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Doctoral Dissertation

Ilkka Keppo

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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Faculty of Engineering and Architecture for public examination and debate in Auditorium AS1 at Helsinki University of Technology (Espoo, Finland) on the 27th of November, 2009, at 12 noon.

Helsinki University of Technology
Faculty of Engineering and Architecture
Department of Energy Technology

Teknillinen korkeakoulu
Insinööritieteiden ja arkkitehtuurin tiedekunta
Energiatekniikan laitos

Distribution:
Helsinki University of Technology
Faculty of Engineering and Architecture
Department of Energy Technology
P.O. Box 4100
FI - 02015 TKK
FINLAND
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ISBN 978-952-248-184-9
ISBN 978-952-248-185-6 (PDF)
ISSN 1795-2239
ISSN 1795-4584 (PDF)
URL: http://lib.tkk.fi/Diss/2009/isbn9789522481856/

TKK-DISS-2677

HSE Print
Helsinki 2009

ABSTRACT OF DOCTORAL DISSERTATION	HELSINKI UNIVERSITY OF TECHNOLOGY P.O. BOX 1000, FI-02015 TKK http://www.tkk.fi

Author Ilkka Keppo

Name of the dissertation
On Energy Modelling for a Range of Spatial, Temporal and Technological Scales

Manuscript submitted 19.5.2009	Manuscript revised 30.9.2009

Date of the defence 27.11.2009

☐ Monograph	☒ Article dissertation (summary + original articles)

Faculty	Faculty of Engineering and Architecture
Department	Department of Energy Technology
Field of research	Energy Economics and Power Plant Engineering
Opponent(s)	Simon Harvey, Professor and Ilkka Savolainen, Research Professor
Supervisor	Risto Lahdelma, Professor
Instructor	Pekka Pirilä, Professor

Abstract

In this dissertation a number of modeling studies, ranging from process specific mathematical formulations to global long term climate consequences of energy and emission scenarios, are presented and the commonalities, and differences, across the existing energy modeling methodologies and applications are reviewed.

For the regional modeling work mathematical representations are developed for the operation of small biofuel fired CHP plants. These mathematical descriptions are then used in a non-linear optimization model, in order to evaluate the economic feasibility of connecting such a CHP plant to a local district heating grid. The results indicate that under the assumed policy and economic conditions, such a CHP plant would not be able to compete with a biofuel fired heat-only boiler.

The global, long term part of this work describes the modification and application of a global energy system model for a range of climate related issues. An endogenous description of "learning by doing" is implemented in the model and the subsequent model results show that although technological progress alone is unlikely to lead to climate stabilization, and therefore specific policies aimed at emission mitigation are a necessity, the lowered costs resulting from the "learning by doing" effect can reduce the mitigation costs considerably. The further studies establish that if the climate policy regime is incomplete, in the sense that some regions join it considerably later than others, more stringent targets might be difficult to reach and they will certainly be more expensive. Finally, a probabilistic study shows that reaching ambitious temperature targets with a high likelihood might not only require a wide portfolio of mitigation options and relatively early action, but it may also be that scenario specific indicators, such as demographic, economic and technological developments would need to progress in favorable manner.

In the summary section the field of energy modeling is reviewed and presented in terms of methodologies and applications on the one hand and in terms of the system borders of the models on the other. The studies presented in this thesis and in the literature are placed within this framework and the commonalities of models appearing very different on the first look are pointed out.

Keywords energy modelling, optimization, system analysis, CHP, climate change

ISBN (printed)	978-952-248-184-9	ISSN (printed)	1795-2239
ISBN (pdf)	978-952-248-185-6	ISSN (pdf)	1795-4584
Language	English	Number of pages	57 p. + app. 97 p.

Publisher Helsinki University of Technology, Department of Energy Technology

Print distribution Helsinki University of Technology, Department of Energy Technology

☒ The dissertation can be read at http://lib.tkk.fi/Diss/2009/isbn9789522481856/

VÄITÖSKIRJAN TIIVISTELMÄ	TEKNILLINEN KORKEAKOULU PL 1000, 02015 TKK http://www.tkk.fi

Tekijä Ilkka Keppo

Väitöskirjan nimi
Energiamallinnuksesta spatiaalisille, ajallisille ja teknologisille skaaloille

Käsikirjoituksen päivämäärä 19.5.2009	Korjatun käsikirjoituksen päivämäärä 30.9.2009

Väitöstilaisuuden ajankohta 27.11.2009

☐ Monografia	☒ Yhdistelmäväitöskirja (yhteenveto + erillisartikkelit)

Tiedekunta	Insinööritieteiden ja arkkitehtuurin tiedekunta
Laitos	Energiatekniikan laitos
Tutkimusala	Energiatalous ja voimalaitostekniikka
Vastaväittäjä(t)	Simon Harvey, Professori ja Ilkka Savolainen, Tutkimusprofessori.
Työn valvoja	Risto Lahdelma, Professori.
Työn ohjaaja	Pekka Pirilä, Professori.

Tiivistelmä

Tässä väitöstyössä esitetään joukko mallinnustutkimuksia, joiden aihepiirit ulottuvat prosessikohtaisista matemaattisista muotoiluista globaaleiden, pitkän aikavälin päästö- ja energiaskenaarioiden ilmastovaikutusten analysointiin, sekä käydään läpi tämänhetkisten energiamallinnusmetodologioiden ja -sovellusten yhteneväisyyksiä ja eroavuuksia.

Alueellisiin sovellutuksiin keskittyvässä osassa mallinnustyötä kehitetään matemaattinen malli joukolle pieniä, biopolttoainetta käyttäviä CHP-laitoksia. Tätä matemaattista mallia hyödynnetään epälineaarisessa optimointimallissa, minkä avulla pyritään arvioimaan taloudellisia edellytyksiä pienen CHP-laitoksen laitoksen liittämiseksi paikalliseen kaukolämpöverkkoon. Tulokset osoittavat, että taloudellisten parametrien ollessa tutkimukseen valitun kaltaiset, CHP-laitos ei pystyisi kilpailemaan biopolttoainetta käyttävän lämpökattilan kanssa.

Tämän työn pitkään aikaväliin keskittyvä osuus kuvaa globaalin energiamallin kehityksen ja sovelluksen joukkoon ilmastomuutoskysymyksiä. Malliin rakennetaan matemaattinen muotoilu teknologioiden ns. ”oppimiskäyrille”, minkä jälkeen mallilla ajetaan joukko ilmastorajoitteisia ajoja. Tulokset näyttävät, että vaikkakaan teknologioiden kehitys yksinään ei malliajoissa takaa ilmastotavoitteiden saavuttamista ja siksi ilmastospesifiset tavoitteet vaikuttavat välttämättömiltä, oppimiskäyrän seurauksena alentuneet investointikustannukset voivat laskea päästötavotteiden saavuttamisesta seuraavia kustannuksia huomattavasti. Seuraavan tutkimuksen tulokset puolestaan näyttävät, että jos osa maailman maantieteellisistä alueista aloittaa päästöjen vähentämisen selvästi muita myöhemmin, kireiden ilmastotavotteiden saavuttaminen saatta osoittautua vaikeaksi ja ainakin kalliimmaksi. Viimeisessä tutkimuksessa joukkoa päästöskenaarioita analysoidaan, osa ilmastonmuutokseen liittyvistä epävarmuuksista huomioiden. Tulokset osoittavat, että aikaiset päästövähennykset ja laaja teknologiaportfolio eivät välttämättä takaa kunnianhimoisten ilmastotavotteiden saavuttamista suurella todennäköisyydellä, vaan mahdollisesti myös energiajärjestelmästä riippumattomien taloudellisten, väestöllisten ja teknologisten trendien tulisi edetä ilmastotavotteiden toteuttamisen kannalta edullisesti.

Yhteenvetoosuudessa käydään läpi energiamallinnusalaa, metodologioita ja sovelluksia, erityisesti huomioiden sovellusten järjestelmärajat. Kirjallisuusviitteiden ja tämän väitöstyön tutkimukset asetetaan tähän kehykseen, pyrkien samalla osoittamaan ensisilmäykseltä varsin erilaisten mallien yhteneväisyydet.

Asiasanat energiamallinnus, optimointi, systeemianalyysi, CHP, ilmastonmuutos

ISBN (painettu) 978-952-248-184-9	ISSN (painettu) 1795-2239
ISBN (pdf) 978-952-248-185-6	ISSN (pdf) 1795-4584
Kieli Englanti	Sivumäärä 57 s. + liit. 97 s.

Julkaisija Teknillinen korkeakoulu, Energiatekniikan laitos

Painetun väitöskirjan jakelu Teknillinen korkeakoulu, Energiatekniikan laitos

☒ Luettavissa verkossa osoitteessa http://lib.tkk.fi/Diss/2009/isbn9789522481856/

PREFACE

The work described in this thesis was carried out at two different institutes, first at the Helsinki University of technology, at the Laboratory of Energy Economics and Power Plant Engineering and then later in Austria, at the International Institute for Applied Systems Analysis. The final touches on the overview section were finalized while I was working for my current employer, the Energy research Center of the Netherlands.

At each of the above institutes there is a number of people I owe my gratitude to. This number is, in fact, much too high for me to list everybody here, but a couple of names I simple need to mention. I would, first of all, like to thank professors Pekka Pirilä and Risto Lahdelma for their guidance and help, especially during the finalization of this thesis. My colleagues at the laboratory are also warmly thanked. The working environment you helped to create was not only stimulating, but also made working there truly fun. From IIASA, I would especially like to thank my two closest colleagues and co-modellers, Ms Shilpa Rao-Skirbekk and Professor Keywan Riahi, whose contribution to the work presented in this thesis has been enormous, both officially, thorough co-authorships, as well as through the numerous informal conversations at work, over a beer or while driving back to Vienna, after a long day at the office. Finally, many thanks are in order for Harm Jeeninga of ECN, who made sure I did not forget that I had a thesis to finish and also gave me the time to do exactly that.

Last and most important, very many thanks to my family and friends, although the latter are heavily featured already in the previous paragraph. It may be that the thesis would've finished earlier without having you around to keep me company on my free time, but I definitely would've had much less fun on the way. And this is one thing that I'm reminded of on daily basis by my two sweet girls; Emma and Lulu, you make each day a bit brighter.

Amsterdam, 3rd of November,

Ilkka Keppo

Table of contents

Original publications and author’s contribution

I. Savola, T. and I. Keppo. Off-design simulation and mathematical modeling of small-scale CHP plants at part loads. Applied Thermal Engineering 2005; 25(8-9): 1219-1232.

The author was responsible for building the mathematical model, defining the model parameters based on the simulation data and writing the section. Coauthor participated in the coefficient definition.

II. Keppo, I. and T.Savola. Economic appraisal of small biofuel fired CHP plants. Energy Conversion and Management 2007; 48(4): 1212-1221.

Author was responsible for all the research, the design, performance, analysis and documentation, except for producing the set of simulation results, which we used for deriving the coefficients for the power plants.

III. Rao, S., Keppo, I. and K. Riahi. Importance of technological change and spillovers in long term climate policy. The Energy Journal 2006; 27 Special Issue on Endogenous Technological Change: 123–139.

Author was responsible for the modeling part of the study and participated in the design, analysis and documentation of the results. The main responsibility of the writing and analysis was with the first author.

IV. Keppo, I. and S. Rao. International climate regimes: Effects of delayed participation. Technological Forecasting and Social Change 2007; 74(7): 962-979

Author was responsible for the design, modeling, analysis and writing. Coauthor participated with the writing.

V. Keppo, I., O'Neill, B.C. and K. Riahi. Probabilistic temperature change projections and energy system implications of greenhouse gas emission scenarios. Technological Forecasting and Social Change 2007; 74(7): 936-961

Author was the main responsible for the calculations and analysis and also wrote most of the text. Co-authors participated especially in the design and writing.

1 Introduction

All decisions are based on models…and all models are wrong (Sternman, 2002)

A model can be defined as *a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs (*definition from Webster dictionary) and correspondingly an energy model, in a general sense, can be considered to be a mathematical description of a system where energy transfer, energy conversion, energy utilization, energy markets or energy transmission and distribution play a significant role. Similarly, the purpose of an energy model may be anything, from helping to design a technical component with optimal performance criteria, to a description of the whole global energy system and its development over several decades. This thesis will present a range of energy model developments and applications, which cover objectives ranging from process design related questions on a local scale [Papers I - II] to global long term environmental, technological and economical implications of energy and climate scenarios [Papers III - V].

The wide range of issues studied with energy models means that the exact motivation behind building a specific energy model is entirely dependent on the problem to be studied and can not be easily generalized. One general characteristic, however, is that the modeled problem is usually fairly complex and the energy model built to describe the problem is expected to reveal information that would not necessarily be discovered, if the components of the system were studied in isolation. This information may also include non-trivial dynamics and interactions between the components of the system that were not foreseen before the model was built. These characteristics make energy models useful for, among other issues, studying the environmental, technological and economic effects of chosen energy policies for a chosen region (e.g. Kannan and Strachan, 2009) as well as studying large and complex industrial systems in order to define optimal design and/or operating conditions (e.g. Sardeshpande et al., 2007).

In this thesis, “energy system” is broadly defined as a system of components that can have technical, economic and/or environmental characteristics and which, either directly or indirectly, affect each other. For example, a decision concerning the temperature of the hot district water in a district heating network during certain heat demand and outside temperature conditions directly affects the operation of the district heating network (e.g. the required mass flow of water, the pumping energy needed and the expected heat losses) as well as other components in the system (Paper II of this thesis). Correspondingly, limitations in the usage of greenhouse gas mitigation technologies in one region of a global climate policy regime, may lead the rest of the system to adapt to these changes (see Paper IV of this thesis). Although the exact problems studied in these two examples differ dramatically in nature, scope as well as level and focus of detail, in essence both of these problems can be described as networks of components linked to and interacting with each other.

The objective of thesis is to contribute to the existing body of energy modeling literature with the inclusion of papers describing a wide range of energy model applications, ranging from local, more technical small-scale applications to long term, global models that can be used for analyzing far reaching issues, such as climate change. Together these articles, in conjunction with the summary of this thesis, present a look on how energy modeling can be used for receiving insights on problems of quite different nature and scale as well as showing some of the implications a different scope of the problem has on the focus and the endogenously modeled subsystems of the problem formulation.

In general terms, the focus of this thesis is thus on the modeling and analysis of energy systems and their economic, environmental and technological components. Although simulation approaches are also used (Papers I - II) the main focus of this thesis is on approaches that use an optimization approach for defining the operation and/or development of the modeled energy system.

This summary continues by presenting a range of methodologies used for energy modeling. Emphasis is slightly more on the mathematical programming methodologies, since they are perhaps the most common methods used in energy system modeling, both in general and also in the papers that make this thesis. The chapter on methodologies is followed by a chapter on energy model applications, where models built using the methodologies presented in the previous section are discussed. This chapter is structured based on how the system boundaries of the energy model are defined, starting with process specific models and ending with national and global applications. At the end some concluding remarks are made and the papers that together make this thesis are summarized.

2 Modeling of energy systems, methodologies

In this section of the summary some of the main methodologies commonly used in energy modeling are briefly discussed. The purpose of this section is to give a general overview of these methodologies, but since this thesis does not focus on the methodologies themselves, the overview presented here is kept fairly brief. Furthermore, since the number of publications in the field of energy modeling is growing nowadays extremely rapidly, the references used here do not cover the full scientific publication history. Instead, the aim is to provide references for both some early efforts as well as more recent studies.

Excluded from the following summary on methodologies are, among others, some thermodynamic approaches, like thermoeconomics and pinch analysis (Linnhoff et al., 1982), which can also be described as modeling approaches, if a more general definition is used. Furthermore, methodologies more typical for systematic decision making frameworks used for multi criteria decision analysis (see e.g. Heinrich et al., 2007, Nussbaumer 2009), are excluded.

In the following sections, the presented methodologies are divided into three subgroups; mathematical programming, dynamic programming and other modeling and simulation approaches[1]. Since mathematical programming approaches tend to be more wide spread among energy models, a stronger emphasis is placed there.

2.1 Mathematical programming

The purpose of using mathematical programming techniques is to determine the minimum or maximum of the defined objective function (e.g. total fuel consumption, discounted capital and operational costs over a time period or utility of a consumer), subject to a set of constraint which may represent e.g. the available resources, existing electricity transmission capacity or environmental regulations. Equation 1 presents a general form of an optimization problem

$$\begin{aligned} & \min\ f(x) \\ \text{s.t.}\quad & h_i(x) = 0 \\ & g_j(x) \leq 0 \\ & x \in X \subseteq \Re^n \end{aligned} \tag{1}$$

In equation (1) x is a vector of variables, $f(x)$ the objective function to be optimized, in this case minimized, and $h_i(x)$ and $g_j(x)$ the constraints.

Mathematical optimization problems can further be divided into subsets based on some of their characteristics. Difference in these characteristics leads to different solution algorithms required and some combinations of these characteristics can quickly lead to problems for which the global optimum is difficult to solve. Although other divisions can be suggested, from the perspective of energy system optimization, the most relevant divisions can be argued to be the division to linear and nonlinear problems on the one hand and problems with only continuous variables or also pure integer variables on the

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[1] The difference between an optimization and simulation model can be somewhat fluid. In this thesis, for example, an agent based modeling approach is considered to rather be a simulation than an optimization model. However, the decision making in an agent based on model is often based on the agent optimizing its utility, therefore indicating optimization as a decision making method. On the macro level, on the other hand, no optimization takes place and the larger patterns emerge from the individual decisions made by the agents. It can also be argued that a large long term linear optimization model of the global energy system is merely trying to capture the dynamics of the system, simulate it, instead of trying to suggest an optimal way to construct it. Also in this case, the optimization is used mainly as the decision making criteria for the simulation. See also Jakeman and Letcher, 2003 for a more general discussion on integrated assessment models.

other hand. Figure 1 shows the optimization problem types that are derived with this division as well as the commonly used abbreviations for these problem types.

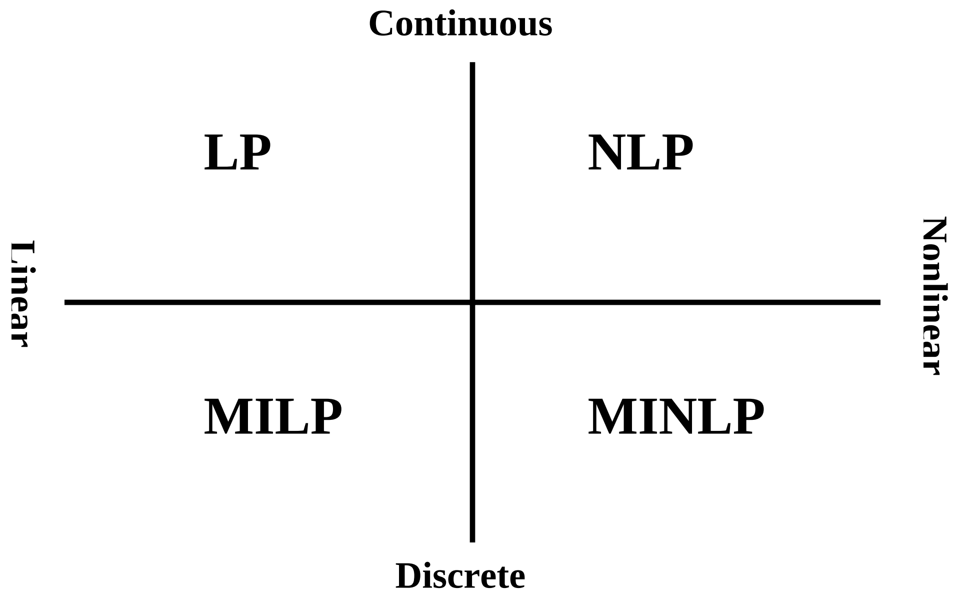

Figure 1. A common division of optimization problem types. The horizontal axis differentiates the problem types based on whether all the equations of the problem formulation are linear or not, whereas the vertical axis divides problems to those with only continuous variables and to those that include also discrete integer variables.

In a special case when all functions f, g and h in equation (1) are linear and all the variables x are continuous, the problem is a linear programming problem (LP), if some of the variables take only integer values while the functions remain linear, the problem is a mixed integer linear programming (MILP) problem. If any of the equations is nonlinear, the problem is either nonlinear programming problem (NLP) or a mixed-integer nonlinear programming problem (MINLP), again depending on whether some of the variables take integer values alone.

The four presented problem types all imply different computational needs for solving the given problem; problems that can be formulated as LP or MILP can usually be solved to the global optimum, although large problems, especially with a large number of integer variables, can also prove to be challenging. The solutions to nonlinear problems, on the other hand, are highly dependable on the starting point, unless the problem can be formulated using convex function only, in which case a global optimum can be expected instead of a local one. Several different algorithms exist for different problem types, each with their strengths and weaknesses, and the exact nature of the given problem usually defines the preferred algorithm to be used (see e.g. Biegler and Grossmann, 2004).

In the area of energy systems modeling, all of the above mentioned problem types are applied, but typically the focus of the modeling exercise defines the exact methodology required. From the perspective of computational requirements, problems formulated as LP problems usually are the easiest to solve to the global optimum. Partially due to this, many data intensive, large models are formulated as LP models, if the described systems allow this. For example, large, global or regional energy system models that include a detailed bottom-up description of energy extraction, production, transmission, trade and consumption are often formulated as LP models (see e.g. Agnew et al., 1978, Rath-Nagel and Stocks, 1982, Henning, 1997, Azar et al., 2003, and Papers III – V of this thesis). MILP-formulation is also often applied for models of this type, among other uses, for allowing the use of specific unit sizes for the energy system components or for linearizing a nonlinear relationship, for example a learning curve(Messner, 1997, Barreto and Kypreos, 2002 Seebregts et al., 2000, Paper III of this thesis. See also Barreto and Kemp, 2008). Examples of other problem types often formulated using MILP are unit commitment (Oliveira et al., 1993) and structural design problems (Söderman and Pettersson, 2006). MILP formulation is computationally considerably heavier than the LP formulation and therefore the number of integer variables is usually kept fairly low, especially when the model is large.

Since linear optimization models are often fairly easy to solve, they can also be altered for experimenting with deterministic nature of the set-up as well as with the number of objectives. For example, formulations including stochastic parameters (Messner et al., 1996, Kanudia and Loulou, 1998, Mattson, 2002. See also Kann andWeyant, 2000), limited foresight with iterative, sequential decision making (Nyqvist, 2005, Martinsen et al., 2006, EIA, 2003, Keppo and Strubegger, 2009) and multi objective (Grauer et al., 1985, Psarras et al., 1990) variations of the linear optimization formulation have been explored. Since for real life decision making there is no certainty concerning, for example, future technologic, economic or demographic trends and usually irreversible decisions are made only for the immediate future, such model formulations may represent the problems faced by a decision maker better than the traditional, deterministic ones do. Additionally, some types of questions can be adequately addressed only with models that do include uncertainty in some endogenous way (for example, if information is assumed to become available only later during the modeled time frame and initial decisions need to be taken with limited and uncertain data).

All of the examples in previous paragraph rely on linear programming for methodology and integrate the desired elements within this framework. For example, in the formulation of stochastic MESSAGE (Messner et al., 1996), objective function parameters for the decision variables are given as probability density functions (PDF). These PDFs are then sampled and if the objective function value calculated with a given sample exceeds the objective function value calculated using expected parameter values, it is added to the objective function (after being multiplied by a parameter value, which is defined by the sample size and the “risk aversion” chosen by the modeler). A formulation like this is often not trivial to implement and execute, especially for larger problems, but the problem type is linear and therefore relatively easy to solve.

Unfortunately, the more detailed and technical description of the energy system and its components is required, the more likely it is that it can no longer be described using linear functions alone. In this case, a nonlinear formulation has to be used. Although large, detailed models with a very large number of variables are rarely formulated using NLP, smaller models, perhaps concentrating on a smaller number of variables, but requiring a more detailed description for these variables, may use these formulations (e.g. Paper II of this thesis, Mariano et al., 2008). The main drawback of non-linear formulation is that it is often difficult to guarantee that the result retrieved is globally optimal, instead of being merely a local optimum.

If the problem is nonlinear and includes also integer variables, the demands for the solution algorithm and problem size are generally the most restrictive. In some cases, however, the problem in question does require such an approach and can also be formulated in a way that a global optimum, or a result close to that optimum, can be reached (see e.g. Tveit et al., 2009, Bruglieri and Liberti, 2008 and Savola et al., 2007 for some recent applications).

2.2 Dynamic programming

Dynamic programming approach differs from linear optimization, among other things, in that it is not as strictly a methodology, defined precisely in terms of specific solution algorithms, but more a decision making framework. In dynamic programming the problem under assessment is decomposed into stages, or subproblems, that are linked to each other in such a way that the solution of one stage is used as an input for the following stage and the problem becomes a sequential decision making problem. The focal rule for decision making in dynamic programming is the principal of optimality, formulated by Richard Bellman (Bellman, 1957) in the following way:

An optimal policy has the property that whatever the initial state and the initial decisions are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision.

In other words, principal of optimality requires that when the problem is divided into several stages, the optimal decision trajectory from any given stage (0 to *n*) until the end of the decision horizon is for these stages identical to the optimal trajectory calculated from the initial starting point (*n*=0). Optimization is done recursively, either by progressing from the initial state towards the end, or more commonly, starting from the final period and progressing towards the initial point. Formally, one loop in the recursive algorithm can be described using the Bellman equation:

$$V\left(x_t\right)=\max_{u_t}\left\{h_t\left(x_t,u_t\right)+\beta V_{t+1}\left(x_{t+1}\left(x_t,u_t\right)\right)\right\} \tag{2}$$

Here *V* is the value function, *h* the payback, *ß* discount factor, *x* a state variable and *u* a decision variable. The initial state x_t is given and the decision variable u_t is chosen in such a way that it maximizes the sum of payback for stage *t* and the discounted value of the value function for the next period.

The use of dynamic programming is common especially within the field of economics (see e.g. Le Van and Dana, 2003) and in the context of energy system models its use has usually been slightly more restricted in scope, mainly concentrating on defining optimal strategies for fairly specific and detailed economic question (i.e. it's much more useful when the number of decision variables, and therefore the number of possible states for each stage, is relatively limited). Since the Bellman equation can easily be extended to include stochastic elements, dynamic optimization can be used for evaluating mostly irreversible decisions, such as investments, made under uncertainty (Dixit and Pindyck, 1994). For example, uncertain future fuel and electricity prices, as well as greenhouse gas emission costs, effect investment and operational decisions strongly and dynamic optimization based real option evaluation methods have been used to endogenize this uncertainty in the analysis (for recent applications see e.g. Hlouskova et al., 2005, Madlener et al., 2005, Fleten et al., 2007, Wickart and Madlener, 2007 and Botterud and Korpås, 2007). In the Nordic context, the use of stochastic dynamic optimization for optimal hydro power operation (e.g. Kristiansen, 2004) is especially widespread and relevant, due to the important role hydro power plays in Nordic system.

2.3 Other modeling methods and simulation approaches

In addition to traditional optimization methodologies briefly presented in the previous chapters, energy models have been built on methods that have a stronger element of simulation, in addition to the optimizing behavior. Although the line between simulation and optimization is anything but clear, a common characteristic of many of the simulation approaches mentioned here is an iterative approach that is central to the solving algorithm and, with some algorithms, the goal may not be to find an optimal solution at all, but to describe, or simulate, the dynamics of the system under study.

As their name suggest, evolutionary algorithms (Wehrens and Buydens, 1998, Whitley 2001) describe populations of solutions, the fitness of individual solutions within the population as well as how the population of solutions develops over generations. The main principle of such algorithms is that the reproduction process that produces the next generation is biased towards better, or fitter, solutions and therefore the next population will hopefully provide better solutions than the previous one. Different evolutionary algorithms emphasize different aspects of evolutionary mechanisms, but they all usually include the main three processes of selection, mutation and crossover. For example, genetic algorithms emphasize crossover, whereas the original form of evolution strategies used mutation as the search operator (Whitley, 2001). Evolutionary algorithms have been used widely also in the field of energy. For an overview and a list of references, see Miranda et al., 1998.

Agent based approaches, intended especially to describe emergence and heterogeneity, move one step away from optimization methods and into the direction of simulation approaches. The principle motivation behind the agent based approaches is that the developments that are observed mainly on the macro level follow from interactions and processes between heterogeneous, autonomous agents interacting on the micro level. Agent based models therefore do not model the macro systems directly, but rather the agents and their interactions with each other and the environment and the emerging macro system is then a result of such interactions. These macro systems can be highly complex and often they are best described as systems in motion, i.e. the object of study may often be the process itself rather than final state of equilibrium (see e.g. Arthur, 1999). In principle, there are few restrictions concerning the topics to be studied or the definitions of the agents and their decision rules (i.e. how the agents define their actions based on their observed environment, inclusive of the other agents), but the main strength of agent-based approaches is in their ability to model emergent phenomena that may not be explainable if modeled on the aggregated macro level (Bonabeau, 2002). Examples of applications include, for example, models describing markets (see Bower et al., 2001, Veit et al., 2004 and Weidlich et al., 2005 for electricity market applications) and diffusion of innovations (e.g. Berger, 2001, Ma and Nakamori, 2005. Also Ma et al., 2008). See also Bonaneau, 2002, who gives examples of applications for the four main general areas of applications identified in that paper; flows, markets, organizations and diffusion. A very large problem formulation, such as a description of the data intensive, global energy system, may be difficult to describe with an agent based formulation. The number of relevant agents in such a formulation would be very high and the environment to be considered would expand greatly, thus increasing the difficulty of describing the individual agent's decision making criteria and the specific parameter values related to agents' decision rules.

Also the methodologies used by many more economically minded models, the so called input-output models (I/O models, see e.g. Moffatt and Handley, 2001. Also Rose, 1995) and computable general equilibrium models (CGE models, e.g. Dimitropoulos 2007, Bergman 1988) fall in between the pure simulation and optimization categories. These models usually have a number of variables equaling the number of equations and all the equations are solved simultaneously. Such models may be static or dynamic, deterministic or stochastic. In addition to the number of equations describing the behaviour of producers and consumers, a very large database, usually based on econometric data and statistics is used as the key input. Such models are especially useful when a lot of focus is put on the economic information to be retrieved from the model, and correspondingly less focus is on the very exact technological detail (e.g. when it is especially important to know what might be the impact of an emission tax on the national GDP, but less important to know what exact technologies are implemented as a consequence of this tax).

Other approaches include, for example, neural networks (see Kalogirou, 2000 for some energy related applications and Knutti et al., 2003 for a climate change projections) and methods used in process simulation (for examples, see Tveit, 2006, Savola, 2007 and Heyne and Harvey, 2009. For a software comparison see Giglmayer et al., 2001).

3 Modeling of energy systems, applications

The discussion presented in the previous section concentrated on some of the tools available for building mathematical models for energy system analysis. In this section the focus is shifted to the application side of such models, with a specific focus on the system boundaries of the energy system described.

A model of an energy system includes within its definition also its limitations; a model describing heat flows of an industrial process, with the focus on optimizing the parameters of the process from an economic or thermodynamic perspective, is likely to take the price of fuel needed for the process as an exogenous parameter, instead of an endogenously modeled variable, depending on other modeled components of the system. Similarly, a global energy model describing a possible development of the energy system for the next century, will not include in its description the heat exchangers of a single plant explicitly, but will make some rough, aggregate assumptions. Both of these models describe an energy system, with several components interacting with each other. In many cases, even similar methods can be used for modeling such systems. However, the system boundaries for these said systems do differ significantly, usually for temporal and spatial scope, but also for the level of detail available. These boundaries, whether represented by exogenous assumptions or aggregation of variables into a “black box” of some kind, both imply limitations for the conclusions that can be drawn from the model. Additionally, such boundaries may also already prioritize methodologies more or less suitable for the given problem. Figure 2 below presents a schematic of the changing system borders across energy model applications.

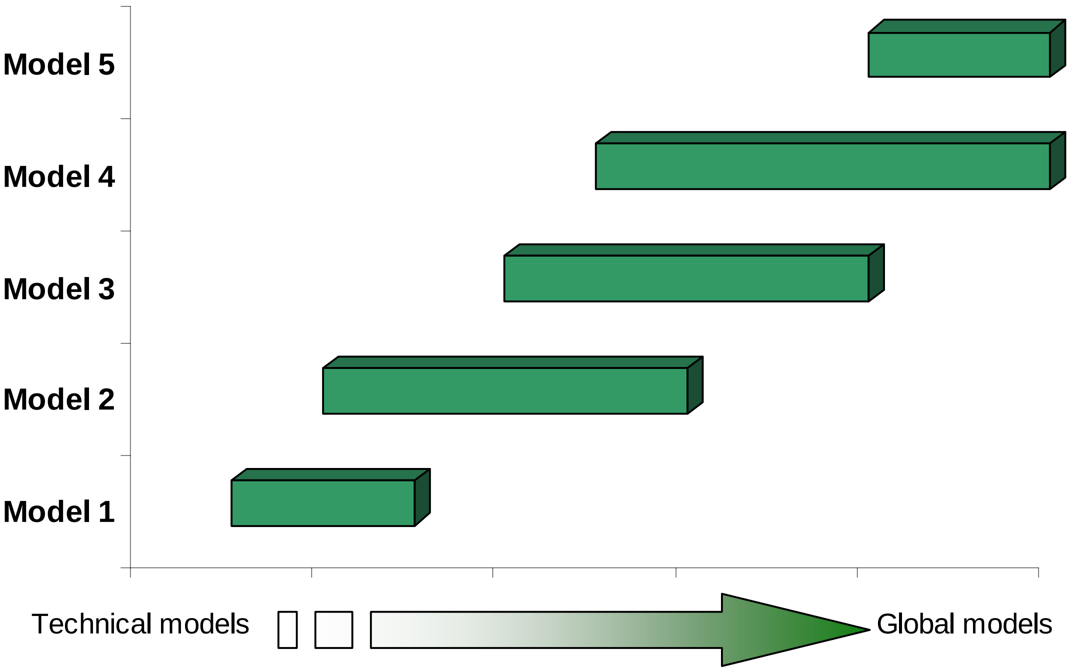

Figure 2. Defining system borders for the explicitly modeled system. The horizontal axis represents the increasing scope of the modeled system, with the models located close to the vertical axis concentrating on detailed, small systems, whereas the models far away from the axis focus on larger, aggregated processes and leave out the micro level detail.

Figure 2 shows five models, with five different boundaries for the modeled system. The green bar illustrates the range within which the model describes the relevant processes in a detailed manner. White areas left of the bars represent the technological, micro level, detail that has been aggregated or used as a black box. White areas on the right side of the bars represent the processes that are still beyond the endogenously modeled system, such as energy prices for a small local model, or migration trends for a global energy model. The model in the first paper in this thesis could be approximately compared to Model 1 in figure 2, system shown in paper two could be Model 2 and the models in the rest of the papers could perhaps be best described by Model 4.

In the following sections a brief summary across the range of energy models is presented, using the scope of the model and the implied systems boundaries as the dividing factor. Again, due to the wide range of modeling studies documented, this summary is not meant to be exhaustive, but to offer a concise outline on some recent, as well as earlier, applications, especially focusing on a couple of problem types particularly typical for the Nordic countries.

The first section presents approaches that have been suggested for analyzing systems consisting of a single technology or problem specific question, such as optimal design of a technical component (e.g. a boiler) within a larger multi-component process. The next section expands the boundaries of the problem to a process level, where several components interact with each other and the emphasis of the problem is moved slightly from design to operation, when flows within the components of the modeled system become endogenous variables. The final section focuses on models that include a large number of processes and sectors in an aggregated form and may even expand the linkages between the aggregated model components of the energy system to non-energy mechanisms (e.g. climate, national or global economy, technology price dynamics).

The division into these three groups should be understood only indicative, since the borders between the groups are far from exact. For example, whether a CHP power plant should be considered a single component of a process or the whole process itself, with many individual components, is more or less arbitrary. Similarly, a large industrial process could be considered to be a single process or a component in a model describing the national energy system. Where exactly the line is drawn is far from clear; as long as the system under study can be disaggregated into several sub components, affecting each other's design and operation, an argument could be made for alternative definition. The general guideline used here is the rough division into models of three scopes of spatial and/or temporal scale in such a way that the full range of applications can be represented reasonably well.

3.1 Energy models for technical components

In this section we focus on a couple of energy model types that have the main purpose of describing a single component of a system rather than the full, multi-component system itself. These models do assume an environment around them and use exogenously defined parameter values and assumptions based on these assumed surroundings. A single component could, of course, also be an explicitly modeled part of a larger model, in which case it is a full process that is being modeled by the macro model, and the submodel for the individual component is merely a part of this larger model. From that perspective, this sections aims at concentrating on models that *might* make up a simplified, or an aggregated "black box", component in a slightly larger model, but does not exclude the possibility that the models described here might also be parts of a larger model.

In essence, for any design or operational problem involving energy flows and conversions, a mathematical or numerical model of some kind can be built to describe it. Due to the extent of energy related technical components that could be modeled in one way or another, the brief sample provided here is by no means exhaustive, not from the side of possible methodologies that can be used, nor from the range of topics investigated.

The optimal design and operation of heat exchangers, and especially heat exchanger networks, is a fairly widely studied and documented field of problems. Designing a heat exchanger in isolation does not yet require a very complicated model; as long as the required thermodynamic information is available, one can design a heat exchanger that fulfills the necessary requirements (see e.g. Chuanshan, 1997 for an analysis of a system based on geothermal heat). However, once costs become a deciding factor, the number of flows to be cooled and heated increases or several heat exchangers can be used, the required model extends and can no longer be considered in terms of thermodynamic relationships alone. Problems of this type emerge especially often within the process industry, where number of flows need to be heated and cooled and therefore process integration solutions offer a useful way for trying to utilize the available energy efficiently.

While the earliest approaches for heat exchanger network synthesis mainly relied on methods, such as pinch analysis (e.g. Linnhoff et al., 1982), later approaches used have usually been based on mathematical programming, some linear with integer variables (e.g. Papoulias and Grossmann, 1983 for defining the minimum number of units), some nonlinear (e.g Floudas et al. 1986 for minimum investment costs). However, if the problem is to be solved simultaneously, instead of sequentially, mixed integer non-linear programming is often used (Ciric and Floudas, 1991, Aaltola, 2003).

A CHP plant, and especially the steam or gas turbine integrated in such a plant, is another often simulated piece of equipment[2]. Use of commercial process simulation software to estimate the process and its sensitivity to changes to parameter values is common (see e.g. Ong'iro et al., 1996 and Paper I of this thesis. A comparison of such process simulation software is presented in Giglmayr et al., 2001). An extension of using a simulation model alone is to use the results obtained from such a model for building an optimization model of the simulated system (Tveit, 2005, also Paper II of this thesis). Naturally, approaches based on pure optimization (e.g. Kralj and Glavic, 2007, Lahdelma and Hakonen, 2003, Rong et al., 2005, Rong and Lahdelma, 2005, the last reference also including stochastic simulations) and also evolutionary algorithms (Burer et al., 2003) exist. A model of a CHP plant is especially useful for analyzing how changes in the design or operation might affect the performance and economics of the facility.

Examples of other component related models include, among many others, simple statistical models for estimating economic lifetime of the components (see, for example, Keppo et al., 2001 for heat exchanges in a district heating substation), models for solar systems (see e.g. Ashhab 2008, Lagorse et al., 2008 for photovoltaic (PV) systems and Nafey 2005 for an overview for methods created for solar heat configurations), for networks of insulated pipes (Lorente et al., 2002) and methods for optimizing the design of wind turbines (e.g. Fuglsang and Madsen, 1999 and Wang et al., 2008).

3.2 Energy models for process systems

In this chapter the focus is turned on to models that include a number of mathematically described components, or groups of components, linked to each other through their inputs and outputs. Although the line is blurred, the main conceptual difference to the models

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[2] As previously mentioned, a model of a CHP plant could already be considered to belong to the category of models describing processes with several components. However, due to the fact that the modeling of the turbine plays such a key role, it is here included in this section

presented in the previous chapter is the switch from design centered problem formulation to a model where flows, interactions and feedbacks between the individual components, and therefore operational issues, start to weigh more heavily. Since these models do concentrate on a fairly strictly defined set of problems, such as design and operation of a local district heating network or (combination of) industrial processes, a number of important variables and parameters still need to be taken as exogenous (e.g. fuel options and prices, regional, national and global energy infrastructures etc). Since no model is able to describe all processes having an impact in the energy sector endogenously, the border between models described here and in the next section, where even more processes are included within the endogenous description of the model, is again blurry. The arbitrary line drawn is that the models described here are spatially limited, local, at most regional, and always subnational, which in itself already defines the extent of parameters and variables that can be considered endogenously.

Another common difference to the models described in the previous section is that the level of detail with which the components of the energy system are described is reduced. This is, in part, done to reduce the size of the full model, which would multiply, if all the components would be included as detailed as possible. Furthermore, such level of detail is often no longer considered necessary, as the focus is now less on individual design options and more on the general operation and dynamics of the full system. In the following short section a couple set of problem specific applications will be presented, namely models for local energy systems, especially those related to district heating, as well as some models incorporating also descriptions of industrial processes. These, by no means, cover the whole range of possible energy problems that can arise on a local level, but perhaps offer a problem description especially typical in the Nordic area.

In the previous section a brief look on some models created for CHP plants was provided. Many of these models assume also a heat load of some kind, implying therefore a district heating network, industrial process or some other processes connected to them. Explicitly including the description of the nature, costs and operation of this heat load into the model extends the borders of the modeled system; now the heat load is no longer merely an exogenous demand to be fulfilled, but deciding e.g. optimal temperature levels for the heating system feeds back to the operation, and therefore design, of the heat producing plant. Some models include also other components, such as heat storages (e.g. Rolfsman, 2004a) or demand side measures (Rolfsman, 2004b), which impact the optimal design and operation of the district heating system. What is included within the modeled system depends on what exactly is the presented research question and what is considered to be the range of endogenous decision variables available for the decision maker. For example, increase in wall insulation, the option included within the modeled system in Rolfsman, 2004b, may be economically a lucrative option on the system level, but in many cases such an option may not be feasible, nor necessarily economic, for the owner of the CHP plant. In such cases, the optimization problem might be rather formulated from the perspective of the plant owner, leaving out of the formulation any measures that can only be taken by other decision makers (i.e. "agents").

As a general division, one can divide district heating related energy systems roughly to two categories; those emphasizing the operational aspects and to those concentrating on the design of the system. The former tend to need a more precise description of the network and therefore may need to use a non-linear formulation. The latter rely on a simpler network characterization and therefore can usually express the relationships using linear equations only[3].

MODEST (Henning, 1997) is a well documented linear programming model used for a range of district heating related studies, including topics such as district heating pricing evaluations (Sjödin and Henning 2004), impacts of fuel prices (Sundberg and Henning, 2002), effects of merged district heating networks (Gebremedhin and Carlson, 2002) as well as waste incineration and external costs (Holmgren and Amiri, 2007) These studies typically take the network into account on a fairly aggregated level, which allows the model to be formulated using linear equations only. If, however, the parameters of the network, such as pressure and temperature levels, are also to be taken as decision variables, non-linear models are usually required (Zhao et al., 1998, Benonysson et al., 1995), sometimes also genetic algorithms may be used (Curti et al., 2000a, 2000b). Models that describe the network in detail are especially useful for problems related to

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[3] All other things being equal, a linear model would always be preferable over a non-linear one, due to the fact that the global optimum is more easily reached with a linear formulation.

operational issues, such as defining the appropriate levels for the network variables or the use of heat storages. Usually, however, such models do not put very much focus on the design and dimensioning of the system. Paper II of this thesis falls somewhat between these two categories; the described model is non-linear and includes several network related parameters as decision variables. However, the operation of the network is still simplified compared to the two references above, whereas the design aspect is respectively stronger in Paper II.

The intersection of the industry and district heating systems has been studied, among other models, also with the linear optimization model MODEST. This is a fairly natural expansion of the district heating focused approach presented in the previous references; a number of heat flows is usually present at an industrial site and optimizing two systems simultaneously will always present a better solution than doing this separately. Although any relevant industrial systems could be used, since district heating is especially common form of heating in the Nordic countries, where also forest industry is strong, it's unsurprising that paper mills are often chosen as the focus of the study (Sundberg and Sjödin, 2003, Gebremedhin, 2003 for MODEST and Svensson et al., 2008, Jönsson et al., 2008, Tveit et al., 2006 for other approaches).

3.3 Energy models for multi-process systems

The boundaries of the energy models presented in the previous sections always implied that a number of variables, parameters and indicators were defined somewhere outside the modeled environment, and were therefore taken as exogenous, predefined values, not affected by the processes modeled. Examples of such parameters are, for example, national and international fuel prices and the availability of the fuels, electricity prices and price dependent demand of energy commodities. In reality, most of these indicators are defined when several of these local energy systems interact, when the production, supply and transmission of the energy commodities is balanced, quantity and direction of these flows is defined, macro level environmental constraints are accounted for and also the macroeconomic and technological impacts of the energy system development reveal themselves.

The models presented in this section include a number of these processes endogenously, trying to establish how the individual processes on the micro level combine to a larger system and how these pieces of the larger system interact and create the whole that emerges from these interactions. These models describe systems that include a large number of processes in an aggregated form, therefore, in principle, combining a number of the smaller models described in previous sections. These models also cross the borders between sectors as well as the spatial borders, describing the energy system, for example, on the national or global level. Due to the wide sectorial and spatial coverage of these models, they often include a large set of energy demands that need to be fulfilled, offer a wide range of technological options that can be used to convert and transfer the required energy[4] and also model the energy market mechanisms, at least on some level.

National models or models describing regions larger than a single country, but smaller than the whole globe, represent a fairly large and important set of modeling tools. Such models are often used to give insights for energy planning and policy making to the specific regions they describe. They attempt to depict the energy system in full, taking into account the limitations imposed by the spatial scale in terms of a) the too small scale for being able to represent all trade flows, global environmental impacts or technological diffusion and learning as well as the b) too large a scale to be able to represent all the technical details of individual processes in an accurate and specific manner. These tools are, however, very useful in the sense that they often describe regions that are political actors and therefore the models can be used for studying issues especially interesting for the policy makers, as well as for addressing impacts of potential policy decisions considered by these actors. Methodologies used for the models usually depend on the characteristics required of the model and results retrieved using it. For example, a model focusing on the power market might be based on agent based or game theoretical modeling, in order to allow the inclusion of competing agents (i.e. there is no single objective function to be maximized or minimized, but a number of agents trying to maximize their own utilities), whereas a model requiring an especially detailed

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[4] This applies to bottom-up models, such as the MESSAGE model, used in papers III – V of this thesis. Top down models, such as e.g. DEMETER (Gerlagh and van der Zwaan, 2003), do not describe the technologies in much detail, but concentrate on the economics instead.

technological description of all the components of the energy system may be rather based on linear optimization.

Most developed countries in the world are nowadays likely to use an energy model of some kind to help their decision making. Most countries probably have several models describing them, developed by different research or policy groups with different kind of problem focus in mind. Since these local models are often used to address fairly specific problems, they are more often using the detailed bottom up approach than the global models, for which purely macroeconomic or climate change related topics may be at least equally important. Examples include IKARUS (Martinsen et al., 2006), a limited foresight, bottom-up linear optimization model for Germany, used previously e.g. to study the impact of high energy prices on the energy system and emissions (Martinsen et al., 2007) as well as the economic feasibility of biomass use for transportation in Germany (Martinsen et al., Forthcoming), NEMS (EIA, 2007), a non-linear general equilibrium model used for simulating the development of the US energy system, year by year, MAPLE-C (Natural Resources Canada, 2006), a model based on NEMS, but modified to represent the Canadian system instead of the American, PRIMES (ICCS/NTUA, 2005), an EU-wide model having non-linear optimization for supply modules, a price dependent demand and an equilibrium model combining supply and demand modules, used for the market clearing (formulated as a global non-linear mixed complementarity problem). Energy related models for the Finnish context, focusing on different aspects of the energy system, include linear optimization energy system model TIMES-Finland (Koljonen and Savolainen, 2005, Kara et al., 2008), used often for the analysis of greenhouse gas mitigation related topics (impact on energy prices, other energy system characteristics), dynamic optimization based power market model for Nordic market area (Tamminen and Kekkonen, 2001a and 2001b) and macroeconomic model incorporating also the whole national economy (Honkatukia, 2009) in its modeled system. Also game theoretical models and other models incorporating a number of agents are common for energy markets, for example for electricity (Lise et al., 2008, for Europe, Bower et al., 2001 for Germany. See also Haldrup and Nielsen, 2006 for an econometric and Halseth, 1998 for game theoretical model of the Nordpool market) and gas (Krey and Minullin, 2006, Lise and Hobbs, 2008. See also Sagen and Tsygankova, 2008 for a non-linear programming based approach for evaluating Russian gas exports to Europe). In addition to the obvious questions of market price development, one key question often studied with such models is the modeled agents' use of market power (Halseth, 1998, Bower et al., 2001, Lise et al. 2008).

Extending the spatial scale of the modeling one final step, the set of energy models describing the global energy system is reached. These models can have different focuses in terms of the questions they are used for, and therefore they implement a widely different level of detail for technologies represented explicitly, sectors included, environmental and economic indicators as well as methodologies used. Some of these models are meant strictly for answering questions related to the energy sector (e.g. Yamaji, 1998, Edmonds and Reilly, 1983), whereas others are better described as integrated assessment models (IAM), usually including some kind of representation of emissions from sectors such as agriculture and forestry (either by hard- or soft linking the modules, see e.g. van Vuuren et al., 2003 and Riahi et al., 2007)). They may also implement a climate module of some kind and fairly often also macroeconomic module is coupled with a technologically more detailed bottom-up model (Messner and Schrattenholzer, 2000, Akimoto et al., 2004, Turton, 2008).

The benefit of global models over the regional ones is that they are able to represent all interregional energy related flows and parameters endogenously. This makes it possible to have an endogenous description of international markets for energy carriers, such as crude oil, as well as study global issues, such as climate change, which can not be addressed with regional or local models. For example, question like where, and when, is it most economical to reduce emissions, what technologies might be important globally and would technology transfer and related technological learning help, how important is it that the effort is truly global or what level of long term emissions could be considered acceptable can not be addressed without having a global description included[5] (see e.g. Riahi et al., 2007 and Papers III – V of this thesis). The downside of global models usually is that since they describe the whole globe, single regions are not modeled as

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[5] However, many of these questions require certain characteristics from the model. For example, unless the model includes some kind of damage functions or other similar considerations, very little can be said of the desirability of any given climate targets themselves, only e.g. how exogenously given targets may be reached economically.)

detailed as they would be, if the focus of the model would be on these regions alone. Furthermore, in order for a model to be able to address many topics related to global issues, especially climate change, a fairly long time frame needs to be used. This means that the current energy system and the inertia within the system is less important for the results and the long term assumptions made for the drivers become more important, therefore more clearly making the model a scenario tool instead of projection or near term policy assessment instrument.

Box 1. The MESSAGE model

The MESSAGE model, the modeling tool used in papers III to V of this thesis, is a fairly typical example of technology rich, bottom-up models that are often used for evaluating long term energy and emission scenarios. The model is driven by exogenously defined projections of energy service demands, which in turn are based on projections for population growth, economic growth, pace and nature of technological development and other scenario specific assumptions. The structure of the energy system fulfilling these demands relies on defining energy forms available at different energy levels (resources, primary energy, secondary energy, final energy and useful energy), conversion and transmission technologies that convert energy forms from one form to another, or from one energy level to another (for example, electricity transmission that transfers electricity from a centralized power plant to the final consumer), as well as the estimates for resource availability. The decision variables, i.e. activity of technologies and investments in new capacity, can also be bounded (as can the flows of commodities, e.g. electricity, emissions etc), either giving them absolute bounds, dynamic bounds (linking the activity of the period to that of the previous) or freely defined limitations (e.g. limit the share of wind power production to a given share of total electricity generation, constrain the share of imports on the primary energy level. Also cumulative bounds on, for example, resource consumption or emissions can be included. Basically, a constraint can be built for linking any chosen variables included in the model). The minimized objective function is discounted, cumulative costs across the modeled time horizon. A full mathematical description, including all the used equations, can be found in Messner and Strubegger, 1995.

The mathematical formulation described above is fairly similar in most bottom-up energy system models based on linear optimization. Therefore the main difference between models is the data, both in terms of *what* is included (e.g. how many regions are modeled, how is international trade included, what greenhouse gases are endogenous to the modeled processes etc) as well as *how* exactly the processes are included (e.g. are growth, and other, constraints used extensively or is the model relatively unbounded, what are the energy demands driving the model, how are the demands quantified and what are the assumptions concerning the demand drivers, what is the data used for the technologies, resources etc). Additionally, the values assumed for indicators such as region specific population and economic growth, impact of drivers on energy demand growth and speed of technological development usually depend on qualitative scenario description, explaining the type of world that is assumed to be behind the numbers (see Nakićenović and Swart, 2000 for the qualitative definitions of the IPCC scenarios that have also been used in Papers III – V. See also a summary of recent quantifications of these scenarios presented in Riahi et al., 2007, which have been used also as the basis of the studies presented in Papers IV and V).

MESSAGE model extends over a timeframe of 100 years and divides the globe geographically into 11 regions. Its description includes emission data for all greenhouse gases, including the non-energy sectors, for which the emissions are modeled as exogenously given paths (mitigation technologies, however, are included for most of these emission sources). As most data intensive models like it, it includes in its description hundreds of technologies, demands, resource types and other variables, therefore requiring a very large number of assumptions for the data. For example, a coal power plant of given type requires data inputs at least on the lifetime, efficiency, costs, availability as well as how all these parameters might differ across the geographical regions and develop across the modeled time horizon. Furthermore, all of these are also dependent on the qualitative scenario description; a scenario assuming low population growth and optimistic cost developments for renewable technologies differs in its choice of parameters from scenarios that expect the population to continue growing rapidly and environmental concerns to be a minor issue in decision making. Finally, MESSAGE is often either soft linked to other models (Messner and Schrattenholzer, 2000, also Riahi et al., 2007, Rokityanskiy et al., 2007), which further increases the total number of assumptions made for the complete multi-model setup (since all the assumptions made for the linked models now also affect the results).

As can be understood from above, results arising from models such as MESSAGE should not be considered as predictions or forecasts; the fact that often the same model is used for producing a range of scenarios, with widely diverging results and assumptions (for MESSAGE, see IIASA, 2006 for an example), already indicates that the uncertainty concerning the future developments is considered to remain very high and none of the individual scenarios alone is considered to forecast the future development of the energy system. In the IPCC terminology, such scenarios are therefore not considered as predictions, but "[They] represent pertinent, plausible, alternative futures" (Nakicenovic and Swart, 2000). In other words, they are plausible quantifications of alternative, qualitatively described worlds, without any one of them being a forecast or a prediction, not even a "most likely" scenario. The power of these models is therefore elsewhere. It lies in providing a systematic, consistent and detailed description of the global energy system, with its interdependencies and dynamics endogenously represented. They offer a framework for studying how the energy system might react to changes in the modeled environment, e.g. changes in environmental regulations, fossil fuel resource estimates or technology costs. Furthermore, this is also where the model can be best judged; do these changes in assumptions lead to changes in results that we, after seeing the results, find plausible? Do the dynamics shown by the model results have a counterpart in real life and if so, are the drivers of these dynamics, qualitatively, the same in reality as in the model? If the answers to these questions are positive, the modeling tool in question can be considered to be a useful tool for providing insights in a holistic, systematic manner that might be difficult to replicate without such a tool.

Examples of global models include the detailed bottom-up linear optimization models, such as MESSAGE (Messner and Strubegger, 1995, Rao and Riahi, 2006. See also Box 1 above.), TIAM (Loulou and Labriet, 2008, Loulou, 2008, Syri et al., 2008) and GMM (Rafaj and Kypreos, 2007). Some of these models may also implement endogenous technological learning, making the costs of technologies dependent on their cumulative implementation, which, due to the linearization of the non-linear learning curve formulation, turns linear models into mixed integer linear optimization models (Messner, 1997, Barreto and Kypreos, 2002, Kram et al., 2000. See also Löschel, 2002, Gillingham et al., 2008, Kahouli-Brahmi, 2008 and Berglund and Söderholm 2006). Soft linked climate models, such as MAGICC (Wigley, 2003), are also often used (e.g. Paper V of this thesis). These additional components extend the range of questions that can be studied with the model even further, bringing the climate system and technological progress within the endogenously modeled components. The other common type of global models is the top-down, macroeconomic models, examples of which include the econometric global model E3MG (Barker et al., 2005), general equilibrium models WIAGEM (Kemfert, 2002), EPPA (Paltsev et al., 2005), GEM-E3 (Pan, 2005) and the hybrid model MIND (Edenhofer et al., 2006). These models can, in general, be used for studying similar topics as the bottom-up models are, but with a different main strength; bottom-up models provide detailed results for technologies whereas top-down models are able to provide more information on the total economy, not only the energy sector. Some global models fall somewhat outside the above top-down, bottom-up division. For example, POLES (Criqui et al., 1999) is a recursive simulation model and PROMETHEUS (Cannon et al., 2005), a stochastic model based on econometric techniques and Monte Carlo simulations. Especially the latter has its very special own niche, as it provides results only in terms of probabilities. See also Nakata, 2004 and Jebaraj and Iniyan, 2006 for some recent reviews of the field of energy modeling.

4 Concluding remarks, contribution of the work and suggestions for future work

This thesis documents the development and use of a number of energy model applications and then uses these models for policy relevant analysis. It furthermore shows how these studies and models fall into the larger framework of energy modeling and how modern energy models are used to answer a number of spatially, temporally and technologically different questions.

The development of a mathematical model for CHP production, based on the simulations of actual existing plants, is presented. This model is then used to evaluate the economic feasibility of such constructions. The novelty of this work lies in the elaborate description of the CHP-plants, especially in terms of operation under part-load conditions, as well as on the way how design and operational issues are balanced in the optimization model. Future work would be especially relevant for evaluating the potential effect incorporation of uncertainty might have for the analysis.

The climate change related research and results presented in this thesis have not been previously derived with such a technologically detailed, global model. The insights retrieved contribute to the ongoing research for climate change related topics, offering new perspectives on policy and uncertainty related angles of the issue. Also here, a more robust incorporation of uncertainty would benefit the results, since a long term modeling framework is especially sensitive to the assumptions made by the modeler.

5 The articles

The first paper of this thesis documents the development of a mathematical model for a set of small CHP plants. The basis of the model is on power plant simulations, made for a set of existing small CHP-plants. A special emphasis was placed on describing the part load operation of these plants accurately. The results indicate that there is a small non-linear reduction term in power output when the power plants are operated under part load conditions. In order to capture this, the simulation results were used to construct a three line regression model of the power plant operation. This model describes the power output of the CHP plant as a function of the heat load and temperature of the district heating water. This regression model was further compared to single and two line regression models, as well as to the original simulation, for both power production and estimated income.

In the second paper of this thesis the regression model developed in paper one is applied, expanded (as are the simulations) slightly by adding also the temperature of the cold district heating water into the formulation and then used as a component in an optimization formulation for a local district heating network. The full optimization model developed also includes a description of the network as well as district heating substations. The data for the network is based on an existing network in western Finland, whereas a Visual Basic based simulation was used to approximate the operation of the substations. Weather data is used for evaluating a heat load curve for the system and a simple approximation is conducted to give electricity prices an outside temperature dependant component. For the application of the model, three small CHP-plants are evaluated against heat only boilers. Although the exact results differ based on the specific assumptions made for each case study, the general conclusion reached is that under the economic conditions applied, small biofuel fired CHP plants may find it difficult to compete against heat only boilers using biofuels.

The third paper uses a global, bottom-up linear optimization model MESSAGE to study energy system and climate related implications of technological change. More precisely, it is studied how implementing learning by doing endogenously changes the results and conclusions drawn and especially what the relevance of this mechanism might be for climate mitigation. Reduction of investment costs through learning by doing means that the investment costs of a technology are reduced as a function of the cumulative investments made in that technology. This formulation is non-linear, due to which a linearized approximation of the formulation is implemented in the model. In order to capture also the macroeconomic impacts, the system engineering model is linked to a macroeconomic module. The results indicate that the learning effects, and especially technology transfer to developing countries, might play an important role in climate mitigation efforts.

In the fourth paper incomplete mitigation regimes are studied using the MESSAGE model. The focus of the analysis is on how delayed entry of some key regions might affect the feasibility and costs of reaching long term climate goals. The results indicate that short term delay in full participation may lead to an overall delay in the climate efforts. However, if the delay is expected to last longer, e.g. until mid-century, the participating regions are forced to increase their efforts already in the short term. Overall mitigation costs are increased, but this increase may also be fairly modest, depending on the importance of the non-participating region, as well as on the length of the delay in joining. Finally, it is also discovered that the cumulated inertia in the energy system can delay the regional energy system transition of the non-participation even decades beyond the moment of joining the regime.

The fifth paper takes a set of emission scenarios and analyses their results in a probabilistic framework. Probability distributions for climate sensitivity are used to derive probabilistic temperature increases for a set of mitigation scenarios. These temperature increase distributions are then used to estimate the likelihoods for staying below given climate targets for temperature increase and rate of temperature change. These probabilistic estimates are further connected to the corresponding results for the energy system, for both costs and technologies. The results indicate that mitigation not only increases the likelihood of reaching climate targets, but also reduces the uncertainty concerning future warming. It is also discovered that for more stringent targets the assumptions concerning the baseline play a key role; some targets may be very difficult to reach unless a favorable baseline development is assumed, thus emphasizing the importance of the socioeconomic development path. From the perspective of choosing mitigation scenarios and climate targets, it is concluded that for a given temperature target there is a range of mitigation scenarios that increase the probability of achieving the target considerably. Smaller reductions make little difference, as they are not enough to bring the target within reach, and larger reductions make little further difference for the likelihood of reaching the target. Similarly, if a given mitigation ambition is chosen, the results suggest a set of climate targets for which the given mitigation is useful, therefore underlining the need to match the ambitions with corresponding actions.

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ISBN 978-952-248-184-9
ISBN 978-952-248-185-6 (PDF)
ISSN 1795-2239
ISSN 1795-4584 (PDF)