 20% is required. Combining the high learning rate and a national subsidy increases the contribution to early deployment. Enhanced building code on the other hand may reduce Norway's contribution to early deployment, and thus the realization of a global emission reduction scenario, unless sufficient electricity export capacity is assured.

1. Introduction

The importance of nascent energy technologies to reduce the emissions of greenhouse gases is widely acknowledged. Moreover, a price on carbon, e.g., a CO_2 tax may not be adequate to reduce emissions at a sufficient pace and scale (Stern, 2006). Commitments[1] under the UN Framework Convention on Climate Change (UNFCCC) and the EU renewable energy directive in particular, aim to promote deployment of nascent energy technologies. Development of indicators for monitoring the contribution by Parties to technology development, deployment and transfer under the UNFCCC has only just begun. The EU is applying an indicator[2] to allocate the commitment based on the relative share of renewable energy and energy efficiency in the national energy system (European Commision, 2008). The EU approach may; however, not promote adequate support for the least developed technologies, e.g., offshore floating wind power, because the subsidies required per MW are higher than those needed for the technologies close to commercialisation, e.g., onshore wind power. Moreover, the need for financial support may vary depending on the global scenario and the corresponding spillover of technology learning[3] from the global energy technology market.

In this paper the deployment of nascent energy technologies because of two different national measures simulating the implementation of EU-directives: (1) technology specific subsidies and (2) improved building code are analysed. They are evaluated against a set of baselines influenced by the spillover in three global scenarios with different technology development paths. Furthermore, a special case with no spillover for offshore floating wind is also included. The exertion to coordinate national efforts to contribute to technology learning with a portfolio of globally desirable low-carbon technologies adds a new element to scenario analysis, not included in the earlier studies. More specifically, insight is sought regarding the following questions:

- What is the additional effect, of the national measures derived from EU-directives, on deployment of nascent energy technologies when including spillover of global technology learning?
- Specifically, do the selected policies and measures provide support to the high cost of early deployment?

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[1] Article 4.1c of the UNFCCC and article 2.1.a.iv of the Kyoto Protocol.

[2] The indicator measures the relative change in ΔQ=(renewable elect.+renewable heat/cooling+direct use of renewable energy carriers)/gross energy use.

[3] In this paper spillover is limited to cost reductions and efficiency improvement embodied in the technologies reflecting accumulated global deployment.

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An indicator for the national contribution to global technology development based on the need for financial support for technology deployment is suggested and used in the analysis.

The work presented is part of a study combining spillover of technology learning from the global market and feedbacks from other sectors of the national economy in a national energy systems analysis. First thoughts on the approach were presented, and feedback received, at an IEA workshop (Martinsen and Wene, 2007). In an experiment where net annual export and import of electricity was constrained to zero the need for the new technologies, e.g., wind power and natural gas combined cycle (NGCC) with carbon capture and storage (CCS) appeared only just before 2050. Consequently the contribution to global learning investments was estimated to be small (Martinsen, 2008). In this paper export and import of electricity may take place at today's cable capacity.

Below a short discussion of the interdependence between global learning and national deployment is presented followed by a description of learning investments and the indicator for national contribution to global technology development. In Section 3 the method applied to include technology learning and a short summary of the models used are presented. The global scenarios, the Norwegian energy system and national circumstances and the measures investigated are described in Section 4. The main part of the paper is devoted to the national energy system response to the combination of global technology learning and the national measures. A special case, where technology learning for offshore floating wind power (OFW) is endogenous, is also investigated.

2. Global learning and national deployment

The influence of global technology learning on the national energy system is briefly discussed in Section 2.1. An argument is provided for why coordinated action between countries in national policy implementation may assist in tackling the challenges of climate change. A description of learning investments and a measure of the national contribution to global technology development is provided in Section 2.2.

2.1. Coordinated national policy implementation

The price of new energy technologies and thus the most cost efficient technology composition of the future energy system of a small open economy like Norway ultimately will be heavily influenced by the selections made in the international energy system and the corresponding development of the international energy technology market. The cost of the energy service from the nascent energy technologies is higher than the existing technologies. Once in production and use; however, experience fosters technology learning and the cost will go down and performance improves (BCG, 1968). The learning system boundary may be assumed to be global given there is – or will be within the early part of the period of analysis – a global market established for the nascent energy technologies, (Junginger et al., 2005).

When the nascent energy technologies become competitive they will most likely be included in the future national energy system. This spillover of technology learning from the global energy technology market thus provides a strong incentive for technology change in the national energy system. The incentive will not be technology neutral but be stronger for the technologies experiencing the largest growth in the global energy system. It will thus try to coordinate the development of the national energy technology portfolio with the evolving technology composition of the global energy system. National circumstances may benefit other technologies or even work against the coordination, but are often not as strong. For example, in the early days of the automobile both gasoline and electricity were used as fuel. As the internal combustion engine using gasoline became the dominant technology globally it has been the preferred choice within most national energy systems. In Brazil; however, alcohol is produced nationally at a low cost and has to some extent displaced gasoline.

On the other hand, realization of cost reductions through global technology learning depends on national policy implementation. However, early deployment has a high cost. Because of the urgency and large risks the Stern review (2006) calls for policies to support the development and deployment of a portfolio of low-carbon technology options. Technology specific instruments and measures are thus needed to establish strategic niche markets to expedite the introduction of new technologies (IEA, 2003; Kemp et al., 1998), i.e., push the technologies into the energy system. Moreover, efficient strategies to shift the development of the global energy system to a low-CO_2 emission technology path call for international cooperation where local deployment contributes to technology learning on a global scale (IEA, 2000). Technology learning links, in a circular causal chain, the development of energy technology to the development of the energy system, because the technology learning system is structurally coupled to the energy system (Wene, 2008). Coordination of national policies with the desired global technology development scenario is needed to accomplish the global rate of deployment required to achieve emission reduction targets. That is, conceptually to make global and national technology learning to pull together towards a common goal.

A jointly implemented CO_2 incentive, e.g., in the form of a CO_2 tax or tradable CO_2 permits already represent a form of coordinated action among governments. However, many new low-CO_2 emitting technologies are still too costly and will therefore require targeted support until they are competitive in the mass markets with the CO_2 incentive.

The structural coupling makes path dependency into an inherent feature of technology learning (Mattsson and Wene, 1997; Wene, 2008). This implies that a more stringent global policy goal may exhibit a different technology portfolio (IEA, 2008).[4] A coordination of national policy and global technology learning depends not only on the national policies and measures, but equally on the chosen global scenario and associated global technology path, which set the external conditions for the national analysis. Path dependency therefore prescribes that the global scenario and the technology cost trajectories must be selected together, because different scenarios will exhibit dissimilar technology paths and therefore dissimilar technology cost trajectories.

Because the learning system boundary is assumed to be global a global model is required to determine the performance of the energy technologies. The performance, e.g., cost trajectory, is a boundary condition for the national analysis. The global scenarios selected in this paper are those described in the Energy Technology Perspectives (ETP)—Scenarios & Strategies to 2050 (IEA, 2008). There are two reasons for this choice of global scenarios. Firstly, the IEA scenarios outline alternative technology paths to 2050 consistent with the energy scenarios. Secondly, they have been extensively reviewed by a large number of policy analysts and experts from IEA government agencies, industries and research organisations. They constitute the basis for the technology road maps (IEA, 2008) indicating key actions required and time scale to commercialisation. The use of road maps is

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[4] ETP-report, Chapter 2, p. 68.

currently also discussed in UNFCCC in relation to a new protocol subsiding the Kyoto protocol. The IEA road maps will inevitably provide a significant input if the UNFCCC road maps should they materialise. Three benchmark scenarios (REF, ACT and the BLUE) and the road map for wind power are used in this study.

2.2. National contribution to global technology development

Technology learning curves are applied to determine the cost development and performance improvement of the nascent energy technologies in the global model (IEA, 2008).[5] The technology learning curves may also be applied to estimate the corresponding cost of deployment, namely the learning investments (IEA, 2000). Wene (2008) defined the learning investments (*LI*) as: the resources needed to reduce the cost of the service from the challenging technology (C_{CH}) until the break-even cost (C_{BE}) with the incumbent technology, that is, until the challenger is cost efficient in the targeted mass market. The *LI* at time *t* needed for one unit, e.g., 1 GW may thus be expressed as

$$LI_{CH}(t) = C_{CH}(t)\text{-}C_{BE}(t) \tag{1}$$

For the electricity generating technologies $C_{BE}(t)$ can be calculated from electricity price, *P*. The challenging technology then becomes competitive when $P_{CH}=P_{BE}$. As the targeted mass market generally is the global market, the break-even cost is a global parameter. It could in principle be estimated from a weighted average of regional electricity prices. For non-fuel using technologies, Eq. (1) can be simplified to express learning investments as the difference between actual investments cost for the challenger and the investment cost required making the challenger cost efficient in the targeted mass market. IEA (2008) (see footnote 5) provides Delphi estimates of such target investment costs, $C_{IEA,}$ for the challenger. These target costs may be used as time-independent estimates of break-even costs, $C_{BE}(t)=C_{IEA}$. For NGCC with CCS the C_{IEA} for CCS is added to the NGCC cost to estimate a P_{BE}.

The cost efficiency of the incumbent technology is measured before the application of any policy measures, e.g., CO_2 incentive or subsidy for specific technologies. Such measures are considered means to persuade the market to provide the necessary learning investments. The learning investments are thus not affected by the global scenario or specific policy, e.g., CO_2 incentive, but the cost when a technology may be viewed by the market actors as commercially viable will be affected. The criterion used in this paper to evaluate national support to global technology development is the *investment support* (*IS*). It is a measure of accumulated financial support *over and above the effect of a general* CO_2 *incentive until* the technology in question becomes commercially viable in the global market with the global CO_2 incentive. A schematic illustration of the break-even cost in the ETP policy scenarios ACT and BLUE are shown in Fig. 1. The break-even cost is linked to the global parameter P_{BE}. Nationally the break-even cost of a particular technology may be different because of national circumstances, e.g., favourable wind conditions. The general CO_2 incentive may therefore cause a contribution to IS when applied at the national level. I have applied the CO_2 incentives used in the IEA (2008) ACT and the BLUE scenarios at 50 US $ and 200 US $, respectively, for the A- and B-scenarios. Because of varying national circumstances, a direct transfer of global scenario break-even cost to a national system is not meaningful. Instead the national support to a nascent technology is considered to continue until the time period when the global market actors deem the technology commercially viable. The IEA (2008) has, in the technology road maps, provided scenario specific estimates of when the nascent technologies will become competitive in the mass market. In a model with 5-year periods the undiscounted IS is given by

$$IS = \sum_{n=1} \sum_{m=1}^{k} (C_{nm} - C_{nk}) D_{nm} \tag{2}$$

where C_{nm} is the national unit cost of technology *n* in the period *m* when deployed [NOK/GW]; C_{nk} is the national unit cost in the time period when technology *n* is deemed commercially viable in global markets [NOK/GW]; D_{nm} is the amount of technology *n* deployed nationally in period; $m=k$ is the period when technology *n* has become commercially viable

The time period, *k*, when a technology has become commercially viable with a given CO_2 incentive is provided in the "technology road maps" (IEA, 2008)[6] and are listed in Table 1. IS captures two important aspects of national support for technology learning. It measures support over and above what is generally required by an agreed international CO_2-incentive, administrated, e.g., through internationally tradable emission certificates. It also focuses strongly on the high cost of early deployment. As an indicator, it measures the economic contribution rather than based on physical units, e.g., MWh and thus serves as a complement to the EU indicator.

3. Method

The analysis of the national measures are done with a bottom-up energy systems model of the Norwegian energy system (Markal) with input from a global model (ETP) and a national macroeconomic model (MSG6), see Fig. 2. The national policies to stimulate technology deployment are input to the Markal model. The special case, where the cost trajectory of OFW from the global model is replaced by endogenous technology learning, is indicated by the feedback loop within the national model box.

Initially, macroeconomic parameters affecting national demand, e.g., economic growth and interest rate in the national models is made consistent with the global scenario. Scenario specific performance of the fossil fuel- and electricity import and export cost/prices are provided by the global model. Moreover, the global energy system model provides scenario specific input from the global energy technology market, e.g., technology cost trajectories reflecting the effect of technology learning.[7] The Markal model handles the energy system including export and import. Demand for energy from the non-energy sectors of the Norwegian economy is provided by the MSG6. The demand for energy differs slightly between the global scenarios because of the changes in the electricity price corresponding to the scenario specific technology cost trajectories and global fossil fuel prices. This influence of spillover on the demand is included for consistency and obtained through a soft-link with MSG6. Feedback on the demand for energy from the national measures discussed in this paper is not deemed significant and thus not included in the analysis. The soft-link is therefore not elaborated further here.

The guiding assumption for the analysis is that a small open economy like Norway is a price taker in the global technology markets. From a policy perspective it is also of interest to look at a case where Norway uses its comparative advantages to take the global lead in developing OFW. Norway is well suited to take this lead because relevant knowledge is gained through development

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[5] ETP-report, Chapter 5, Table 5.3.

[6] ETP-report, Chapter 3, p. 135 and 139.

[7] The cost trajectories, based on accumulated global deployment reflect spillover embodied in the technologies.

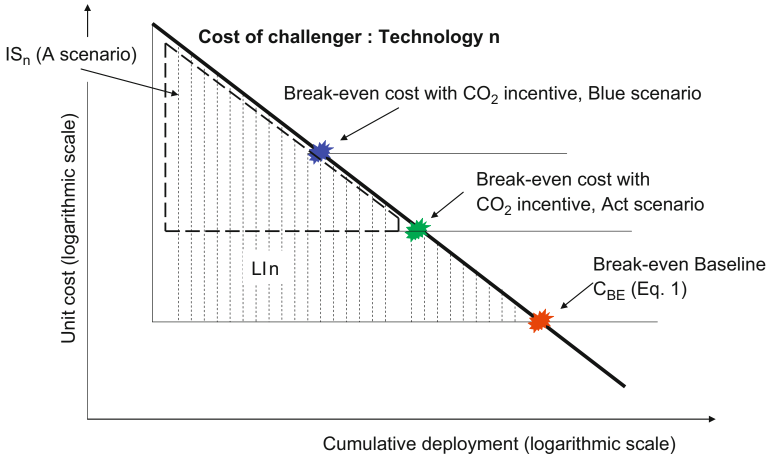

Fig. 1. Schematic illustration of the relationship between learning investments (LI), investment support (IS) and the technology learning curve. The area covered by the fine dotted line equals LI while the IS is only the area captured by the large dotted line.
Adapted from IEA (2008)

Table 1
The global capacity in 2050 of selected technologies relevant for the Norwegian energy system. The cost of NGCC with CCS and wind power is dependent on the installed effect. An indication of the global installed capacity is given in parenthesis.
Source: Energy Technology Perspectives (IEA, 2008)[a].

REF	ACT map	BLUE map
Measures enacted or decided	50 US $/ton (300 NOK/ton)	200 US $/ton (1200 NOK/ton)
Gas power with CCS negligible (83 TWh). Not commercially viable exempt for selected enhanced oil recovery	Gas power with CCS significant (1962 TWh). Commercially viable in most favourable locations by 2030, and in general by 2035	Substantial gas power with CCS (5458 TWh). The first commercially viable by 2020 and in general by 2030
Installed effect of wind power doubles 3.5 times from 2005 but only onshore (1208 TWh). Onshore commercially viable in favourable sites but generally only from 2045. Offshore not commercially viable	Wind power significant (3607 TWh). Onshore commercially viable by 2025 and offshore by 2035	Wind power substantial (5147 TWh). Onshore commercially viable by 2020 and offshore by 2030 in favourable locations

[a] ETP Report, Chapter 3, p. 135 and 139.

of technologies for offshore oil exploration, significant OFW research activity and large wind resources offshore. Moreover, the oil production is expected to go down and offshore wind exploitation may provide a possibility to continue technology development and export energy. Such a case is simulated by considering the Norwegian energy system as a strategic niche market for OFW. The assumption is then that within the chosen time horizon the OFW technology is only deployed in the Norwegian energy system. In this particular case, there is no spillover for OFW and the effect of technology learning on investment cost is determined by an endogenous variable in the optimizing routine. The effect of technology learning on the investment cost of the other technologies is still determined by the global model. The result will thus not only depend on the national circumstances but also on the choice of global scenario.

Three global scenarios from the IEA (2008) are applied; the REF, ACT and BLUE scenarios. The national response to these boundary conditions, e.g., technology performance, makes up a set of references representing a potential range in global development. The national measures are subsequently added, and the results compared with the respective “no additional policy” scenarios. Existing national policies and measures, including the emission trading system applied to the industry and the CO_2 tax on offshore emission and transport fuels, are replaced by a general national tax incentive of 150 NOK/ton CO_2. When the global CO_2 incentive is higher it replaces this value.

3.1. The models

The ETP model is a global bottom-up energy systems model with 15 regions. It belongs to the Markal family of models (Fishbone and Abilock, 1981). It represents the global energy economy including primary energy production, e.g., oil, and conversion to final energy carriers, e.g., gasoline and electricity. The model applies 5-year intervals and optimizes the global energy system up to 2050 (IEA, 2005).[8] The cost development of the nascent energy technologies are affected by technology learning (Gielen et al., 2004). The cost trajectories are determined on the basis of the accumulated global deployment and technology specific learning rates (IEA, 2008).[9] For large plant like technologies with very long lifetime, e.g., NGCC with CCS several vintages with declining cost are used rather than a technology learning curve approach. The ETP model framework includes an oil price module estimating the market prices of fossil fuel endogenously (IEA, 2005).[10]

The Markal (Fishbone and Abilock, 1981) Norway model applies a system boundary for the Norwegian energy system following the national boundary, but including the offshore oil producing installations. The current electricity export/import capacity may be exchanged across the system boundary. The option to add additional export capacity is not included in this study. The Norwegian Markal model includes about 400

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[8] Annex 1, pp. 202–203.
[9] Chapter 5, p. 207.
[10] Annex 1, p. 207.

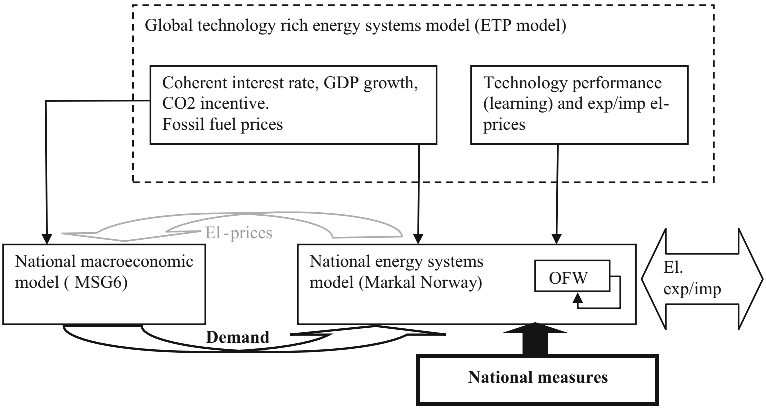

Fig. 2. The model set-up consists of three models where the link with the global model provides a boundary condition for both the national models. The demand for energy service is provided by the MSG6 model. The emphasis in this paper is the influence on deployment of nascent energy technologies by the national measures measured against a baseline with spillover of global technology learning.

technologies and is most detailed in electricity generation, heat generation and demand side technologies, and light duty vehicles. For the model experiments with endogenous technology learning (ETL) for offshore floating wind, the ETL version of Markal is used (Loulou et al., 2004).

The macroeconomic model of the Norwegian economy is a computable general equilibrium—multi-sector growth model version 6. It has a detailed description of the structures of economic policy, production and consumption sectors in the Norwegian economy. The model has 41 private and 8 governmental production activities (Heide et al., 2004).

4. The global scenarios and national measures

This section initially gives a brief description of the Norwegian energy system. Subsequently, the global and national scenarios are described.

4.1. The Norwegian energy system

The Norwegian energy system is embedded in a technological regime with hydroelectric power, and where electricity is dominating as energy carrier outside the transport and oil producing sectors. The main technology for electricity generation in Norway will continue to be large scale hydropower. Hydroelectric power generate about 118 TWh [11] and supply almost all domestic electricity today, equal to about 65% of total energy consumption. The demand for energy service from buildings is about 23% of stationary energy service demand without electricity specific uses for appliances. While the demand for electricity across the scenarios is projected to increase 35% to about 160 TWh by 2050, its share of stationary energy use remains at the same level. The future potential for electricity production in large hydroelectric plants is limited. The only existing gas power plant was completed in 2006 but has not been in regular operation until very recently; however, because of the high price of natural gas. Coal and nuclear power plants are currently ruled out because of political decisions and not included in this study. Potential future conversion technologies include NGCC with CCS, small-, mini- and micro-hydropower, wind power onshore and offshore, salt wedge power and wave and tidal power. Norway has a relatively large wind power potential both onshore and offshore. There are substantial research programmes investigating two different OFW concepts and the first prototype was deployed in the summer 2009. The government has declared ambitious intentions to develop the CCS technology. Moreover, Norway has pioneered the technology for storage of carbon dioxide under the seabed in the North Sea.

The Norwegian energy system is physically coupled to the Nordic and the European energy system through export/import cables. Electricity prices in Norway, though traded on the Nordic electricity exchange (Nor-Pool), are affected by the limitations in transmission capacity and thus lower on the annual average than the price in Sweden and Denmark. The price of electricity to consumers has historically been low. The export/import cable capacity, together with the establishment of a fully competitive market for electricity, has increased the "import" of European electricity prices. Still, the electricity price in the national market is sensitive to the spillover of technology learning from the global technology market.

4.2. The global scenarios

Among the global scenarios in the ETP study, the REF, the ACT Map and the BLUE Map are selected. They are stabilising the CO_2 emissions at today's level and reducing the CO_2 emissions 50% by 2050 respectively and represent a relatively optimistic view with respect to technology development. They include a disaggregated representation of both of the technologies most interesting for Norway, wind power and NGCC with CCS. Up to 2030 the REF scenario is calibrated to the World Energy Outlook 2007 (IEA, 2007). Increasing energy efficiency is identified as a key element in all the ETP scenarios (IEA, 2006, 2008).[12] In the global scenarios with increased CO_2 incentives the market price of oil is expected to reach a maximum around 2035 and then fall slightly up to 2050 (Gielen, 2006; IEA, 2008). The national market for fossil fuels is fully competitive and prices follow the global market. The global capacity in 2050 of selected technologies relevant for the analysis of the national contribution to global technology development is given in Table 1.

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[11] The actual generation varies from year to year.

[12] ETP 2006 Report Summary, p. 31.

Table 2
Nomenclature and summary description of national policy scenarios.

Global scenario	National CO_2 incentive	National measure	Scenario acronym	Description
REF	150 NOK/ton	No add. measure	R	
		Technology subsidy (Wind: NOK/MWh, DH: NOK/MWh, CCS: NOK in % of investment)	R–L	Wind low: 2005:80/2010–15:100/2020:50 DH low: 2005–15 :40//2020:20 CCS Low: 40 % of CCS cost
			R–H	Wind high: 2005:80/2010–20:150/2025:80 DH high: 2005:100/2010–20:150/2025:50 CCS high: 100 % of CCS cost
		Building code (reduction in energy for space heating, %)	R–B	Commercial 2010: 37, 2020: 43, 2035: 67 Multifamily 2010: 60, 2020: 78, 2035: 90 Single family 2010: 35, 2020: 50, 2035: 70
ACT	300 NOK/ton	No add. measure	A	
		Technology subsidy	A–L	Low: see R scenarios above
			A–H	High: see R scenarios above
		Building code	A–B	See R scenarios above
		ETL—No add. meas.	AE	
		ETL—H	AE–H	Wind subsidy high, no subsidy for CCS
BLUE	Increasing to 1200 NOK/ton	No add. measure	B	
		Technology subsidy	B–L	Low: see R scenarios above
			B–H	High: see R scenarios above
		Building code	B–B	See R scenarios above

4.3. *The national measures*

The national climate change- and energy security policy are, in addition to international commitments, influenced by EU-directives. There are two EU-directives of particular importance for this paper: the Energy Performance of Buildings Directive (EPBD) and the Promotion of the Use of Energy from Renewable Sources directive (ERSD). EU-directives are to a large extent descriptive and thus leave a great deal of freedom for each member state to adapt the implementation to national circumstances. The impact on energy use and the build environment will be highly variable as exemplified by a study of the implementation in the United Kingdom (Ekins and Lees, 2008). The EU 20/20/20 target aiming at increasing new renewable energy, reducing energy demand through energy efficiency and reducing CO_2 emissions all by 2020 are concrete, though the extrinsic national targets vary. The national policies applied here are made to illustrate the potential of the directives to push member states to contribute to technology deployment and identify potential conflicts between different national goals. Two different policy measures are included in this study: (1) subsidies for new renewable energy conversion technologies, renewable district heat generation (DH) and carbon capture and storage and (2) improved building code to reduce energy demand. The national policies are further described below. A nomenclature of the national scenarios is given in Table 2.

4.3.1. *Technology subsidies*

The technology subsidies are applied to wind mills, NGCC with CCS and DH using renewable energy carriers such as wood and waste. There are two levels, a low and a high level of subsidies. All the subsidized technologies receive a feed-in tariff applied to the energy carrier generated. Various initiatives to stimulate wind power development have been launched since the early 1980s, and in 2002 a national target of 3 TWh wind power by 2010 was established. An electricity feed-in subsidy of 50 NOK/MWh was introduced in 1998. Later, the subsidy was rather provided as a contribution to the initial investment (Buen, 2006). The level of subsidy chosen here is consistent with the levels of contribution suggested in Norway. The feed-in tariffs for the CCS technologies are consistent with an investment subsidy of 10% and 25%, respectively, of the cost of power plant with CCS in the high and the low policy scenario. The high CCS subsidy level is about equivalent with the total cost of the CCS. This may seem high; however, the feed-in tariffs are of the same order of magnitude as for wind power. The wind power subsidy ends in 2025 and the CCS subsidy is applied up to the end of the period of analysis in 2050 because some of the CCS technologies are not available before 2030.

4.3.2. *National strategic niche market for offshore floating wind*

In the special case where Norway proceeds alone with deployment of OFW, the technology learning system boundary for this particular technology is national. There is thus no spillover from the global technology market and deployment is a prerequisite to reduce cost. A technology learning curve is used to determine the cost trajectory $C(X_{cum})$ given by (IEA, 2000)

$$C(X_{cum}) = C_0(X_{cum})^{-E} \tag{3}$$

Rather than the learning parameter E the learning rate (LR) is often used. The LR is the relative cost reduction or percentage for each doubling of production.[13] Two different learning rates (LR) are considered. Consistent with the ETP study 9% LR (IEA, 2008) corresponds to OFW as a grafted technology of an onshore wind mill and a base using technology from offshore oil installations. The OFW will then benefit from the experience gained in onshore deployment. Consequently the starting capacity X is large. However, if OFW develops into a new technology 20% LR may be obtained (Neij, 2008; Wene, 2008) and the starting capacity is low while the starting cost may be high. In the AE–H scenario, a national subsidy for wind power only is investigated. There is thus no subsidy for CCS in that scenario.

4.3.3. *Improved building code*

This measure may be viewed as a national implementation of the EPBD directive. It is implemented as an efficiency improvement forced upon commercial and residential buildings. It is applied to new building construction and major refurbishments

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[13] $LR = 1-[C_0(2X_{cum})^{-E}/C_0(X_{cum})^{-E}] = 1-2^{-E}$.

Table 3
Key national results in 2050 with spillover of global technology learning and with the additional policy measure.

		R	A	B
System cost (Billion NOK)	No add. policy	5375.0	5043.1	5011.5
	L (low subsidy)	+3.5	+4.2	+4.1
	H (high subsidy)	+17.5	+21.9	+13.8
	B (building code)	+100.0	+102.0	+108.0
CO_2 (Mton)	No add. policy	59.8	48.4	32.6
	L	−0.5	+0.2	+0.2
	H	−4.1	+0.5	+0.4
	B	−4.3	−0.1	0
El-production (TWh)	No add. policy	162	201	200
	L	+1	0	0
	H	+2	+2	+2
	B	−15	−26	−21

consistent with today's practice. All commercial buildings are assumed new or refurbished by the end of the analysis period and thus influenced by the measure. For residential buildings, only about 16% of existing building stock is assumed replaced by new buildings. The building code is implemented in a stepwise manner beginning in 2010, strengthened in 2020 and further strengthened from 2035. The levels of efficiency improvements in the first step are about equal to the new building code of 2007. The level of improvement in the second step, determined by the available data, is equal to a medium improvements compared to today's level. The final step is about equal to the performance of "passive houses" (Wigenstad and Tyholdt, 2005).

5. Effect of the national policies with technology learning

The effect of the national policies on deployment, and thus indirectly on the system cost,[14] CO_2 emissions and level of electricity generation, is evaluated against a set of scenarios labelled "no additional policy" corresponding to each of the global scenarios. These scenarios include only the influence of technology learning. Subsequently, the effect of each of the measures is described. Finally, the result from the special case with ETL and no spillover for OFW is provided.

An overview of the national scenario results in 2050 with spillover from global technology learning is listed in Table 3. The impact of global technology learning is substantial. In the R-scenario the CO_2 emissions are increasing from about 44 Mton in 2005 to about 60 Mton in 2050. New electricity generation capacity is then obtained from NGCC. The choice of new electricity generation technology in the "no additional policy"—A- and B-scenarios, new electricity generating capacity is dominated by OFW as shown in the small graph inset in Fig. 3. The cost of OFW is heavily influenced by global technology learning. In the scenarios A and B, spillover of global technology learning facilitates both reduced national CO_2 emissions and lower system cost because utilizing the full electricity export capacity generates significant revenue.

Both targeted national measures increase the system cost, though marginally. The influence of the measures on total annual CO_2 emissions is only significant in the R-scenario though still very small. The impact of the measures on total electricity generation is also small exempt from the building code.

5.1. Subsidies for wind power and CCS

In the R–L scenario the amount of onshore wind increases displacing gas power. In the R–H scenario onshore wind increases further and a small amount of OFW is introduced by 2020. By 2050; however, NGCC with CCS displaces about half of the wind power and reduces the share of small new hydropower, see Fig. 2. The subsidies thus significantly influence the technology composition, initially increasing deployment wind power and later shifting deployment to gas power with CCS because the subsidy for CCS is retained longer than for wind power. At first post combustion CCS is selected, while oxy fuel is added in 2045. Gas power with CCS then generates about12.5 TWh electricity by 2050.

The A–L scenario exhibit similar behaviour except NGCC with CCS is introduced already in 2020 rather than part of the onshore wind power and OFW. With high subsidy, in the A–H scenario, onshore wind and significant OFW is introduced by 2020 displacing NGCC with CCS. Some new hydro is also displaced. Towards 2050 the subsidy for CCS in both the A–L and A–H scenarios displaces some of the OFW, but also the small amount of NGCC without CCS in the "no additional policy" scenario.

In the B–L scenario wind power is increased in 2020. This outcome is accentuated in the B–H scenario where both onshore and OFW increases displacing more new hydro compared to the A–H scenario. The long term effect of the subsidies is modest. In 2050 a very small amount of NGCC with CCS is pushed into the energy system and then only in the B–H scenario, see Fig. 3.

Across the national policy scenarios the subsidies alter the technology composition. They increase deployment of wind power in the early periods, displace NGCC and introduce NGCC with CCS particularly in the late periods. This is less pronounced in the B-scenarios because of the small remaining CO_2 emission becoming expensive with the high CO_2 incentive.

5.2. Building code

The building code has limited effect by 2020. In the A–B scenario the demand is significantly reduces demand for final energy in the long term. Because the export is constrained the electricity generation in 2050 is also reduced, see Table 3. This is predominantly through significantly reduced deployment of OFW. Both NGCC without CCS and with CCS is also reduced, but as these are small in the A scenario they are of minor significance, see Fig. 3. Together, total electricity generation in the A–B scenario is increasingly less than the A-scenario, at 5.2 TWh in 2020 and 26 TWh less in 2050. The CO_2 emissions are also reduced in the R–B scenario because additional NGCC capacity is eliminated from the energy system. In the A–B and B–B scenarios, the effect of a more stringent building code on electricity generation is more pronounced as electricity increasingly is used as energy carrier for heating. The increase in system cost; however, is then about 100 billion NOK, equivalent to about 2% of total system cost up to 2050. The uncertainty in the cost of this measure should be investigated further. In particular, the potential impact from technology learning on a regional implementation of a "passive house" standard.

5.3. National strategic niche market for offshore floating wind

Using the ETP assumptions, 9% LR and high starting capacity, OFW is not selected in any of the scenarios. A subsidy targeting both wind power and NGCC with CCS increases the use of NGCC with CCS and reduce the use of other renewable energy technologies, e.g., near shore wind power. Providing the subsidy

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[14] Discounted total system cost, net of taxes and subsidies.

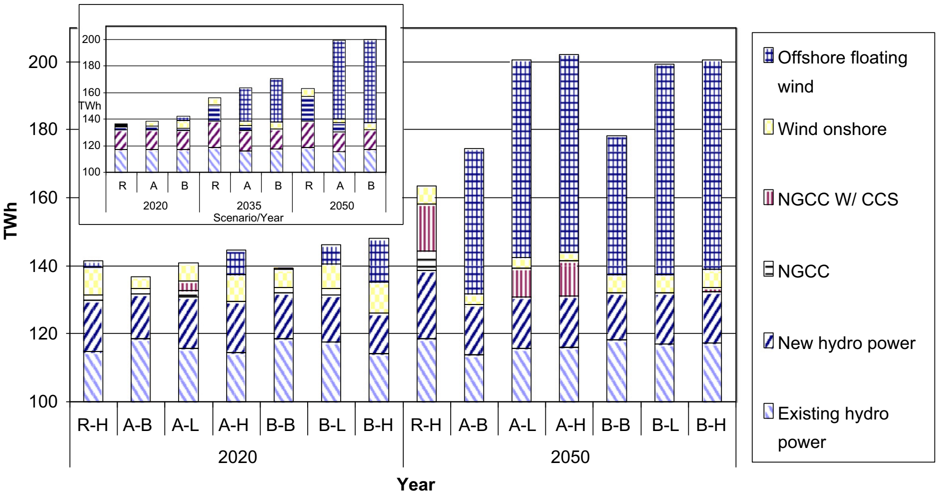

Fig. 3. The technology composition in electricity generation for selected scenarios in 2020, 2035 and 2050. The national reference scenarios R, A and B corresponding to the global scenarios and technology paths REF, ACT Map and BLUE Map are shown in the inset graph. The high and low subsidy cases end with L and H and the scenario with strengthen building code is indicated with a "B".

to wind power only with 9% LR, near shore wind and wave still dominates the nascent electricity generation technologies. The high subsidy ending in 2025 is thus still not sufficient to push OFW into the national energy system. The sensitivity of this result to extending the wind power subsidy period and increasing LR is investigated further. A shift the dominant nascent technology to OFW is observed when the high subsidy is extended until 2035. The OFW technology may thus still become competitive within the national strategic niche market with sufficient subsidies. On the other hand, assuming that OFW is a new technology, where 20% LR and 0.3 GW starting capacity is appropriate, OFW is deployed in both the AE and the AE–H scenarios. OFW is then barely deployed in 2015 followed by 3 GW in the next 5-year period.

6. National contribution to global technology learning

This section analyses the national contribution to global technology development and thus responds to the second research question posed in the introduction. The special case, where a strategic national niche market simulates no spillover for OFW is also discussed.

6.1. With spillover from global technology development

All the national scenarios include the electricity generating technologies deployed in the corresponding global scenarios and thus contribute to global technology development. Nevertheless, there are differences in the technology composition of the future national energy system reflecting the national policies and thus affecting the national contribution to technology development. There are also large differences in the IS depending on the global scenario. Using IS as measure of the national contribution to global technology development is illustrated for the R, A, A–H, AE and AE–H scenarios below.

In the R-scenario the national CO_2 incentive of 150 NOK/ton may initiate an IS. The IS is very small; however, because NGCC are selected to meet the increased electricity demand. The national subsidy, in the R–H scenario, shifts the investments to NGCC with CCS. Because it does not become commercially viable within the analysis period all of these investments contribute to IS. This increases the IS substantially, see Fig. 4. In the A scenario, with a CO_2 tax at the level of the global CO_2 incentive only, significant IS is provided. This may seem inconsistent with the definition of IS. Firstly, the decision to provide IS is internal to the optimizing routine and thus determined by the system cost for the whole analysis period. More important are probably the favourable conditions for wind power in Norway compared to the global average. In 2015–2020 the IS is directed to onshore wind power. From 2025 when spillover of global technology learning reduces the investment cost, IS is directed to OFW. The large contribution to IS in 2025 compared to 2035 is because the difference between C_{nm} and C_{nk} is much greater in 2025. Introducing the subsidy, in the A–H scenario, the IS starts one period earlier. Moreover, the fraction of IS in 2015 is more than three times higher than without the subsidy. Likewise, the support provided for OFW also starts earlier. The contraction of IS for OFW to 2020 is because the model maximizes the benefit of the subsidy ending in 2025. The phase in of NGCC with CCS observed in the A–H scenario hardly influence the IS because it occurs after it becomes commercially viable in 2035. While the early contribution to IS is of particular interest, we may also note the fraction for the different technologies as well as the value of IS. The support for OFW is slightly less in the A–H scenario because of the export constraint. The fraction of IS for onshore wind power; however, is substantially higher. The IS in the A–H scenario is therefore higher than the A scenario. A similar pattern is also observed for the B–H scenario but with even more support for OFW by 2020. Because of the export constraint other electricity generation is intermittently displaced in 2020, mostly large hydro, see Fig. 3. Because large hydro is already commercially viable, displacing it by OFW increases the IS. The subsidy thus both increases the national contribution to early learning investments and it is provided earlier than in the A scenario with the CO_2 tax only.

The building code reduces the national energy demand, particularly beyond 2020. The electricity generation from nascent energy technologies follows because of the export constraint. The building code may thus reduce the IS, particularly in the A

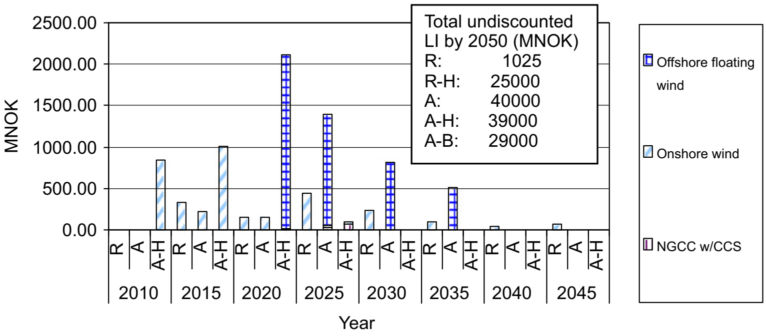

Fig. 4. National investments support provided for the scenarios R, A and A–H allocated to the technologies onshore wind, offshore floating wind and NGCC with CCS, and learning investments provided over the period of analysis.

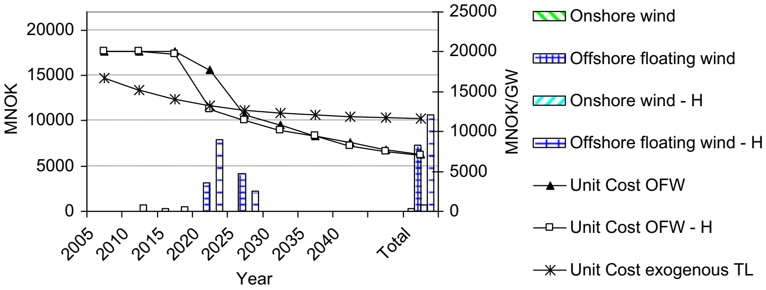

Fig. 5. Contribution to IS per 5-year period, total undiscounted IS and unit cost trajectory for OFW with and (MNOK/GW) without the additional subsidy provided and a LR of 20%. The cost trajectory for exogenous global technology learning is also included.

scenario. In the B scenario electricity displaces to some extent other energy carriers and thus reduces the influence of the export constraint. Onshore wind deployment is delayed by 10 years in the A scenario. In the B scenario the introduction of OFW is delayed by 15 years until 2035. OFW has then moved beyond the global deployment phase and become competitive in the global energy technology market, see Table 1. Norway would then no longer contribute with IS.

The national contribution to LI is also estimated for comparison, see inset table in Fig. 4. They are an order of magnitude larger than the IS. There are two reasons for this difference between IS and LI. Firstly, IS measures the national investment support relative to the break-even in markets with the general CO_2 incentive while LI measures total additional support relative to a break-even cost in the Baseline without any general CO_2 incentive, see Fig. 1. Secondly, LI covers a longer time period than IS because it will take longer time for the technology to reach the Baseline. In some cases the technologies may not reach the baseline break-even cost (C_{BE}) within the analysis period. Moreover, NGCC with CCS may only reach the C_{BE} based on a fossil plant without CCS if integrated in a manner such that externalities make it more cost efficient. The difference between the LI and IS increases when there is a more ambitious global CO_2 reduction target resulting in a higher CO_2 incentive, i.e., the A and B scenario. This is because the IS only credit early deployment and because increased deployment globally makes the technologies become competitive earlier. The building code also reduce the national contribution to LI, see inset in Fig. 3. This is predominantly because the deployment of OFW is significantly reduced as demand is lower and the export is constrained.

In the R-scenario the national contribution to LI is increased substantially by national policy, while in the A-scenario it is merely affected. This is because the national energy system aligns itself with the global technology path in the A scenario as a result of the pull from spillover of global technology learning.

6.2. National strategic niche market

Finally, it may be of interest to investigate the IS if Norwegian market actors believe they can obtain a LR of 20% for OFW and moves ahead alone. Because no others deploy this technology there is thus is no spillover. National deployment is now a prerequisite to obtain the cost reduction for OFW. The decision to provide LI for OFW is internal to the optimizing routine. As described in 5.3, only with a LR of 20% the technology is deployed. The case investigated here is the AE and AE–H scenarios with 20% LR for OFW and spillover of technology learning for the other technologies.

We may then no longer use the road map (IEA, 2008) to determine the time period (k) when the technology becomes commercially viable in the global market. While the global break-even electricity price P_{BE} may not change very much because the total global deployment of OFW is relatively small, the time period (k) when OFW becomes competitive may be delayed because of less deployment. However, with the higher LR less deployment is required to reduce the cost and thus for the technology to become competitive. From inspection of the unit cost curves in Fig. 5 applying the cost in 2030 for C_{nk} seems to be a reasonable assumption.

In the AE–H scenario, the effect of the subsidy is similar to the response with spillover of global technology learning. The early investment, in OFW in particular, increases, see Fig. 5. The level of IS is more than double than with spillover because the early deployment costs for OFW is higher and total national deployment has increased slightly.

In the AE and AE–H scenario, the installed capacity of OFW by 2050 is 15–18 GW. The building code combined with the electricity export constraint again causes learning investments to be insufficient to make OFW cost efficient and it is thus not deployed within the analysis period. The early cost reductions exhibited for OFW without the building code, combined with delayed introduction of the building code may; however, initiate other strategic niche markets. While investigating this is beyond the scope of this paper, further studies with two or more strategic niche markets interacting is recommended.

7. Conclusion

Introducing a targeted national subsidy for the nascent energy technologies onshore-, near shore- and floating offshore wind power and NGCC with CCS has only marginal influence on the Norwegian CO_2 emissions by 2050. Norway's contribution to early deployment of the nascent energy technologies; however, increases significantly. Both onshore wind power and offshore floating wind power is, under the global Energy Technology Perspectives scenarios ACT and BLUE, deployed earlier with the subsidy than with spillover of global technology learning only. Moreover, the suggested indicator for national contribution to global technology development, investment support, IS, increases with the subsidy. The indicator measures the contribution of national policies to early deployment, over and above the effect of a globally agreed CO_2 incentive and spillover of technology learning from the global market. Realization of the cost reductions in the Energy Technology Perspectives scenarios, through technology learning, depends on national deployment. The indicator, measuring the national contribution to global technology development in monetary unit, facilitates crediting the high cost of early learning investments. It may complement the indicator in energy units used by the EU to monitor the member states compliance with, e.g., the 20/20/20 target. The value of IS depends both on the global scenario and the targeted national measures. A special case with no spillover of technology learning is analysed for offshore floating wind. Substantial subsidy, or a learning rate of 20%, is then required to make deployment of this technology cost efficient for the analysis period 2005–2050. Applying the 20% learning rate, the investment support more than doubles compared to the case with spillover. Adding a national subsidy further increase the investment support and shifts it to an earlier time period.

Overall, the investment support exhibits the same behaviour with, and without, spillover. Coordinated action facilitates spillover of technology learning and reduces the need for national investment support and the risks connected to the obtainable technology learning rate. The special case with no spillover for offshore floating wind may also exhibit the situation where a country who is the first to deploy the technology. The contribution by a country who takes on the role of ''first mover'' may then be acknowledged through crediting the high value of the national investment support compared to the case with spillover.

Implementation of an improved building code reduces demand for energy and may reduce Norway's contribution to global technology development unless sufficient electricity export capacity is assured. Without spillover the combined effect of the electricity export constraint and the building code prevents offshore floating wind from becoming commercially viable within the analysis period.

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