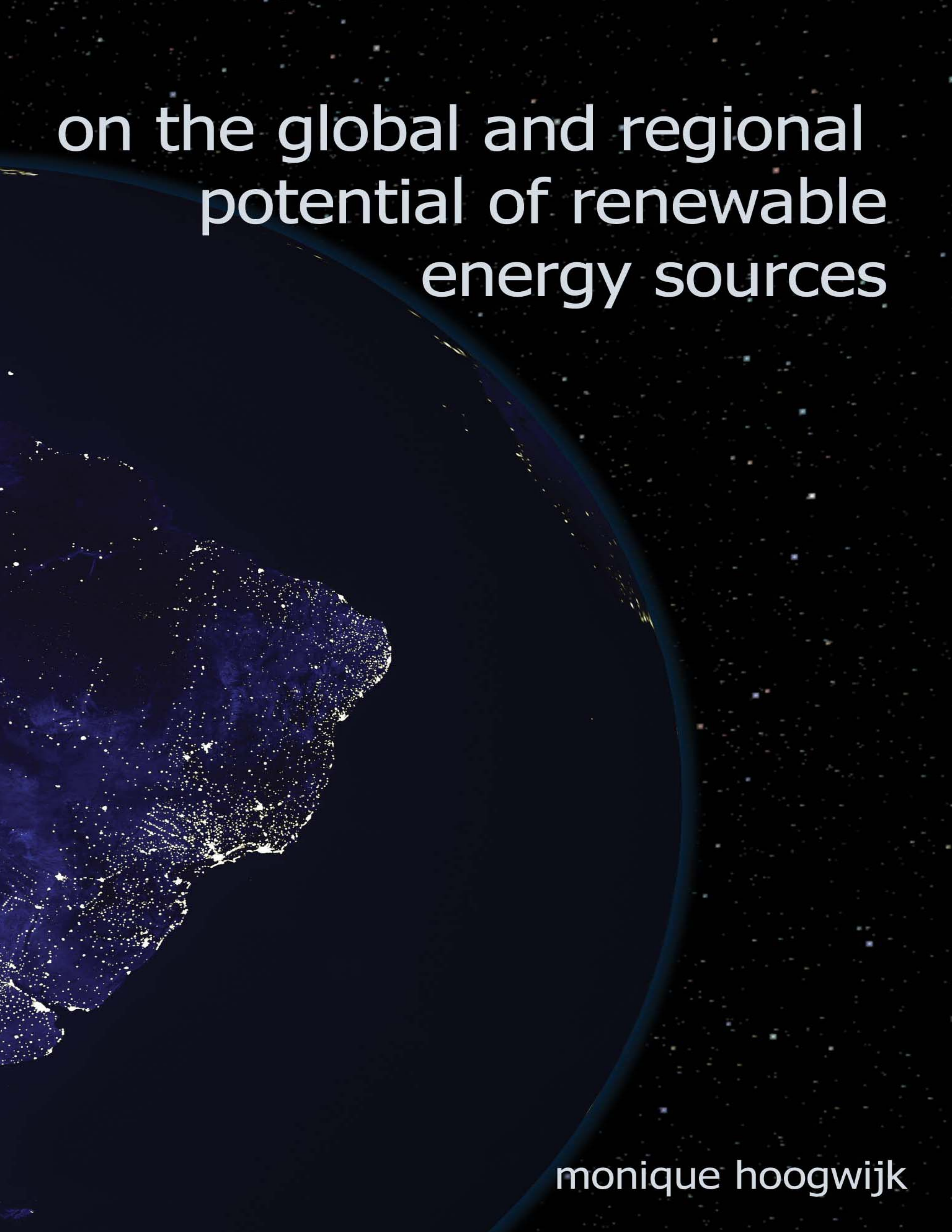

on the global and regional potential of renewable energy sources

monique hoogwijk

ON THE GLOBAL AND REGIONAL POTENTIAL OF RENEWABLE ENERGY SOURCES

Over het mondiale en regionale potentieel van hernieuwbare energiebronnen

(met een samenvatting in het Nederlands)

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR
AAN DE UNIVERSITEIT UTRECHT OP GEZAG VAN
DE RECTOR MAGNIFICUS, PROF. DR. W.H. GISPEN,
INGEVOLGE HET BESLUIT VAN HET COLLEGE VOOR PROMOTIES
IN HET OPENBAAR TE VERDEDIGEN OP VRIJDAG 12 MAART 2004
DES MIDDAGS OM 12.45 UUR

door

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geboren op 22 november 1974 te Enschede

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Dit proefschrift werd mede mogelijk gemaakt met financiële steun van het Rijksinstituut voor Volksgezondheid en Milieu (RIVM).

CIP GEGEVENS KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Hoogwijk, Monique M.

On the global and regional potential of renewable energy sources/
Monique Hoogwijk – Utrecht: Universiteit Utrecht, Faculteit Scheikunde
Proefschrift Universiteit Utrecht. Met lit. opg. – Met samenvatting in het Nederlands
ISBN: 90-393-3640-7

Omslagfoto: NASA
Omslag ontwerp: Dirk-Jan Treffers en Monique Hoogwijk, met dank aan Jacco Farla

ON THE GLOBAL AND REGIONAL POTENTIAL OF RENEWABLE ENERGY SOURCES

Aan mijn ouders

CONTENTS

CHAPTER ONE

INTRODUCTION

1. Energy and sustainable development

Energy plays a crucial role in the development of economies and their people. The energy system, considered as the whole of the energy supply sector, which converts the primary energy to energy carriers, and the end-use technologies needed to convert these energy carriers to deliver the demanded energy services (see Figure 1), has developed significantly over time. Two main transitions can be distinguished in the history of the energy system (Grübler et al., 1995; Grübler, 1998). The first was the transition from wood to coal in the industrialising countries, initiated by the steam engine in the late 18th century. The use of coal, which could more easily be transported and stored, allowed higher power densities and related services to be site independent. By the turn of the 20th century nearly all primary energy in industrialised countries was supplied by coal. The second transition was related to the proliferation of electricity, resulting in a diversification of both energy end-use technologies and energy supply sources. Electricity was the first energy carrier that could easily be converted to light, heat or work at the point of end use. Furthermore, the introduction of the internal combustion engine increased mobility, as cars, buses and aircraft were built, and stimulated the use of oil for transportation. These innovations together lead to a shift in the mix of commercial energy sources from mainly coal towards domination of coal, oil and later natural gas and increased the global commercial primary energy use from 1850 to 1990 by a factor of about 40 (Grübler, 1998).

However, the energy system has developed differently over the world. At present we are living in a world where about 4 billion people use mainly fossil fuels as their primary energy sources and rely for about 16% on electricity for their energy services, whereas about 2.4 billion people rely for most of their energy supply on traditional fuels and energy sources, such as biomass (IEA/OECD, 2002a). As the latter consumption corresponds to only about 11% of the total primary energy use, it is not directly visible and often neglected in statistics on energy consumption (Goldemberg, 2000). This disparity in the availability of energy services reflects the disparity in possibilities for (economic) development. For that reason energy plays a crucial direct or indirect role in order to achieve several Millennium Development Goals (MDGs) constructed at the Millennium Summit held in 2000 at the United Nations General Assembly (Goldemberg and Johansson, to be published). Consequently, in the debates at the World Summit on Sustainable Development (WSSD) in Johannesburg held in September 2002, energy was one of the key issues. It was concluded that the current use and production of energy carriers is incompatible with the goal of sustainable development in view of the following (Goldemberg and Johansson, to be published):

- Opportunities for economic development are constrained for more than two billion people that do not have access to affordable energy services.
- Social stability is threatened due to a growing disparity in access to affordable energy.
- Human health, regional and local air pollution and ecosystems are threatened due to energy-related emissions like suspended fine particles and precursors of acid deposition.
- There is increasing evidence that the anthropogenic greenhouse gas (GHG) emissions originating from the combustion of fossil fuels and unsustainable use of biomass energy have a severe impact on the climate system.
- As economies rely for a significant part on imported energy, they are also increasingly vulnerable to disruption in the supply.

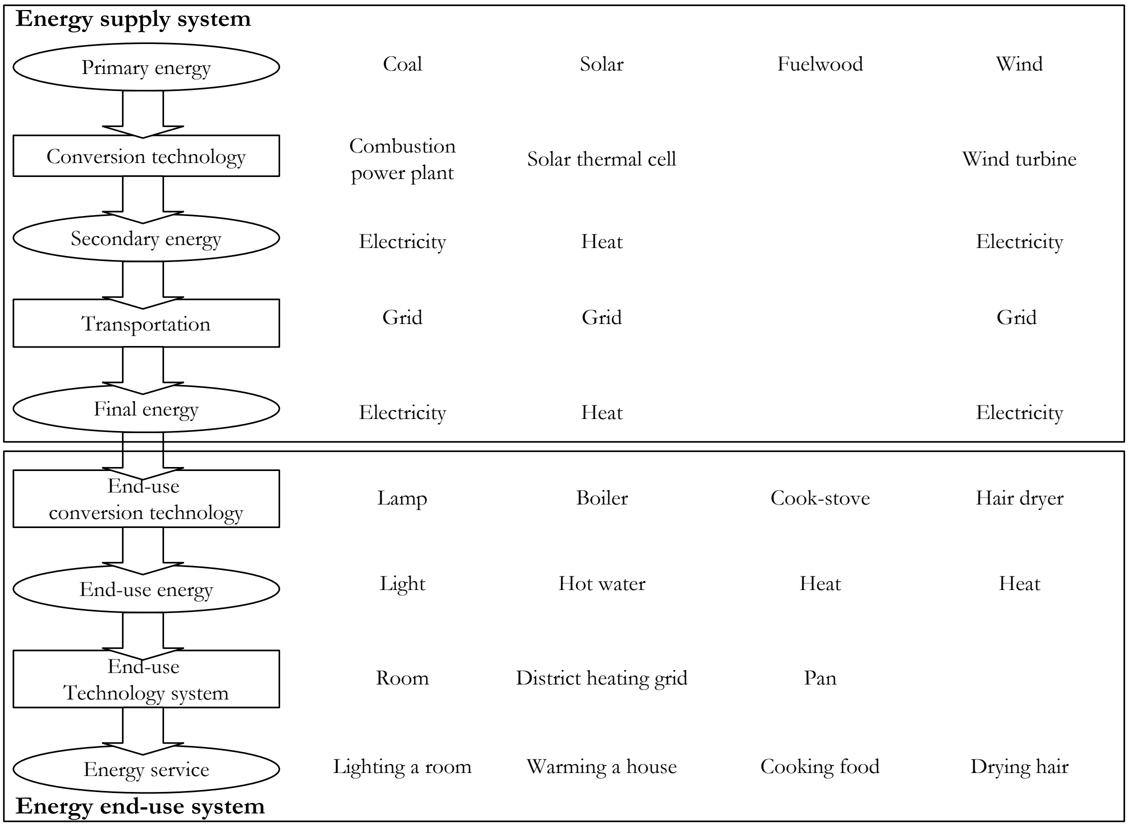

Figure 1: Description of the energy system consisting of the energy supply and end-use system and four examples of energy systems (based on de Beer, 1998).

One of the pathways to follow in order to achieve the goals of sustainable development is an increased reliance on renewable energy. Renewable energy conversion technologies ('renewables') generally depend on energy flows through the earth's ecosystem fed by solar radiation and the geothermal energy of the earth (Turkenburg, 2000). A major advantage is that they can be extracted in a 'renewable' mode, i.e. their rate of extraction is lower than the rate at which new energy is arriving or flowing into the reservoirs (Sørensen, 2000). Renewables are expected to be suitable alternatives in a sustainable energy future for several reasons (Turkenburg, 2000):

- They lead to a diversification of energy sources by increasing the share of a diverse mixture of renewable sources, and thus to an enhanced energy security.
- They are more widely available compared to fossil fuels and therefore reduce the geopolitical dependency of countries as well as minimise spending on imported fuels.
- They contribute less to local air pollution (except for some biomass applications) and therefore reduce the human health damages.
- Many renewable energy technologies are well suited to small-scale off-grid applications and hence can contribute to improved access of energy services in rural areas.
- They can balance the use of fossil fuels and save these for other applications and future use.
- They can improve the development of local economies and create jobs.
- They do not give rise to greenhouse gas (GHG) emissions to the atmosphere. This also holds for the use of biomass, if produced in a sustainable way, as the emitted carbon has been produced before in the process of photosynthesis. Biomass energy can then be considered as carbon dioxide neutral.

2. Future energy scenarios

For the reasons mentioned above, e.g. energy security, accessibility to affordable energy services, energy related emissions to the atmosphere, etc., it is interesting to assess the potential supply of renewables to long-term energy demand at a global scale. Since several decades, the possible developments and dynamics of the energy system is analysed at various levels of geographical detail. These studies give insight in energy security at the long term, in the rate the resources may be depleted, in how the energy prices may develop, and in possible developments of energy-related emissions to the atmosphere. Amongst others this type of analyses facilitates the international policy debate regarding climate change. To assess the future energy consumption and supply mix, assumptions on technical, demographical, economic, social, institutional and political parameters have to be made. To study these issues in a consistent manner, a scenario approach is usually adopted.

2.1 Scenarios on future energy system and energy models

Scenarios are images of possible alternatives for the future. They are neither predictions nor forecasts, but are consistent descriptions of how the future may unfold (Grübler et al., 1995), (Nakicenovic, 2000). One of the first global energy scenarios has been constructed at the International Institute of Applied System Analysis (IIASA) during the late 1970s. Since then a large number of global energy scenarios have been developed.

Two types of scenarios on the future energy system can be distinguished: *descriptive* scenarios, and *normative* scenarios. The first type gives insights in possible pathways for the future; the latter explores the future routes that can be taken to end at a certain pre-defined end-point. Some typical normative scenarios developed in the context of sustainable development are (Goldemberg et al., 1988), RIGES (Renewable Intensive Global Energy Supply) (Johansson et al., 1993), and the Fossil Free Energy Scenario (FFES) scenario developed by the Stockholm Environmental Institute in collaboration with Greenpeace (1993) (Lazarus, 1993). Typical descriptive scenarios are the emission scenarios that have been developed in the context of the Intergovernmental Panel on Climate Change (IPCC), like the most recent so-called SRES scenarios (Special Report on Emission Scenarios) (Nakicenovic, 2000).

Main driving forces of the scenarios that influence the future energy system are:
- population dynamics;
- economic dynamics;
- technological change;
- social dynamics.

Population dynamics influence the demand side of the energy system. Economic development affects the demand as well as the availability of the energy resources or the supply mix, as it is a measure for the future availability of financial resources for investments in the energy supply sector. Technological change is reflected in the demand for energy, e.g. through technological improvements on energy efficiency, as well as on the supply side, e.g. through conversion technologies that come available, specific investment costs and limits to up-scaling. These driving forces need to be consistent within a scenario and are quantified within a modelling framework. For that reason, scenarios are often characterised by the development paths of the driving forces described above.

Scenarios on the future energy system can be quantified by using energy models. Energy models are widely used by national governments and international agencies to aid the decision-making process, e.g. regarding energy and environmental policies, prospects of future technologies and energy supply strategies (Audus, 2000). One can distinguish various types of energy models, e.g. regarding their geographical coverage (e.g. national versus global), their timeframe (e.g. a year versus a century), their number of energy carriers and sectors included in the model and the main approach that is used for the calculation (e.g. optimisation towards cost or deterministic simulation model). Examples of energy models that compute the global long-term energy system are the MESSAGE model (Messner and Schrattenholzer, 2000), the POLES model (Criqui, 1996), the

MERGE model (Manne et al., 1995) and the IMAGE/TIMER1.0 model (de Vries et al., 2002). These models are linked to sub-models that amongst others include the GHG emissions that are related to the conversion of primary energy to other energy carriers and the final use of these carriers. The demand for energy services is estimated and from there, via conversion and end-use technologies efficiencies, the required primary energy can be computed. The type of primary energy sources that is used is mostly determined by the operational cost and performance of the final energy.

2.2 The SRES scenarios

Recently developed descriptive scenarios are the SRES scenarios from the IPCC (Nakicenovic, 2000). Their aim is to simulate the long-term (up to 2100) greenhouse gas emissions due to the combustion of fossil fuels. These scenarios are based on four storylines that describe how the world could develop over time. Differences between the scenarios concern the economic, demographical and technological development and the orientation towards economic, social and ecological values. The four storylines are constructed along two axes, (see Figure 2). The A1 and A2 storylines are considered societies with a strong focus towards to economy, economic development. Whereas the B1 and B2 storylines are more focused on welfare issues and are ecological orientated. The A1 and B1 storylines are globally oriented, with a strong focus towards trade and global markets. A2 and B2 are more oriented towards regions. These storylines are the origin of a large set of scenarios. Figure 3 describes the energy mixture and the total energy demand of the four marker[1] scenarios from the IPCC. In all scenarios biomass and renewable energy sources, mainly solar energy and wind energy, are expected to contribute at significant levels.

[1] The marker scenarios were originally posted in draft form on the SRES website to represent a given scenario family. The choice of the marker was based on which of the initial quantification best reflected the storyline, and the features of specific models.

Material/economic

A1

Population: 2050: 8.7 billion
2100: 7.1 billion

GDP: 2050: $24.2 \bullet 10^3$ billion $\$_{95}\ y^{-1}$
2100: $86.2 \bullet 10^3$ billion $\$_{95}\ y^{-1}$

Technological growth: high

Trade: maximal

A2

Population: 2050: 11.3 billion
2100: 15.1 billion

GDP: 2050: $8.6 \bullet 10^3$ billion $\$_{95}\ y^{-1}$
2100: $17.9 \bullet 10^3$ billion $\$_{95}\ y^{-1}$

Technological growth: low

Trade: minimal

Global oriented

Regional oriented

B1

Population: 2050: 8.7 billion
2100: 7.1 billion

GDP: 2050: $18.4 \bullet 10^3$ billion $\$_{95}\ y^{-1}$
2100: $53.9 \bullet 10^3$ billion $\$_{95}\ y^{-1}$

Technological growth: high

Trade: high

B2

Population: 2050: 9.4 billion
2100: 10.4 billion

GDP: 2050: $13.6 \bullet 10^3$ billion $\$_{95}\ y^{-1}$
2100: $27.7 \bullet 10^3$ billion $\$_{95}\ y^{-1}$

Technological growth: low

Trade: low

Environment/Social

Figure 2: Description of the main four storylines from SRES (for reference, see text).

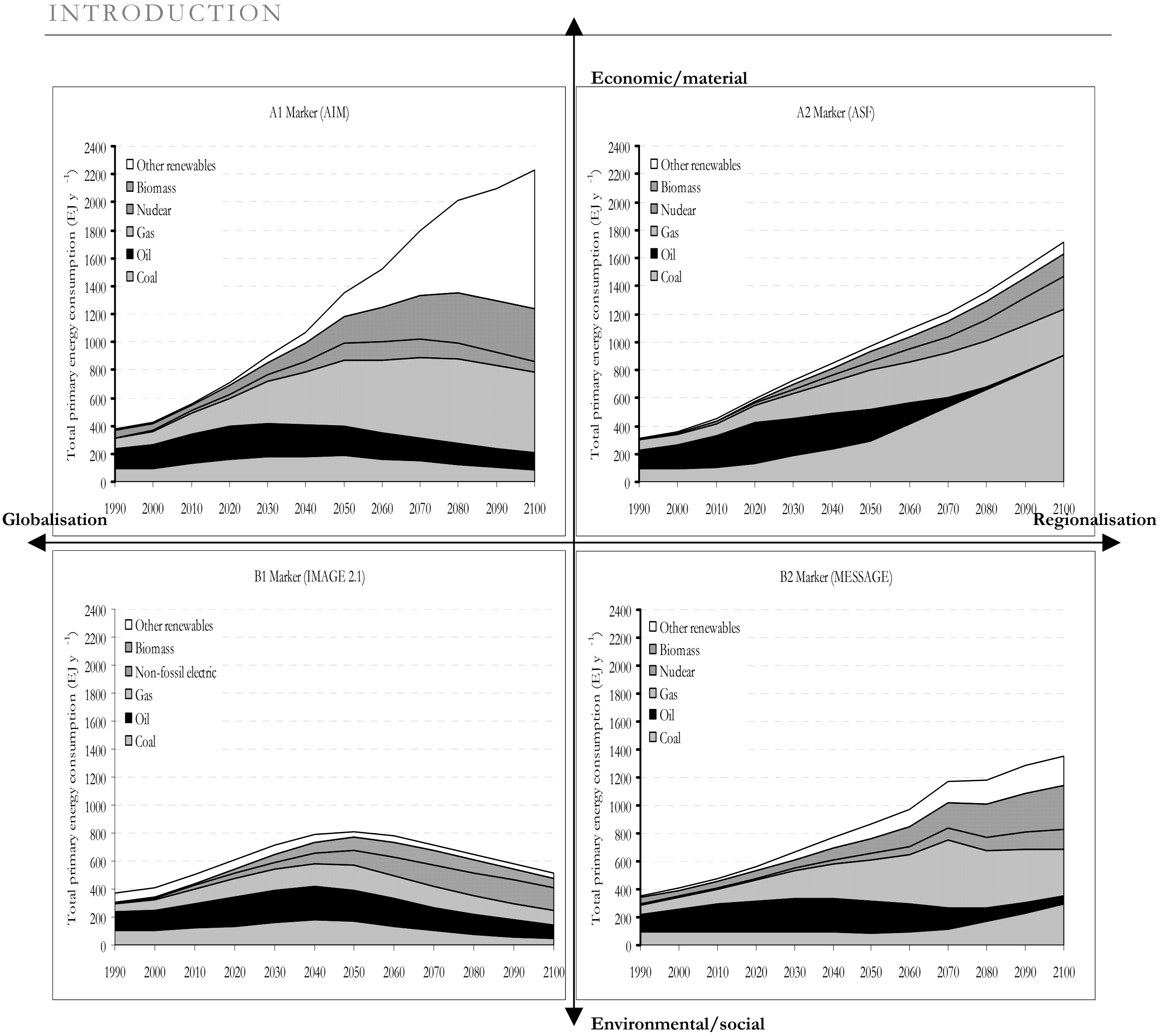

Figure 3: The simulation of the energy mixture and total primary energy demand over time for the four SRES marker-scenarios of the IPCC (Nakicenovic, 2000). In parenthesis, the name of the energy model is given.

From Figure 3 it can be seen that due to the variation in the population dynamics, and the economic and technological development, the various scenarios of the future energy system show large differences, both regarding the total demand, as well as the mixture of the used primary energy sources. Regarding the latter, most studies simulate a significant contribution of 'renewable energy sources' in the future, although among scenarios and among modelling frameworks the quantitative estimated of their market share varies considerably. Variation also consists when the same storyline is used (Nakicenovic, 2000). What are the reasons for these variations?

A variety of questions or driving sources are conceptualised differently in the different scenarios. One of them is how prices of fossil fuels will evolve. When and how the transition to more costly variants – such as tar sands and oil shales – will occur and whether and how political (in)stabilities will affect prices is quite uncertain. Then, although most analysts would agree that the large cost reductions of wind turbines and solar photovoltaic in the last decades will continue, there are controversial views on the rate at which this will or can happen, and hence on the penetration rate of these technologies. Moreover, there are the large uncertainties on costs and land requirements for large-scale production of commercial biomass energy, and on the interference with food production and climate change. Compounding these uncertainties are the prospects and problems of novel end-use technologies and carriers such as fuel cells and hydrogen. It is increasingly recognized that the answers to these questions are not merely a matter of cost and technology; also societal developments such as life-styles, the role of market institutions and the balance between decentralized and centralized options are important aspects.

The considerations put forward to explain the differences in the results for the different scenario analyses shown in Figure 3 emphasize the importance of the use of a set of scenarios that are well-chosen, well-described and sufficiently transparent to show the impact of the separated input parameters. Important input parameters are the potential availability of the separate energy sources and the developments of the conversion technologies and the associated production costs. This thesis therefore focuses on the cost-supply curves of wind, solar PV and biomass energy. As such, insight is gained in the main input parameters of energy scenarios.

3. The potential of wind, solar and biomass energy

The main characteristic of renewable energy sources is that they can be extracted in a 'renewable' mode. Wind, solar and biomass energy are all derived from the sun which, when considered at timeframes of centuries, supplies a constant flow of energy to the earth. The potential availability of wind, solar and biomass energy over time and between regions is therefore hardly varied by the resource availability (theoretical limit), but rather by geographical developments, e.g. land-use demands, by technical developments, e.g. innovative conversion technologies, economic developments, e.g. labour cost variations, or implementation constraints, (e.g. legislations). These aspects vary the potential availability over time and among regions.

When studying the potential of (renewable) energy sources, the aspects like geographical, technical and economic developments need consideration. As a result, different types of potentials can be defined, e.g. the categories introduced by van Wijk and Coelingh (1993):

- The **theoretical** potential is the theoretical limit of the primary resource. For solar-driven sources this is the solar energy or solar energy converted to wind or biomass.
- The **geographica**l potential is the theoretical potential reduced by the energy generated at areas that are considered available and suitable for this production.

- The **technical** potential is the geographical potential reduced by the losses of the conversion of the primary energy to secondary energy sources
- The **economic** potential is the total amount of technical potential derived at cost levels that are competitive with alternative energy applications.
- The **implementation** potential is the total amount of the technical potential that is implemented in the energy system. Subsidies and other policy incentives can give an extra push to the implementation potential, but social barriers like noxious smell can reduce the implementation potential. The implementation potential can be both higher and lower then the economic potential, but can never exceed the technical potential.

In the literature, there are various studies that assess the potential of wind energy (Grubb and Meyer, 1993; World Energy Council, 1994; Fellows, 2000; Sørensen, 1999; Rogner, 2000); solar energy (Hofman et al., 2002; Sørensen, 1999; Rogner, 2000); or biomass energy (Berndes et al., 2003; Rogner, 2000) at a global scale. The studies show that for each of the sources, the potential availability is significant and exceeds the present electricity consumption. However the above-presented distinction between the different types of potentials is in these studies mostly not made, except for the assessment of the potential fo wind energy, formulated by Utrecht University and presented by the World Energy Council (1994). Moreover, most studies, except World Energy Council (1994), Fellows (2000) and Hofman et al. (2002), do not include the production cost, or the economic potential of renewable resources. In addition, most studies, neglect the impact on the operational costs if intermittent sources of wind or solar PV electricity penetrate the electricity system. For biomass energy it is concluded that no potential assessment has been conducted with the use of different land-use scenarios. Finally, the studies differ according to their regional aggregation and approach. Therefore no comparison could be made between the categories of potentials for the three renewable energy sources at similar regional aggregation. In this thesis, the theoretical, geographical, technical and economic potential of wind, solar PV and biomass energy is assessed, using a similar approach. As such, not only more insight is gained in the factors that influence the availability; the types of potentials can also be better compared among the energy sources.

4. Renewable electricity in the IMAGE/TIMER 1.0 model

4.1 The IMAGE/TIMER 1.0 model

In this thesis we focus on the energy model IMAGE/TIMER 1.0, or simply TIMER 1.0 (de Vries et al., 2002). The TIMER 1.0 model is a system-dynamic, simulation model of the global energy system at an intermediate level of aggregation. TIMER 1.0 is a sub-model of the IMAGE 2.2 model (Integrated Model to Assess the Global Environment) (IMAGEteam, 2001) (Figure 4). The IMAGE 2.2 model is developed at grid cell level of 0.5° x 0.5° (longitude, latitude). It is also this level that is mainly used in this thesis. All results of IMAGE 2.2, TIMER 1.0 and this thesis are aggregated to 17 world-regions:

Canada, USA, Central America, South America, Northern Africa, Eastern Africa, Western Africa, Southern Africa, OECD Europe, Eastern Europe Former USSR, Middle East, South Asia, East Asia, South East Asia, Oceania, Japan.

TIMER 1.0 distinguished itself from top-down or optimisation models using a combination of bottom-up engineering information and specific rules and mechanisms about investment behaviour and technology development to simulate the possible development and characteristics of the energy system over time. TIMER 1.0 aims to analyse the long-term dynamics of energy conservation and use and the transition to non-fossil fuel use within an integrated modelling framework, and to calculate energy related greenhouse gases emissions, which are used as an input in other sub-models of IMAGE 2.2. The competition among energy sources within the TIMER 1.0 model is based on long-term cost-supply curves per energy technology and the technical potential of supply per technology and energy source.

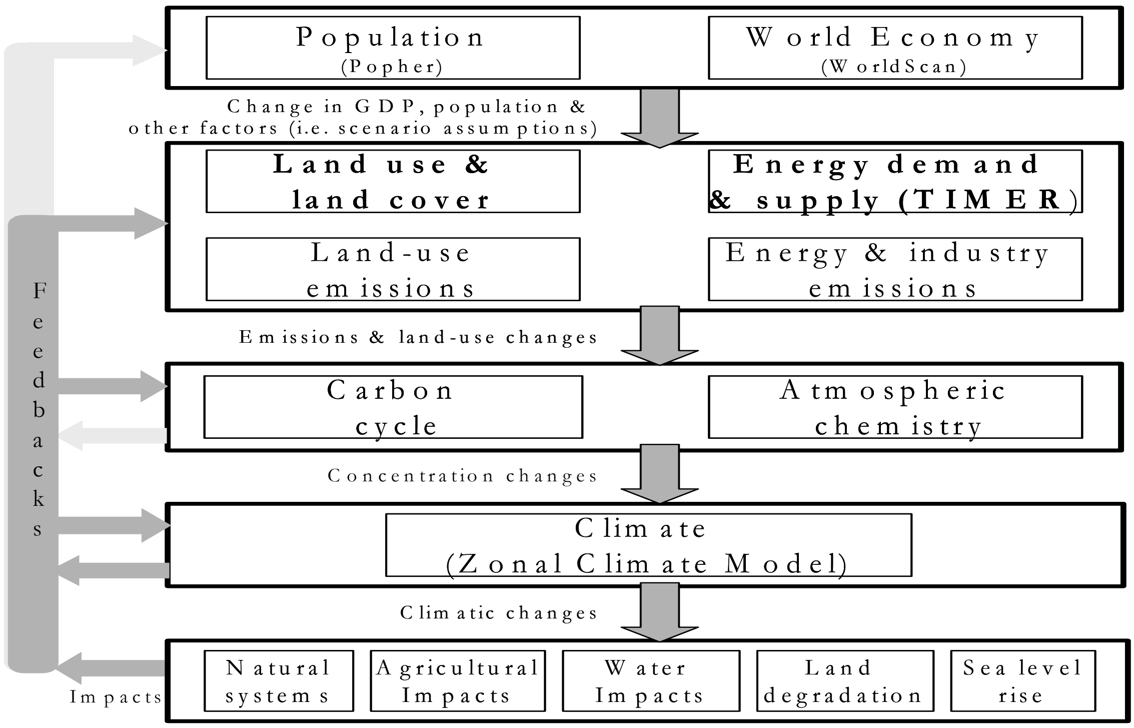

Figure 4: Framework of the IMAGE 2.2 models and the connection with the energy demand and supply model TIMER 1.0 (source: IMAGEteam, 2001).

4.2 Restriction to wind, solar PV and biomass electricity

We focus ourselves on renewable electricity only. This has been done because electricity is increasingly used in the energy system. It is widely applicable but cannot be stored at short and longer timeframes in large quantities. Wind, solar and biomass energy can all be converted to electricity. They are included in one sub-model of the TIMER 1.0 model. It is therefore rather easy to implement the results of the assessment of the potential of these sources in the TIMER 1.0 model. The restriction to electricity only means that we exclude the production of heat and fuel using renewables. Furthermore, we focus on grid-connected applications since, in terms of quantities involved, these are most significant in the energy system and are only included in TIMER 1.0. The renewables that are included in this thesis are shown in Figure 5 in bold, we also mention the options and technologies that are not investigated.

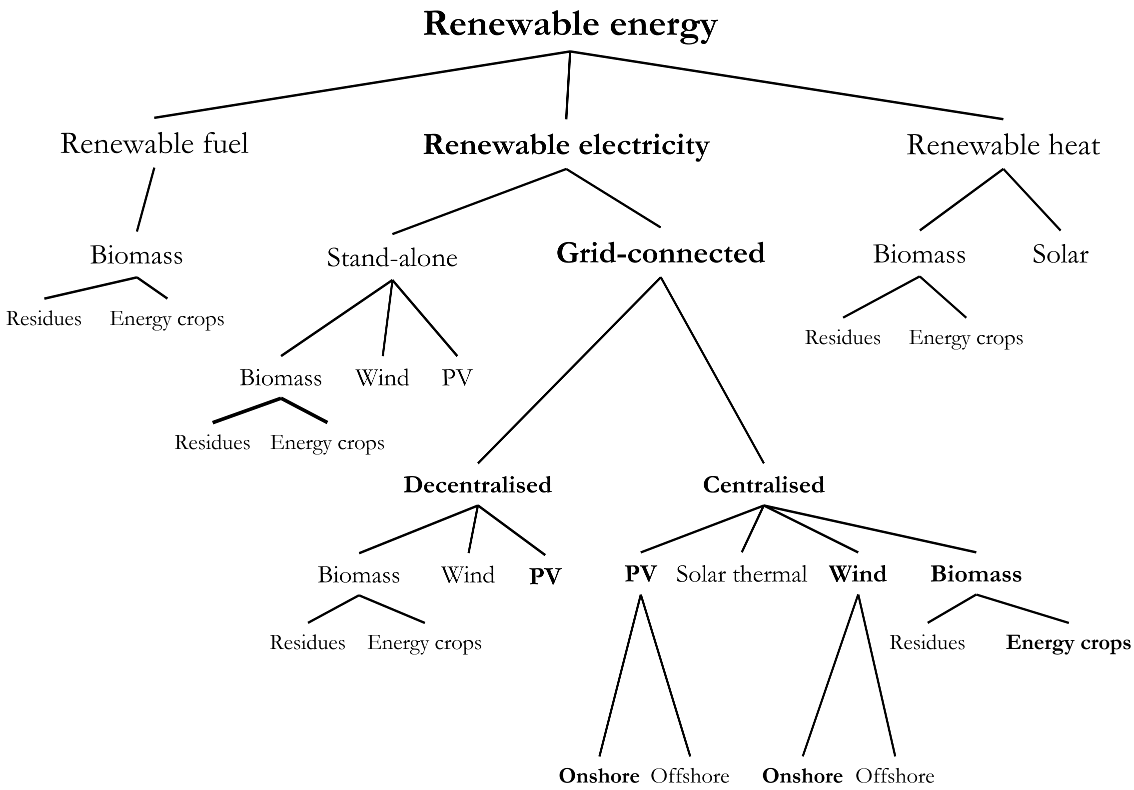

Figure 5: The types of renewable energy carriers and technologies that are included in this thesis (in bold).

4.3 The electricity simulation in TIMER 1.0

TIMER 1.0 consists of various sub-models. The Electric Power Generation (EPG) sub-model focuses on the overall long-term dynamics of regional electricity production. The model can be summarised in two parts (Figure 6). The first part is the investment strategy, which simulates the investments in various forms of electricity production in response to a demand for expansion and for replacement capacity. The investment strategy is based on changes in relative fuel prices and changes in relative generation costs of thermal and non-thermal power plants. The second part simulates the operational strategy. The operational strategy determines how much of the installed capacity is used and when. It reflects that electric power companies minimise the production costs while maintaining the required system reliability. The basic rule-of-thumb here is the merit order strategy: power plants are operated in order of variable costs. Technological learning is included using exogeneous assumptions and using an experience curve for the renewable energy sources, resulting in a decrease of the operational costs. Depletion is included using a cost-supply curve resulting in an increase of operational costs.

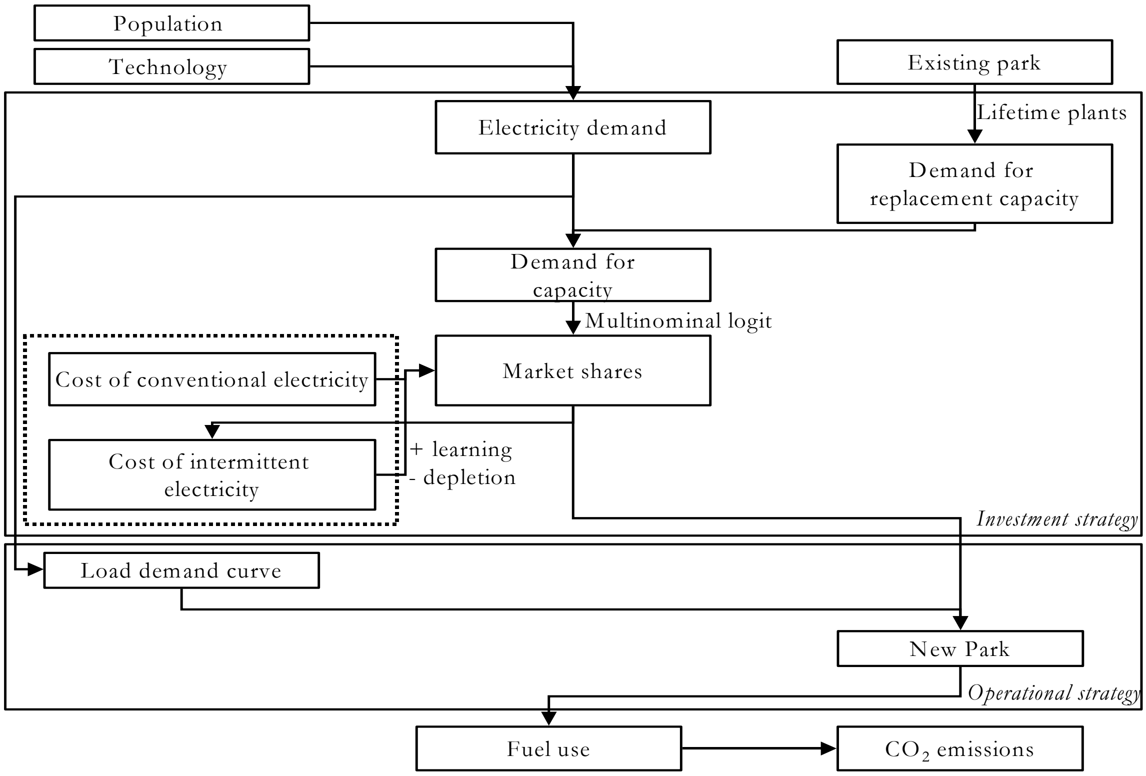

Figure 6: Schematic description of the TIMER 1.0 model.

The current version of TIMER 1.0 simulates renewable electricity sources in an aggregated manner. To enhance the detail of TIMER 1.0 these sources should be simulated separately. Therefore, similar main input (cost-supply curve) per source and technology is required, at similar regional aggregation and timeframe (1970 to 2050 and/or 2100). In this thesis we construct cost-supply curves of wind, solar PV and biomass electricity that can be used for scenario simulation in the TIMER 1.0 model. We also analyse in this thesis how the intermittent sources wind and solar PV can be implemented in the TIMER 1.0 model and how this would influence the cost of wind electricity and the CO_2 abatement costs.

5. Central research question

In the above sections we have addressed the importance of analysing the theoretical, geographical, technical, economic and implementation potential of wind, solar PV and biomass electricity in a consistent way. We also have indicated the importance of studying the renewable electricity sources, in particular wind and solar PV in the context of an energy model. The main objective of this thesis is:

To assess the geographical, technical and economic potential of wind, solar and biomass electricity for seventeen world regions by constructing regional cost-supply curves for these renewable electricity options using a grid cell approach. In addition, we aim to investigate the dynamics and main factors that influence the additional overall production and CO_2 abatement costs of intermittent sources with increasing penetration in the electricity market.

To analyse this objective, relatively more attention is given to biomass energy. This is done the feedstock availability depends on the land-use system development over time (Berndes et al., 2003). Furthermore, the costs of biomass energy are more regionally varying, so more regional detail is needed to analyse the regional cost-supply curves of biomass energy.

The objective of this thesis is reached by addressing the following research questions:

- What range can be expected of the geographical potential of biomass energy?
- What factors determine the geographical potential of biomass energy?
- What is the geographical and technical potential of biomass energy for four different land-use scenarios?
- What are the regional cost-supply curves and the economic potential of biomass energy?
- What is the geographical, technical and economic potential of onshore wind electricity?
- What is the geographical, technical and economic potential of onshore solar PV electricity?
- What factors influence the amount of wind and solar PV electricity absorbed by the electricity system?
- How do the operational costs of wind electricity change with increasing penetration levels?
- What factors determine the CO_2 abatement costs of wind electricity at increasing penetration levels of wind in the electricity system?

To meet the objective we will assess the theoretical, geographical and technical potential of wind, solar PV and biomass electricity in this thesis. This has been done using climatic and land-use data at grid-cell level of 0.5°x 0.5° (except for *Chapter 2*). This geographical aggregation level is consistent with the level used in the terrestrial environment system of the IMAGE 2.2 model. The results are aggregated to the regional level of the TIMER 1.0 model. For the biomass energy potential assessment we will use four land-use scenarios as the assessment of the availability of biomass energy requires an integrated approach with land-use development.

The cost-supply curves at a regional and global level are derived by calculating the electricity production costs in each grid cell. These include the costs of the fuel (zero for wind and solar PV), specific investment costs and the operation and maintenance costs. These grid cells are ranked according to their production costs resulting in the cost-supply curve.

6. Outline of this thesis

This thesis is structured as follows. *Chapter 2* starts with an exploration of the ranges of the geographical potential of biomass energy. This study identifies the factors that determine the long-term geographical potential of biomass energy. In *Chapter 3* a similar approach is used to assess the regional geographical and technical potential of energy crops based on four land-use scenarios. These potentials are used in *Chapter 4* to estimate the long-term development of regional cost-supply curves of energy crops within the four assumed scenarios. The following chapters focus on the potential supply and cost-supply curves of wind and solar PV electricity. In *Chapter 5* the theoretical, geographcial and technical potential of wind electricity and cost-supply curves of onshore wind electricity production is estimated on the basis of a static land-use pattern. A similar study is presented in *Chapter 6* for solar PV. In *Chapter 7* the TIMER-EPG model is used to simulate the impact of high penetration levels of wind and solar PV on the amount of intermittent electricity in the system, the overall production and CO_2 abatement costs of wind electricity in the USA and OECD Europe. The final *Chapter 8* summarises the main findings and conclusions of this thesis.

Part 1

Biomass energy

CHAPTER TWO

EXPLORATION OF THE RANGES OF THE GLOBAL POTENTIAL OF BIOMASS FOR ENERGY[#]

Abstract

This study explores the range of the future global potential of primary biomass energy. The focus has been put on factors that influence the potential biomass availability for energy purposes rather than give exact numbers. Six biomass resource categories for energy are identified: energy crops on surplus cropland, energy crops on degraded land, agricultural residues, forest residues, animal manure and organic wastes. Furthermore, specific attention is paid to the competing biomass use for material. The analysis makes use of a wide variety of existing studies on all separate resource categories. The main conclusion of the study is that the range of the global potential of primary biomass (in about 50 years) is very broad, quantified at 0 – 1135 EJ y-1. Energy crops from surplus agricultural land have the largest potential contribution (0 – 988 EJ y-1). Crucial factors determining biomass availability for energy are: 1. The future demand for food, determined by population growth and future diet; 2. The type of food production systems that can be adopted world-wide over the next 50 years; 3. Productivity of forest and energy crops; 4. The (increased) use of bio-materials; 5. Availability of degraded land; 6. Competing land use types, e.g. surplus agricultural land used for reforestation. It is therefore not 'a given' that biomass for energy can become available at a large-scale. Furthermore, it is shown that policies aiming for the energy supply from biomass should take factors like food production system developments into account in comprehensive development schemes.

[#] Published in *Biomass and Bioenergy* (2003), Vol. 25, Issue 2, pp: 119-133. Co-authors are André Faaij, Richard van den Broek, Göran Berndes, Dolf Gielen and Wim Turkenburg. Joep Luyten is kindly thanked for his support of Section 4. The authors furthermore are grateful to Eric Kreileman (RIVM) for his help on Figure 2. This work has been conducted with financial help of the Netherlands Agency for Energy and the Environmental (NOVEM).

1. Introduction

Biomass is seen as an interesting energy source for several reasons. The main reason is that bioenergy can contribute to sustainable development (van den Broek, 2000). Biomass energy is also interesting from an energy security perspective. Resources are often locally available and conversion into secondary energy carriers is feasible without high capital investments. Moreover, biomass energy can have a positive effect on degraded land by adding organic matter to the soil. Furthermore, biomass energy can play an important role in reducing greenhouse gas emissions, since if produced and utilised in a sustainable way, the use of biomass for energy offsets fossil fuel greenhouse gas emissions. Since energy plantations may also create new employment opportunities in rural areas in developing countries, it also contributes to the social aspect of sustainability. At present, biomass is mainly used as a traditional fuel (e.g. fuelwood, dung), globally contributing to about 45 ± 10 EJ y^{-1}. Modern biomass (e.g. fuel, electricity) to about 7 EJy^{-1} (Turkenburg, 2000). In this study we include both traditional and modern biomass energy.

Many energy scenarios suggest large shares of biomass in the future energy system e.g. (Nakicenovic, 2000; Shell, 1995; Johansson et al., 1993; Goldemberg, 2000). The availability of this biomass is not always separately analysed. Furthermore, large-scale utilisation will have large consequences for land demand and biomass infrastructure, which should be assessed. Many studies have been undertaken to assess the future primary biomass energy potential, e.g.: (Battjes, 1994; Dessus et al., 1992; Edmonds et al., 1996; Fischer and Schrattenholzer, 2001; Grübler et al., 1995; Hall et al., 1993; Lashof and Tirpak, 1990; Lazarus, 1993; Leemans et al., 1996; Rogner, 2000; Shell, 1995; Swisher and Wilson, 1993; Williams, 1995; World Energy Council, 1994; Yamamoto et al., 1999).

To get insight in the main assumptions that have been made in these studies Berndes et al. (2003) have conducted an analysis of the approaches used to assess the global biomass energy potential. Overall, it has been concluded that the results vary widely. Furthermore, most of the investigated studies do not include all sources of biomass in competition with other land use functions. The studies are not always transparent in the procedure for calculating the energy potential. Insight in factors that are of main importance to realise the investigated potential is therefore not always presented. Finally, many studies tend to neglect competition between various land use functions and between various applications of biomass residues (Berndes et al., 2003). Therefore, in this study we consider a different approach of exploring the primary biomass potential.

The main objectives of this study are: 1) to gain insight in factors that influences the primary potential of primary biomass for energy in the long term; 2) To explore the theoretical ranges of the biomass energy potential on the longer term in a comprehensive way, including all key categories and factors; 3) To evaluate to what extent the potential of biomass supply can be influenced. This analysis focuses on a global scale. The chosen timeframe for this exercise is the year 2050.

In this study we first describe the methodology applied (Section 2). Next, in Sections 3 and 4 the potential production of biomass is assessed. In Section 5, the potential future demand of biomass for production of materials as a competing option is taken into account by evaluation of utilisation, and potential growth in demand for the long term with the use of economic projections. Finally, the ranges found for land availability, biomass productivity levels, availability of biomass residues and of organic wastes are translated into primary energy supply potentials (Sections 6 and 7).

2. Methodology

2.1 Biomass categories

First we define the concept 'potential' that is used in this study. We are interested in an upper limit of the amount of biomass that can become available as (primary) energy supply without affecting the supply for food crops. This is defined as the geographical potential.

We define our biomass supply system by dividing biomass production and use into different resource categories (Figure 1). These categories increase transparency in competition and synergy of separated biomass resources. The scheme presented in Figure 1 is a simplification of the real system, and hence not complete. E.g. one could think of aquatic biomass from the fresh water or oceans. Furthermore, the land use category 'other land' includes all kind of land types such as desert, semi-arid land, ice, etc. This scheme also implies that biomass supply from protected nature conservation areas is not included in this study. Competing land use functions like recreation and human settlements are also excluded. Nevertheless, residues from forest areas are included in this study. Figure 1 also shows the total surface per land use type. Out of the total land surface of 13 Gha, about 5 Gha is used for food production (Wirsenius, 2000). To some extent the figures vary among different studies, e.g. Fischer and Schrattenholzer (2001) take a figure of 5.3 Gha.

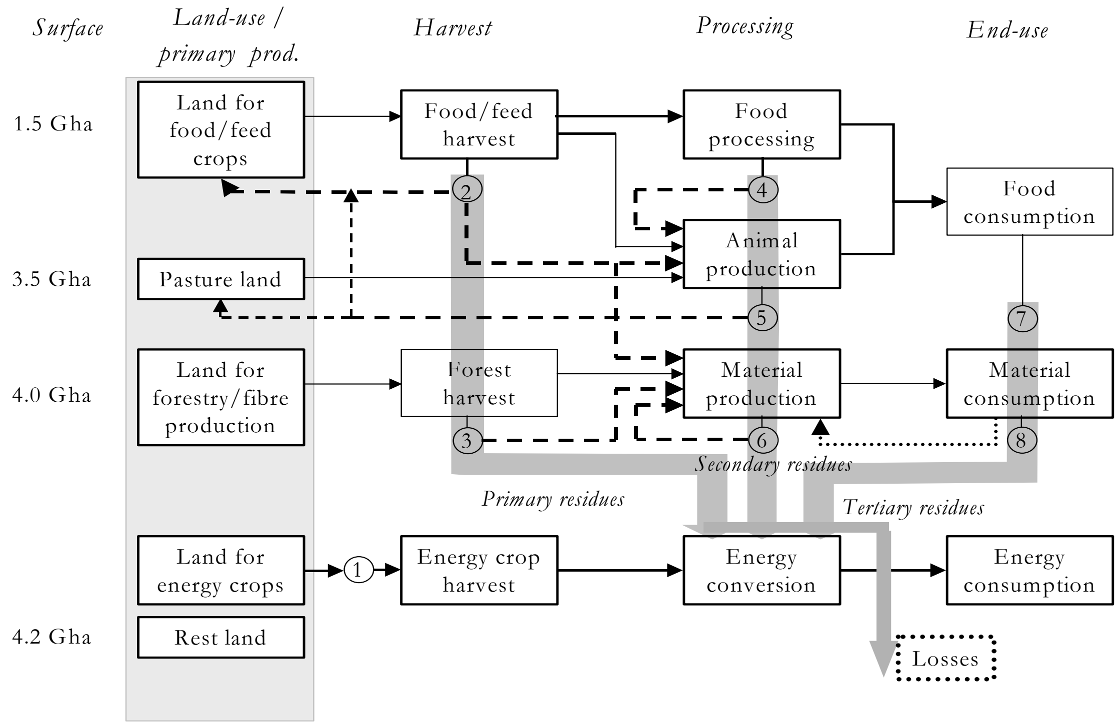

Figure 1: Overview of competition and synergism among various types of biomass flows and the global land surface. Based on: (van den Broek, 2000 and Wirsenius, 2000). The black arrows indicate the main product flows, whereas the dotted lines show potential non-energy applications of various residue categories. The gray arrows represent the potential energetic use of the resources (1 = energy crops, 2 = energy crops at degraded land, 3 = agricultural residues, 4 = forest residues, 5 = animal manure, 6 = organic waste, 7 = bio-material).

In the system defined (Figure 1) there is on the one hand competition for land, for the production of energy, food and materials; i.e. farmers may compete with foresters or energy producers on the use of land for their products. Furthermore, competition exists between the use of residues (dotted lines). Residues can be used for energy purposes, but also for fiber, fertiliser or fodder. On the other hand, synergies occur between energy and food material production (the end-use options, right part of the figure), since residue flows increase with increasing food production and these flows can also be utilized for energy purposes.

To explore the ranges of biomass potential for energy that includes all those flows and applications we define -based on Figure 1- seven categories of biomass resource types (Table I). Land for energy crops from Figure 1 is divided in two categories (here referred to as categories I and II): surplus agricultural land and degraded land. Degraded land is included in the land use category ‘other land’ in Figure 1. The primary and secondary residues, as shown in Figure 1, are estimated separated, but merged due to lack of detailed disaggregated data. This is done for both agricultural residues (Category III) and forest residues (Category IV). The use of biomass for material applications (such as solid products or fiber or wood for pulp) may increase in the future, and should be subtracted from the biomass production for energy applications on surplus agricultural and degraded land. However, after a delay of time (which can cover a time period between several weeks (paper) up to decades (construction wood), this biomass becomes, at least partly, available as waste and adds to Category VI (organic waste).

Table I: Biomass resource categories distinguished in this study to assess the global available potential of biomass for energy use on the long term.

Category	Description
Category I: Biomass production on surplus agricultural land	The biomass that can be produced on surplus agricultural land, after the demand for food and fodder is satisfied.
Category II: Biomass production on degraded land	The biomass that can be produced on deforested or otherwise degraded or marginal land that is still suitable for reforestation.
Category III: Agricultural residues	Residues released together with food production and processing (both primary and secondary).
Category IV: Forest residues (incl. material processing residues)	Residues released together with wood production and processing (both primary and secondary).
Category V: Animal manure (dung)	Biomass from animal manure.
Category VI: Organic wastes	Biomass released after material use, e.g. waste wood (producers), municipal solid waste.
Category VII: Bio-materials	Biomass directly on used as a feedstock for material end-use options like pulp and paper, but also as feedstock for the petrochemical industry.

2.2 Approach

The potential supply of the various categories presented in Table I is assessed using the results of existing studies. For the assessment of biomass produced on surplus agricultural land (Category I), the demand for land required for food is assessed. Therefore various population scenarios, three different diets and two different food production systems are assumed. The potential of Category II is mainly based on an overview of studies with the objective to assess the amount of degraded land available for reforestation. The potential biomass productivity at both surplus agricultural and degraded land is estimated using a grid cell based crop growth model. The potential assessment of residues (Category III, IV, V and VI) is based on various potential assessments. The approaches are compared and similar assumptions and results combined to construct a lower and upper limit of the potential. The demand for bio-materials (Category VII) is based on scenarios on the future economic development, production figures and share of bio-materials in the total material production. The results of the separated categories are combined to give an overall estimation of the upper and lower ranges of primary biomass supply.

3. The potential for energy farming on agricultural land

3.1 Availability of surplus agricultural land (Category I)

To assess land areas available for production of biomass for energy use on surplus agricultural land, the future demand for land for food and fodder production has to be estimated. In order to do so, we use a study from Luyten that explores the potentials of food production on a global level (Luyten, 1995), as basis for the assessments. Several adaptations are made to the Luyten study, mainly regarding the land areas included. The adaptations can be done since the study by Luyten has been reported transparently. While Luyten considers all land that can be used in principle for food production (e.g. including current forests), we limit ourselves to the current 5 Gha in use for food production (see also Figure 1). At present, (forest) land is converted into agricultural land. And so, the agricultural land is increasing. If more land is required for food production, there is no land available for energy crops. We assume furthermore that the land area that is abandoned because of a decreased quality is included in the second category of biomass sources (energy crops on degraded land). The first category only includes (high quality) surplus agricultural land. Furthermore, more recent insights on population growth scenarios are used (Nakicenovic, 2000). We assess the potential future world food demand assuming three population projections and three food consumption patterns. To assess the required land to supply this demand, two types of food production systems are assumed, based on very different input levels of fertilisers and pesticides and more intensified management techniques and thus different intensities of farming (Luyten, 1995). Hence, eighteen different food scenarios are produced.

3.1.1 Future demand for food

Total food demand depends primarily on population figures and the average diet consumed. Three average food consumption patterns are considered, taken from (Luyten, 1995): a vegetarian diet with little or no animal protein; a moderate diet; and an affluent diet with a large share of meat and dairy products (Table II). The diets are composed of different shares of plant, dairy and meat products. To make the diets comparable, they are expressed in grain equivalents (gr. eq.). Grain equivalents are universal measures for the amount of dry weight in grains used directly or indirectly (as raw material for other food products e.g. milk or meat) in our food consumption. In this approach some crops, which are not cereals (e.g. fruit) are translated to grains (Luyten, 1995). Losses when converting grains and grasses to dairy and meat products are taken into account. Luyten assumes conversion efficiencies of 33% for dairy and 11% for meat[2]. The three diets are all sufficient with respect to daily caloric intake and daily protein requirements, but differ strongly with respect to their composition and thus daily consumption per adult in grain equivalents (see Table II). The conversion factor that converts the diets to grain equivalents, are weighted averages of the conversion factors of each separate product consumed in the diet, respectively 0.92, 1.45 and 2.77 kg grain eq/kg product, for the vegetarian diet, moderate and affluent diet (Luyten, 1995).

[2] Taking into account an annual increase of productivity of about 2%, these data compare reasonably with present production efficiencies as studied by Wirsenius. Wirsenius mentions a variation of conversion efficiency from corn (in corn equivalents) between 5.2 and 19%, for cattle milk and dairy products respectively. For meat production a range is given of 0.58 – 1.8% for beef, 2.8 – 6.4% for pork meat, 4.1 – 8.3% for chicken and 10-18% for eggs (Wirsenius, 2000).

Table II: Assumed global average daily consumption per adult for three different diets expressed in MJ day^{-1} and in grain equivalents in kg dry weight per day, source: (Luyten, 1995).

	Current situation	Vegetarian diet	Moderate diet	Affluent diet
Energy intake (MJ d^{-1})	9.4	10.1	10.1	11.5
Plant prod. (gr eq, kg^{-1}d^{-1})		1.05	0.90	1.13
Meat prod. (gr eq, kg^{-1} d^{-1})		-	0.22	1.91
Dairy prod. (gr eq, kg^{-1}d^{-1})		0.28	1.23	1.16
Total (gr eq, kg^{-1}d^{-1})	2.3	1.3	2.4	4.2

Population projections are taken from recent scenario studies of the Intergovernmental Panel on Climate Change (Nakicenovic, 2000). Projections for 2050 vary between 8.7 to 11.3 billion people, compared to the present (2000) figure of 5.9 billion global citizens. Combined with the three average diets described, and assuming that the entire world population adopts those diets, this results in the total future food demands for the three diets as indicated in Table III. Hence, it can be concluded that the total global demand (represented in grain equivalents) can, in principle, vary between $4.1 \cdot 10^{12}$ and $17.3 \cdot 10^{12}$ kg dry weight, which is 80% up to 350% of the current demand for food.

Table III: Population projections for 2050 (in 10^9 people) and the food requirement in grain equivalents (in 10^{12} kg dry weight) for three population scenarios (L = low, M = medium and H = high).

	Current	Vegetarian diet			Moderate diet			Affluent diet		
	situation	L	M	H	L	M	H	L	M	H
Population size 10^9 people	5. 9	8.7	9.4	11.3	8.7	9.4	11.3	8.7	9.4	11.3
Global food requirement (10^{12} kg d.weight gr. eq.)	5.0	4.1	4.5	5.4	7.6	8.2	9.9	13.3	14.4	17.3

3.1.2 Future supply of food

Two fundamentally different production systems are defined to assess the future supply of food: a High External Input (HEI) system and a Low External Input (LEI) system (Luyten, 1995). These systems differ mainly in the way diseases and plagues are combated and in the use of fertilisers.

HEI production system

The HEI production system is based on the concept of 'best technical means': crop production is maximized, and realized under optimum management, with an efficient use of resources (WRR, 1992 and Luyten, 1995). Nutrient requirements are fully covered by fertiliser application. The crop production is only limited by the availability of water if no irrigation water can be applied. The most effective methods of weed, pest and disease control are used to avoid yield losses and there are no restrictions in biocide use. Typical yields are 14.3 tons dry matter of gr. eq. ha^{-1}y^{-1} for irrigated areas and 5.9 tons dry matter of product in gr eq $ha^{-1}y^{-1}$, for non-irrigated areas (Luyten, 1995). These figures are relatively high (about a factor 2) compared to the present yield figures (2000) of cereal crops in Western Europe, of 5.7 ton $ha^{-1}y^{-1}$, and a world average figure of 3.1 ton $ha^{-1}y^{-1}$ (FAO, 2003).

LEI production system

The LEI system aims at an agricultural system that minimises environmental risks. Within this system, no chemical fertilisers and biocides are applied. Fertilisation is only obtained through biological fixation and is kept in the system by recycling animal and crop residues. Potassium and phosphorous availability to the crop are assumed optimal, but production is limited by both water and nitrogen availability. Herbicide application is replaced by mechanical weeding and the control of pests and diseases is carried out by means of prevention. This results in an average yield of 4.0 tons dry matter of gr eq $ha^{-1}y^{-1}$ for irrigated areas and 2.2 tons dry matter of product in gr eq $ha^{-1}y^{-1}$ (Luyten, 1995). These figures are close to present global average cereal yields of 3.1 ton $ha^{-1}y^{-1}$ (FAO, 2003).

Luyten has calculated the rainfed crop production for the two systems with a simple crop growth model. Calculations are done for grid cells of 1° x 1° (with site-specific climate and soil conditions) over the globe (Luyten, 1995). We use the global mean irrigated and non-irrigated yields as assessed by Luyten and presented in Table IV[3]. The assessed yields are applied at the 5 Gha agricultural land, divided into grassland (3.5 Gha) and cropland (1.5 Gha) (see Table IV). We assume that with both systems, 20% of the agricultural land area is irrigated, and that on grassland no irrigation is applied[4].

Table IV: Potential area, potential yields and total potential food production.

	Area (Gha)		Global mean yield gr. eq. in ton $ha^{-1}y^{-1}$		Potential production gr. eq. in Gton y^{-1}	
	HEI	LEI	HEI	LEI	HEI	LEI
Irrigated	0.75	0.75	14.3	4.1	10.7	3.1
Rainfed	0.75	0.75	5.9	2.1	4.4	1.6
Grassland	3.5	3.5	5.9	2.1	20.5	7.4
Total	5.0	5.0			35.6	12.0

3.1.3 Future land requirement for food production

The ratio between global food production and global food requirements (see Table V) is used to calculate the fractions of agricultural land needed for food production. It is assumed that the remaining fraction in principle can be used for the production of biomass for energy. The demand is only fulfilled under optimal infrastructure to match

[3] Luyten has used the following values for the Harvest Index (ratio between of harvested part and total crops), being representative for current major cereals: 0.4 (LEI, grain), 0.45 (HEI, grain), 0.7 (LEI, grass) and 0.6 (HEI, grass) (Luyten, 1995).

[4] Currently 20% of the present arable land in developing countries and 13% in developed countries is irrigated. In 2030 the share of irrigated versus non-irrigated land in developing countries is estimated to be 22% (FAO, 2000).

supply and demand. However, food production between years and regions may vary, and unequal income distribution may keep food inaccessible to the poor if food supply is limited. Furthermore various transportation and distribution losses require a higher production compared to the consumption. Therefore, we use a ratio of 2 to guarantee food self-sufficiency. This assumption is based on discussions among several experts (Luyten, 1995 and Luyten, 2001). It is stressed that this value is rather arbitrary, as it depends on a large set of factors (e.g. unequal spatial distribution of demand and supply, variation among years and losses in transport).

The fraction of agricultural land that may be used for biomass production and the total area available for biomass production are given in Table V, Table VI and Table VII.

Table V: Ratio between the potential global food production and global food requirement in 2050, calculated for two production systems (HEI and LEI) using three population scenarios (low, medium, high).

	Vegetarian diet			Moderate diet			Affluent diet		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
HEI	7.7	7.1	5.9	4.2	3.9	3.2	2.4	2.2	1.8
LEI	2.7	2.5	2.1	1.5	1.3	11	0.8	0.8	0.6

Table VI: The area available for energy plantations agricultural land area using a food security factor of 2.

	Vegetarian diet			Moderate diet			Affluent diet		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
HEI	3.7	3.6	3.3	2.6	2.4	1.9	0.8	0.5	0
LEI	1.3	1.0	0.2	-	-	-	-	-	-

Table VII: The fraction of the total global area available for energy plantations using a food security factor of 2.

	Vegetarian diet			Moderate diet			Affluent diet		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
HEI	74%	72%	66%	52%	48%	38%	16%	9%	3%
LEI	26%	20%	3%	-	-	-	-	-	-

3.2 Availability of marginal/degraded land for energy farming (Category II)

To investigate the potential availability of marginal/degraded land for energy farming, we have analysed a selection of studies that assess land availability for forest-based climate change mitigation strategies (see Houghton, 1990; Houghton et al., 1991; Grainger, 1988; Hall et al., 1993; Lashof and Tirpak, 1990). The approach in these studies is first to identify areas where human activities have induced soil and/or vegetation degradation. The identified areas are subsequently evaluated in order to estimate availability for reforestation. In this context biomass energy plantations offer one of several possible land use options. Forest replenishment and agroforestry systems are alternative strategies for reclamation of degraded land. The studies attempt to refine the reforestation concept in order to evaluate the feasibility for specific reforestation strategies. Otherwise, it is difficult to evaluate the feasibility of establishing biomass production for energy purposes on degraded land identified as potentially available for forestry based climate change mitigation strategies. The reason is that land availability assessments within the context of bioenergy plantations establishment require a more restricting set of evaluation criteria than if the assessment is employed within the context of forestation strategies in general.

Hall et al. (1993) assumes that out of the 760 Mha of degraded land as mentioned by (Grainger, 1988), about 430 Mha can be used for energy crops. US-EPA (Lashof and Tirpak, 1990) assumes an amount of land available for reforestation of 380 Mha. Houghton (1990) and Houghton et al. (1991) estimates 500 – 580 Mha. However, a pessimistic scenario by (Houghton et al., 1991) gives a figure of 0 Mha. This pessimistic scenario was described to state that, due to financial, policy and social aspects, the effort for this deforestation could also be zero. However, as we do not include these aspects in this study, the range taken in this study, based on above-mentioned references is 430 – 580 Mha of degraded area potentially available for energy crop production. The lowest figure applies to the scenario when competing land use options are chosen. The upper limit assumes high priority input and marginal competing options. However, one should be aware that these figures are difficult to quantify, so these values are highly uncertain.

3.3 Productivity and primary energy potential of energy crops

In this study the species of energy crop is not specified. For the productivity assessment we restrict the energy crop to woody short rotation crops, like eucalyptus and willow. Energy crop productivity depends on environmental conditions (i.e. climate, soil, etc.) and management (i.e. crop protection, nutrient supply, irrigation, etc.) and can therefore vary considerably among different areas. We distinguish two types of biomass cultivation for energy. The first type of cultivation is reforestation on degraded land, characterized by (more) extensive management and often on less productive land. The second category is 'dedicated fuel supply systems', with a more intensive management methods, (e.g. eucalyptus, grasses, willows). The latter is assumed to have a higher productivity. The value of this future productivity is difficult to assess, as well as the difference in productivity between both production systems. We have studied the productivity of energy crops, using the crop growth model of the IMAGE 2.1 model (see Figure 2). This crop growth model is similar to the one used by Luyten to estimate the food productivity. It includes climatic and soil characteristics and is applied at grid cell basis, here at 0.5° x 0.5°. To convert the theoretical yield to actual yield, a management factor is introduced. This management factor can be seen as a weighting factor for the losses due to non-optimal biomass agricultural practices, and is based on empirical values as described in literature (Alcamo et al., 1998 and IMAGEteam, 2001). For the simulation of the management-based productivity, a constant management factor of 0.7 is assumed in this study, see Figure 2.

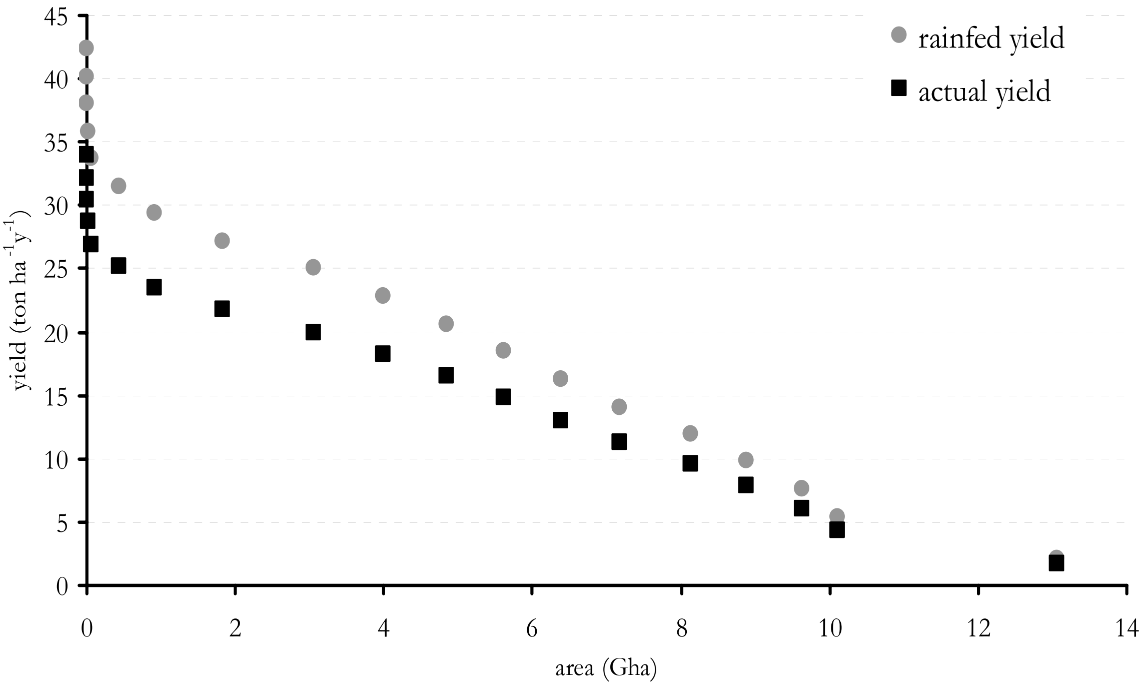

Figure 2: Global average yield of woody short rotation crops, based on (IMAGEteam, 2001).

The graph in Figure 2 shows decreasing yields with decreasing soil and climate quality. So the highest productivity is assumed to be found for energy plantations of the 'dedicated fuel supply systems', the lower for plantations at degraded land. Taking Figure 2 as a basis for the yield assumptions on both surplus agricultural land and degraded land, a range of 10 - 20 ton $ha^{-1}y^{-1}$ for surplus agricultural land and 1 - 10 ton $ha^{-1}y^{-1}$ for degraded land is used in this study for the year 2050. These figures are consistent with future yield assessments presented in literature (Hall et al., 1993; Swisher and Wilson, 1993; Johansson et al., 1993 and Williams, 1995). It is to be noticed that our estimate is based on the assumption of no improvements of the production system on the long term, (i.e. we assume a constant management factor). This may be conservative, see Chapter 3.

3.4 Summary of the potential of energy crops

The area potentially available for energy crop production ranges from 0 and 3.7 Gha. 2.6 Gha could be available on a global scale for the moderate diet in a low population growth scenario (see Tables VI and VII). This may be a reasonable set for establishing the upper limit and is used in the final figure in Section 6 and considered more realistic than the vegetarian diet applied on a global scale. The degraded area potentially available for energy crop production may lie between 430 and 580 Mha. Using the upper level of productivity of energy crops on these land types and a higher heating value (HHV) of 19 GJ, this results in a primary potential for energy on surplus agricultural area of 0 – 988 EJ y^{-1} and for degraded land of 8– 110 EJ y^{-1}.[9]

4. The potential supply of biomass residues

4.1 Agricultural residues (Category III)

The availability of agricultural residues depends on food and fodder production (see Section 3). The residues are either field based or process based (primary or secondary, see Figure 1). The availability of field-based residues depends on the residue to product ratio and on the production system. Most studies included in the overview of (Berndes et al., 2003) assume that about 25% of the total available agricultural residues can be recovered (Johansson et al., 1993; Swisher and Wilson, 1993; Williams, 1995; Yamamoto et al., 1999 and. Hall et al., 1993) presents the potential of agricultural residues based on this assumption, respectively 14 EJ y^{-1} and 25 EJ y^{-1}. The potential contribution of crop residues is assessed by Lazarus (1993) at 5 EJ y^{-1}. Fischer and Schrattenholzer (2001) have assessed the crop residue potential for five crop groups: wheat, rice, other grains, protein feed, and other food crops similar to Hall. The contribution of crop residues is 27 EJ y^{-1} in their high potential assessment and 18 EJ y^{-1} in their low potential assessment. Hence, the range of primary agricultural residues we include in this study varies between 5 and 27 EJ y^{-1}.

Secondary or process-based residues are residues obtained during food processing, like bagasse and rice husk. This has to be derived from the production of crops that produce valuable secondary residues and from the residue fraction available after processing these crops. Of the secondary residues, only bagasse has been included by some studies in the overview. It is assumed that all bagasse can be recovered and used for energy applications (Williams, 1995; Yamamoto et al., 1999; Hall et al., 1993; Johansson et al., 1993). Based on these assumptions, the total potential of secondary residues is assessed at 5 EJ y^{-1}.

Hence, the range of total agricultural residues included in this study varies between 10 and 32 EJ y^{-1}.

4.2 Forest residues (Category IV)

Hall (1993) assumed that 25% of logging residues plus 33% of mill and manufacturing residues could be recoverable for energy use (total 13 EJ y^{-1}). Yamamoto and the RIGES scenario gave higher figures, i.e. 50% harvesting residues and 42 % sawmill residues in the developing regions (Yamamoto (1999)) and 75% in developed regions (Yamamoto et al., 2001; Johansson et al., 1993); this results in a forest residue contribution of 10 - 11 EJ y^{-1}, for the year 2025. However, this figure is assumed for the lower limit in this study for the year 2050. Lazarus assumes that the forest residues availability could increased from 0 to 16 EJ y^{-1} over a 40 year period (Lazarus, 1993).

Hence, the range of forest residues included in this study varies between 10 EJ y^{-1} and 16 EJ y^{-1} depending on the recoverability of the residues and the productivity of the forests.

4.3 Animal residues (Category V)

One can consider animal residues as dung and slaughter residues. Here we only include dung. The available amount of dung depends on the number of animals and the requirement of manure as fertiliser. Wirsenius has assessed the total current average (1992-1995) amount of manure produced annually at 46 EJ y^{-1} (Wirsenius, 2000). Several studies have assumed that 12.5% (Hall et al., 1993) to 25% (Swisher and Wilson, 1993; Williams, 1995; Yamamoto et al., 1999; Johansson et al., 1993) of the total available manure can be recovered for energy production. With the figure of Wirsenius the net available amount would be 6 – 12 EJ y^{-1}. For scenario simulations with IMAGE 2.1 (SRES A1b and B1), it is assumed that the number of animals may increase annually with 1% from 1990 to 2050. Thus, if we assume that the manure production per animal is constant over time, the amount of animal residues may increase also with 1% per year. This results in a range of 9 to 19 EJ y^{-1}. Other studies that have included the growth of animals and manure production resulted in assessments of 25 EJ y^{-1} (Johansson et al., 1993) and 13 EJ y^{-1} (Williams, 1995) annually available for energy production.

Hence, the availability of energy from animal manure included in this study ranges from 9 EJ y^{-1} to 25 EJ y^{-1}, depending on the animal growth and the recoverability of the residues.

4.4 Organic waste (Category VI)

The availability of organic waste for energy use depends strongly on variables like economic development, consumption pattern and the fraction of biomass material in total waste production. Several studies on the primary biomass energy potential have considered the theoretical availability of organic waste for energy purposes. The RIGES (Johansson et al., 1993) and the LESS-BI scenario (Williams, 1995) have assumed that 75% of the produced organic urban refuse is available for energy use. Furthermore, it is assumed that the organic waste production is about 0.3 ton capita^{-1} y^{-1}, resulting is 3 EJ y^{-1}. Dessus et al. (1992) have assumed in their assessment of the biomass energy potential in 2030 that the urban waste production could be between 0.1 and 0.3 ton per capita (less developed regions and developed regions), resulting in 1 EJ y^{-1}. Hence the range of organic waste could vary from 1 – 3 EJ y^{-1}.

5. Bio-material production (Category VII)

The biomass use for materials ('biomaterials') is analysed in more detail, since it can be an important competing application of biomass for energy. Production of bio-materials can make sense from an energy and CO_2 point of view because use of biomass can have a double benefit: its use can save fossil fuels by replacing other materials (e.g. oil feedstock in the petrochemical industry) and waste bio-materials can be used for energy and material recovery. In case bio-materials can be recycled several times before energy recovery (e.g. in the case of construction wood and for pulp and paper), the material and energy savings may even increase further. Often, the quality of the waste materials poses constraints for recycling, resulting in down-cycling. In such a case, biomass is used in a cascade of applications, energy recovery being the final step in the cascade.

The use of biomass for materials in industrialized countries varies widely. Wood is currently used for building and construction materials. Rubber and natural fibres such as cotton are examples of important materials crops. The use of biomass for materials can be expanded to new applications. For example, biomass can be used further as a carbon neutral alternative for coal and coke in the iron and steel industry. Biomass can also be used as a renewable carbon feedstock in the production of synthetic organic materials such as basic chemicals, plastics, paint and solvents (de Feber and Gielen, 2000).

The future demand for bio-materials depends on the present demand for materials, the expected annual growth of this demand, the market share of bio-materials and the biomass use per unit of bio-material product. The present global wood production (sawnwood and wood-based panels) is 600 million m^3 according to the FAO statistics (FAO, 2001). In order to make a projection for the potential future biomass demand for material applications we assume the following: the projected growth for wood is assumed to be 3% based on historical trends presented by the FAO (ECE/FAO, 2000). The expected growth for pulp is related to the growth in GWP of 3%, based on SRES scenarios of the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic, 2000). The demand for cotton and rubber is based on historical trends in FAO statistics (resp. 4% and 3% growth) (FAO, 2003).

The data for the potential use of biomass as feedstock in the petrochemical industry are based on Gielen and Yagita (Gielen and Yagita, 2002). For the year 2020 this potential is assessed at 550 Mton. To assess the demand for 2050, this number is assumed to increase annually with 2%. The total demand for materials is converted to areas using average oven dry ton yields for the production of biomass. The assumptions and results are shown in Table VIII. The global potential biomass demand for materials in the year 2050 is calculated at about 4335-6084 Mton y^{-1}, 83 - 116 EJ y^{-1}.

Table VIII: Demand projections for biomaterials (de Feber and Gielen, 2000)

Type of material	Current prod. (Mton y^{-1})	Yearly growth (%)	Potential product demand (2050) (Mton y^{-1})	Market share bio-materials (%)	Biomass use per ton product[a]	Global potential biomass demand (Mton y^{-1})	Yield[b] (ton $ha^{-1}y^{-1}$)	Land use (Mha)[c]
Pulp [d]	175	3	307	100	1.7	511	10	51
Petrochemicals	200	2	398	5 – 100	2.5	50-996	10	5-100
Wood	350	3	1756	100	2	3512	10	351
Sawn wood			*975*			*1950*		
Woodboard			*781*			*1561*		
Crude iron[e]	550	1	1274	5 – 100	0.7	89-892	10	9-89
Cotton	20	4	142	100	1	142	2	71
Rubber	7	3	31	100	1	31	2	15
Total	1300		3338			4335-6084		503-678

[a] Indication of required biomass per product (ton biomass per ton product). When producing construction wood for example, 50% can be lost during sawing.
[b] Various land types (ranging from cropland to grassland) and crop types (e.g. woody crops, cotton and rubber) are assumed for yield figures.
[c] Based on assumed yield and the required biomass for biomaterial production.
[d] It is assumed that the share of recycled products increases from 40% in 2000 to 60% in 2050.
[e] It is assumed that the share of recycled products is 30% over the whole time period.

In case cascading is applied, the primary biomass demand for materials decreases. Maximum cascading can be obtained when all wood residues from building and construction are used for petrochemicals, pulp or charcoal for iron production. In this case (maximum cascading), the demand for biomaterials can be reduced to 820-2570 Mton (325-230 Mha). Part of this biomass returns as process residue, e.g. black liquor in the pulp and paper industry and processing waste in petrochemical industry and construction materials. We assume an upper limit for residue availability of 0.5 ton residue per ton pulp (HHV of 18 GJ ton^{-1}), and 0.25 ton residues per ton bio-material for the other materials (HHV of 19 GJ ton^{-1}) and a lower limit of no residues available. This is similar as studies presented in Section 4.2. This results in an extra amount of organic waste of bio-materials that becomes available of 32 EJ y^{-1}. The bulk of the land required for bio-materials production is woodland. As a consequence the impact of a bio-materials strategy on surplus agricultural land use will to a large extent depend on the future intensity of forest use.

6. Integration and discussion

6.1 Integration

The final range is composed by two extreme possible combinations (Table IX). The first combination, the overall lowest limit of the biomass potential, is composed of the lowest figure in categories I, II and the upper limit of category III, V and VI, minus the upper limit of the bio-materials. It is assumed that bio-materials compete for the energy crops, as well as the residues. Therefore, the potential processing residues from bio-materials (32

EJ y^{-1}) are added to category VI. The highest range is based on the most optimistic estimates (opposite figures). Furthermore, it is assumed that no bio-materials are used. This results in a range for the potential of primary biomass of 0 – 1130 EJ y^{-1}. The highest figure implies a potential of energy on surplus land and degraded areas at 988 EJ y^{-1} and 110 EJ y^{-1}. The lowest figure is caused by low numbers for energy crop potential and high figures for bio-materials.

Table IX: Contribution of each category to the global site potential

Category	Remarks	Potential bioenergy supply in EJ y^{-1}
I: Biomass production on surplus agricultural land	Available area 0 – 2.6 Gha, yield energy crops 10 – 20 ton $ha^{-1}y^{-1}$	0 – 988
II: Biomass production on degraded lands.	Available area 430 – 580 Mha, yield 1 – 10 ton $ha^{-1}y^{-1}$	8 – 110
III: Agricultural residues	Estimate from various studies	10 – 32
IV: Forest residues	The (sustainable) energy potential of the world's forest is unclear. Part is natural forest (reserve). Range is based on estimate from various studies.	10 – 16 (+ 32 from bio-materials waste)
V: Animal manure (dung)	Estimates from various studies	9 – 25
VI: Tertiary residue (organic waste)	Estimates from various studies	1 – 3
VII: Bio-materials	This depends highly on demand for bio-materials. Area 416 – 678 Mha. This demand should come from categories I and II.	Minus (0) 83 – 116
Total		0– 1130

6.2 Discussion

This study has aimed to explore the ranges of the geographical potential of biomass energy on the longer term. Six supply options are identified and one competing option; (biomass for material applications). By taking these potential supply options into account, we have included the main possible biomass resources. The categories are described independently, i.e., interactions between categories are not taken into account in an integrated matter. Two extreme scenarios have been used. Using this approach, the transparency of the results is high and therefore insight in influential factors is increased.

The high estimate for energy crop is a result from the high estimate of surplus agricultural area assessed in this study. This range can be explained by several factors:

1. It is assumed that all surplus agricultural (and degraded land) can be used for energy farming whereas other estimates only use part of the surplus area.
2. The assumed future food consumption is low compared to other studies. The FAO for example assumes 13.0 MJ day $^{-1}$ person^{-1} in 2030 (FAO, 2000) while IMAGE simulations with baseline A and B, as developed by the RIVM (Alcamo et al., 1998), assume an energy intake from agricultural products in 2050 of respectively 15 and 14 MJ day^{-1} person^{-1}. Based on Luyten (Luyten, 1995) we use a figure of 11.7 MJ day^{-1}

person^{-1}. Assuming a further increase of energy intake will not change our results, as with the present upper limit, already no surplus agricultural land has been assessed. However, it can be a signal that even the assumed moderate diet might be rather low compared to other studies.

3. The assumed agricultural yields of the HEI system (highest figure) are high compared to present yields and historical yield growths. The yields from the HEI system can only occur if the present yield increases 2% per year. Between 1990 and 1999 the global average yield increased by only 1% per year.

We are aware of the uncertainties accompanying the input data and assumptions. Some assumptions have been discussed above. The result of the biomass production on surplus agricultural land depends furthermore highly on the assumed yield of energy crops that may be considered conservative and to the assumed security factor. However, results of the biomass production on surplus agricultural area are not sensitive to the assumed share of irrigated area.

7. Conclusions

The study presented analyses ranges of the global potential of primary biomass for energy on the long term. It is stressed that this study is explorative. The focus is not on the exact figure of the biomass energy potential, rather on the underlying factors influencing this potential. The analysis shows that the future geographical potential of biomass energy ranges from nill to 1135 EJ y^{-1}. The result is mainly determined by the potential of energy farming that is the result of land availability and biomass productivity. The biomass productivity, assumed to range from 10 – 20 ton ha^{-1} y^{-1}, is mainly determined by local factors, like soil quality, climate, water availability and management factors. However, the upper limit requires higher energy inputs. At this point energy balances of the biomass production should be studied. The land availability is determined by the land requirements for food demand. This is a function of the future diet, population growth, but most important, the food production system (e.g. HEI vs. LEI system and meat and dairy production methods). In order to achieve high biomass energy potentials, considerable transitions are required in the agricultural system, especially in the way meat and dairy products are being produced. Application of high production levels implies that the knowledge available in the western countries is diffused world-wide (e.g. in developing countries in particular, the present efficiency of cattle breeding and food production is relatively low). This requires transfer of capital and adaptation of production technologies to local conditions. However, this might be a difficult task: ‘although the time horizon of fifty years encompasses two generations, the feasibility to achieve ‘best technical means’ world-wide may be doubted’ (Luyten, 1995).

As indicated by the lowest range, a shortage of agricultural land may also occur, e.g. when the world population and food intake increase sharply (the latter accompanied by a high share of meat and dairy products) and the agricultural technology development stagnates. Due to interactions between food/forest products supply systems and energy, a high demand for food/forestry products results in less available land for energy farming (Category I and II). However, more residues are coming available (Category III and IV). Nevertheless, the net impact is a significant reduction of the bio-energy potential.

Hence, from this study, one can conclude that the range of biomass potential is large, ranging from nill – 1135 EJ y^{-1}. To what extent biomass can contribute to the primary energy consumption, depends on crucial factors:

1. Population growth, economic development, global diet, and so food demand
2. The efficiency of the production of food (e.g. HEI versus LEI food production system).
3. Yield of energy crops on surplus agricultural area and degraded land.
4. Future developments of competing products, like bio-materials, and competing land use types, e.g. other applications of surplus agricultural area and degraded land.

These figures imply that in order to release this amount of biomass, considerable transitions are required. Particularly in the way meat and diary products are being produced in developing regions. Large-scale implementation of biomass could only be possible under affluent diet consumption if the global average productivity per hectare increases. Hence, sustainable development policies could on the one hand meet economic development policies in improving the efficiency of the food production system. On the other hand they could diverge if extensive food production systems and biomass for energy are both pushed on a large scale.

CHAPTER THREE

POTENTIAL OF BIOMASS ENERGY UNDER FOUR LAND-USE SCENARIOS. PART A: THE GEOGRAPHICAL AND TECHNICAL POTENTIAL[#]

Abstract

Various scenarios have resulted in high estimates of biomass energy in the future energy system. The availability of the resources is an important factor if high shares of biomass penetrate the electricity, heat or liquid fuel market. We have analysed the geographical and technical potential of energy crops for the year 2050-2100 for three land-use categories; at abandoned agricultural land, low-productive land and 'rest land', i.e. remaining no-productive land. We envisaged these future development paths using four scenarios resulting in different future land-use patterns, developed by the IPCC in its Special Report on Emission Scenarios (SRES): A1, A2, B1 and B2. The geographical potential is defined as the product of the available area for energy crops and the related productivity level for energy crops. The geographical potential at abandoned agricultural land is the largest contributor. For the year 2050 the geographical potential at abandoned land ranges from about 130 to 410 EJ y^{-1}. For the year 2100 it ranges from 240 to 850 EJ y^{-1}. The potential at low-productive land is negligible compared to the other categories. The rest land area is assumed to be partly available, resulting in ranges of the geographical potential from about 35 to 245 EJ y^{-1} for the year 2050 and from about 35 to 265 EJ y^{-1} in 2100. At a regional level, significant potentials are found in the Former USSR, East Asia and South America. The geographical potential can be converted to transportation fuels or electricity resulting in ranges of the technical potential for fuels in the year 2050 and 2100 equal to several times the present oil consumption. Similar applies for the technical potential of biomass electricity.

[#] Submitted to Global Environmnetal Change. Co-authors are: André Faaij, Bas Eickhout, Bert de Vries and Wim Turkenburg. We are grateful to Pita Verweij of the Utrecht University and Bart Strengers of the RIVM for their comments on earlier drafts and to Lex Bouwman of the RIVM for his support with the exclusion factor for the grazing systems.

1. Introduction

Biomass has been used for energy purposes since millennia. It still is the main energy source in a number of countries and regions (e.g. Bhutan 86%, Nepal 97%, Asia 16%, East Sahelian Africa 81% and Africa 39% (RWEDP, 1997; Amous, 1999; Lefevre et al., 1997)). Dominating the use of biomass energy in these countries is firewood for cooking and heating. Part of this traditional biomass use is considered to be not sustainable, as it may contribute to land degradation, sometimes even desertification. Furthermore, one of the major problems of traditional biomass use for heating and cooking is the negative impact on the indoor air quality (Holdren and Smith, 2000).

The modern use of biomass is distinguished from the traditional use of biomass energy. The terminology of modern biomass is often used for primary biomass being converted into high-quality energy carriers, like electricity and biomass liquid fuels for transportation. Examples of modern biomass use are the ethanol production in Brazil from sugarcane (Moreira and Goldemberg, 1999), the Combined Heat and Power (CHP) district heating programs in Austria and Scandinavian countries (Turkenburg, 2000), and co-combustion of biomass in conventional coal based power plants in the Netherlands (AEA Technology, 2001). Of the total consumed biomass energy in 1998, estimated at 45 ± 10 EJ y^{-1}, about 7 EJ y^{-1} is considered modern biomass (Turkenburg, 2000).

Modern biomass energy is expected to gain share in the future energy market, because the production and conversion costs of biomass energy are expected to be reduced, the resources are widely available and because there is an expected increase in the demand for CO_2 neutral fuels. Various studies assume penetration levels of biomass in the future energy system in the order of 10% to about 50% of the total primary energy demand (Berndes et al., 2003; Lashof and Tirpak, 1990; Lazarus, 1993; Johansson et al., 1993; Fischer and Schrattenholzer, 2001; Nakicenovic, 2000; Williams, 1995; Shell, 1995). To what extent biomass will penetrate future energy markets depends on various aspects, e.g. the availability of the resources, the costs of primary biomass, the development of conversion technologies, the cost of converted biomass energy and implementation, social and/or institutional factors. Examples of the latter are installation constraints like license requirements, noxious smell and investment rates. Also of importance are the demand for energy carriers and the costs of other energy sources.

In this study we analyse the availability of the resources. Technical, economic and social factors are included as driving forces for the land-use system. Previously, many biomass energy potential assessments have been conducted at a global scale (see Berndes et al. (2003) for an overview). However, most studies are conducted at a high aggregation level, i.e. at level of regions. Except for the studies conducted by Fischer and Schrattenholzer (2001) and Sørensen (1999), the studies have not included spatial distribution of the biomass available for energy and are limited to primary biomass resources only.

Furthermore, the studies are not always transparent in the procedure for calculating energy potential; they do not present insight in factors that are important for the potential. None of the studies have included a detailed link with the use of land for other activities like supply of food and timber, whereas this competition has a high influence on the potential to grow biomass for energy as was calculated in Chapter 2. In Chapter 2 we have addressed these issues at a highly aggregated geographical scale (global). From this approach, interesting conclusions could be drawn. The potential availability of primary biomass for energy is influenced by:

1. the demand for food as a function of population and diet consumed;
2. the food production system that can be adopted world-wide, taken into account the water and nutrient availability;
3. productivity of forest and energy crops;
4. (increased) use of bio-materials;
5. other competing options for land-use like for nature development.

Because of the development of these variables over time, and the spatial distribution of the resources, a potential assessment that integrates food demand and supply at a detailed geographical level can supply new insights in the spatial and time dynamics of the potential of biomass for energy.

The objective of this study is to assess the geographical and technical potential of biomass energy. The focus lies on the geographical potential, which is assessed taking into account the use of land for other purposes, like production of food and timber. In this study we conduct a global and regional geographical biomass energy potential assessment based on investigations at grid cell level (0.5° x 0.5°)[5] integrated with the simulation of food, feed and timber demand and supply over time at grid cell level. This assessment includes various interactions between population dynamics, technology change and the land-use pattern. The simulation is conducted over time, using a timeframe to 2100. For the assessment of the technical potential, regional assumptions regarding the conversion efficiencies are made.

We use the IMAGE 2.2 model (Integrated Model to Assess the Global Environment) as the main framework for our analysis. The IMAGE 2.1 model was used to develop the B1 marker scenario (de Vries et al., 2000) of the SRES scenarios for the IPCC (Nakicenovic, 2000). The IMAGE 2.2 model was used to implement all four main SRES scenarios with more focus on the land-use system than in the IPCC report. Results and methodology are published and shown at a CDRom (IMAGEteam, 2001). The geographical and technical potential of biomass for energy is assessed in the context of the IMAGE 2.2 implementation of the four SRES scenarios that differ regarding aspects like population, GDP, social behaviour (e.g. diet, rate of self-reliance) and technology change. Given the four SRES storylines, factors like demand and supply of food and forestry products can be quantified. This output of the scenarios is taken as input for the analysis of the potential of biomass for energy in this study.

We start with a description of the approach and the boundaries of this study (Section 2). In the third section the modelling framework and the scenarios that are used in the assessment are described. Section 4 describes the assessment of the land availability and crop productivity of energy crops. The results of the geographical potential are described in Section 5. In Section 6 the approach for the technical potential assessment is described and the results are given. The results are discussed, including a sensitivity analysis and a comparison with previous studies in Section 7. A discussion and the conclusions are presented in Section 8.

2. Definitions and system boundaries

2.1 Categories of potentials

We distinguish five categories of potentials using a similar division as the wind energy potential assessment study of the Utrecht University published in 1993 and 1994 (van Wijk and Coelingh, 1993; World Energy Council, 1994).

- The theoretical (available) potential: the theoretically upper limit of primary biomass; i.e. biomass produced at the total earth surface by the process of photosynthesis (EJy^{-1}).
- The geographical potential: The theoretical potential at land area available for the production of biomass for energy ($EJ\ y^{-1}$).
- The technical potential: the geographical potential reduced by losses due to the process of converting primary biomass to secondary energy carriers ($EJ\ y^{-1}$).
- The economic potential: The technical potential that can be realised at profitable levels, depicted by a cost-supply curve of secondary biomass energy ($EJ\ y^{-1}$).
- The implementation potential: The maximum amount of the economic potential that can be implemented within a certain timeframe, taking (institutional) constraints and incentives into account ($EJ\ y^{-1}$).

The estimation of the theoretical potential of biomass energy is based on productivity assumptions for energy crops. The data required for the calculation are presented in Section 4 and results are presented in Section 5. The focus of this study is, however, on the **geographical potential** of primary biomass energy and on the **technical potential**

[5] To get a feeling for the order of magnitude, there are about 66 000 onshore cells at this resolution. At the equator, one grid cell covers an area of 3025 km^2. The Netherlands (about 4.2×10^4 km^2) is represented by about 15 cells.

of biomass for transportation fuels or electricity. The economic potential is assessed in Chapter 4.

2.2 Description of primary biomass categories

We only consider terrestrial options to produce biomass[6]. One can distinguish two main categories of primary biomass: residues, e.g. forest and agricultural residues, and energy crops. The competition and synergism of various primary biomass sources are shown in Figure 1. Residues or waste streams become available both at the point of harvesting and when processing food or forest crops (respectively field and processing residues). The residues can for instance be used for fibres, fodder, and fertiliser (see Figure 1). Residue flows can also be used for energy. The final type of residues (waste) becomes available after a delay. This can be several months, but also years. Examples of biomass from dedicated energy plantations are short rotation wood (e.g. willow, poplar or eucalyptus), sugar or starch containing crops (e.g. sugarcane or maize) or herbaceous grass (e.g. switchgrass or miscanthus).

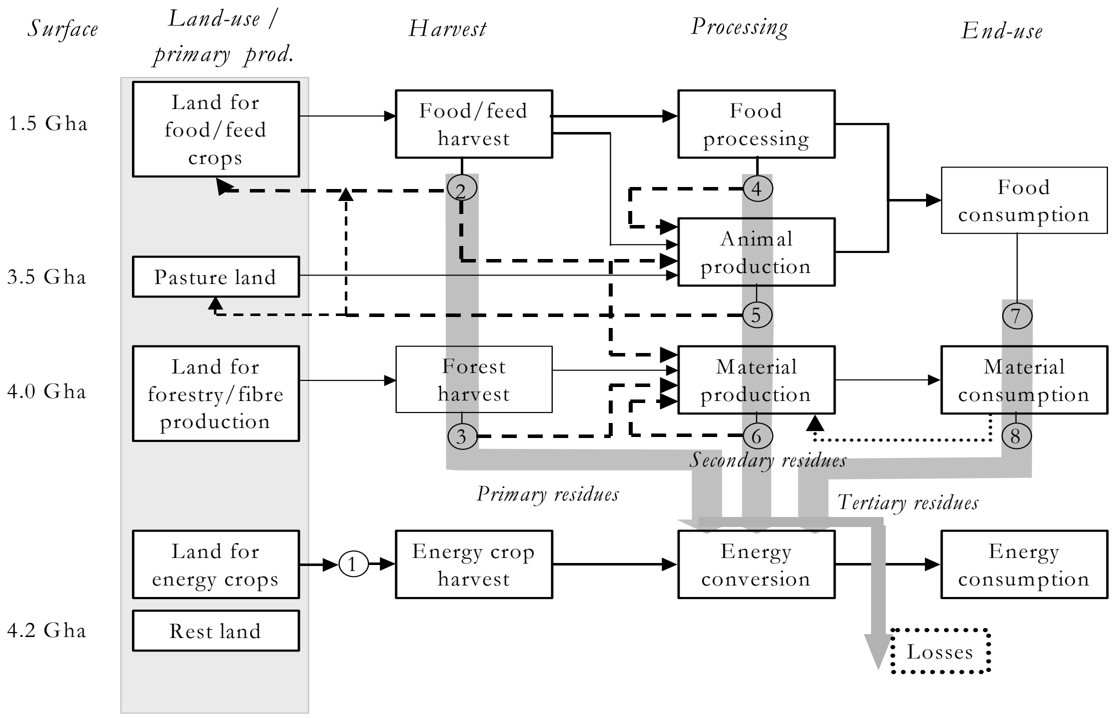

Figure 1: Overview of various present types of biomass flows and the global land surface, based on: (van den Broek, 2000 and Wirsenius, 2000). The black arrows indicate the main product flows, whereas the dotted lines show potential non-energy applications of various residue categories. The thick grey arrows represent the potential energetic use of the resources (1 = energy crops, 2 = agricultural residues, 3 = forest residues, 4 = food processing residues, 5 = animal manure, 6 = material processing residues, 7 = food consumption waste; 8 = non-food consumption waste).

[6] Regarding aquatic biomass, we consider the knowledge of the availability and productivity of this resource as limited, therefore, we exclude of this type of primary biomass.

2.3 Restriction to woody energy crops

From Figure 1 we have seen the complexity of the competition and synergies among the various types of biomass energy sources. Including all types of sources would require a comprehensive dynamic model that simulates the food and forest demand and supply integrated with the simulation of the demand and supply of alternative applications for the produced biomass, e.g. materials, fertilisers and fodder. The IMAGE 2.2 model does not simulate material or fodder flows in such comprehensive way that synergism and competition can be studied. Models that focus more on the interaction between material flows and biomass for energy have been published by Fujino et al. (1999; Gielen et al., (2000); Yamamoto et al. (2001). However, these models do not include the full dynamics of land-use integrated with food and timber demand and supply spatially explicit. Therefore, the available land for energy crop potential cannot be computed (dynamically) in relation with food and forestry demand and supply over time with the use of these models. Results of assessments of the potential of residues are shown in Table I. Compared to traditional biomass energy use, the potential of residues is in the same order or considerably higher.

Table I: Estimates from the literature on the global (geographical) potential of biomass residues for energy.

Source[a]	Types of residues[b]	Biomass residue potentially available (EJ y^{-1})			
		Year			
		1990	2020-2030	2050	2100
1	FR, CR, AR		31		
2[c]	FR, CR, AR, MSW		30	38	46
3	FR, MSW		90		
4					272
5	FR, CR, AR, MSW			217-245	
6		88			
7[c]	FR, CR, AR, MSW		62	78	
8	FR, CR, AR		87		

[a] 1: (Hall et al., 1993); 2: (Williams, 1995); 3: (Dessus et al., 1992); 4: (Yamamoto et al., 1999); 5: (Fischer and Schrattenholzer, 2001); 6:(Fujino et al., 1999); 7:(Johansson et al., 1993); 8 (Swisher and Wilson, 1993).
[b] FR = forest residues, CR = crop residues, AR = animal residues, MSW = municipal solid waste
[c] These studies rather estimated the potential contribution, instead of the potential available.

Here, we focus in more detail on the geographical potential of energy crops. A focus on energy crops is considered sensible as previous studies have concluded that the geographical potential from the residues flows is in most of the timeframe (significantly) lower than the geographical potential of the energy crops, e.g. (Johansson et al., 1993; Williams, 1995; Dessus et al., 1992; Yamamoto et al., 2001). Energy crops are further divided in three categories specified in more detail in Section 4.

We restrict ourselves to one energy crop category (see Figure 1): woody biomass grown in short rotations. First of all, this is due to the fact that there is plentiful experience with short rotation forestry for the pulp and paper industry. Furthermore, woody biomass can be converted into all types of secondary energy carriers. Although we use woody crops to investigate the geographical potential of energy plantations at a global scale, we acknowledge that in tropical regions higher productivity levels can be expected when herbaceous crops are used (Hall et al., 1993). The species of energy crop is not specified further in this study. It is assumed that mostly indigenous crops are used. Within the IMAGE 2.2 model productivity of energy crops is parameterised in a generic way, by assuming optimal photosynthesis efficiency (e.g. optimal water use efficiency) at grid cell level. For moderate climates a typical crop is probably willow or poplar. In more tropical climates, eucalyptus is often the most suitable perennial woody biomass crop.

2.4 Restriction of conversion technologies.

Biomass can be converted to a number of secondary energy carriers (electricity, gaseous, liquid and solid fuels and heat) using a wide range of conversion routes. Here we focus on conversion to electricity and liquid transportation fuels, as these are large-scale options that can be considered in a generic manner. The conversion routes to fuels and electricity can be distinguished in thermal, chemical and biochemical conversion routes (see for an overview of present technologies e.g. (Turkenburg, 2000; van den Broek, 2000)). For conversion to electricity, co-combustion of biomass in coal-fired power plants is at present the most applied technology. However, only low shares of biomass can be co-combusted. For the future, gasification of biomass in combination with power generation using combined cycle is expected to reach high efficiency levels and lower electricity production cost and is included in this study (Williams and Larson, 1993; Faaij et al., 1998; Turkenburg, 2000).

Transportation fuels from biomass are at present mainly derived from sugar- or starch-containing crops (e.g. ethanol from sugar cane or maize) (Moreira and Goldemberg, 1999). From lignocellulosic crops, advanced technologies are the conversion via gasification to methanol and hydrogen, the conversion to ethanol using a hydrolyses and fermentation step and the conversion to larger hydrocarbon fuel as Fisher-Tropsch (Schulz, 1999; Tijmensen et al., 2002; Lynd, 1996). In this study we simulate the advanced fuel conversion technologies in a generic way taking data that apply both for Fischer - Tropsch and ethanol. These conversion technologies are presently not commercially available, however, for the long term (~2050), the chosen technologies are considered interesting according to their projected technology and cost developments (Faaij et al., 2000; van Hooijdonk, 2002; Tijmensen et al., 2002; Lynd, 1996; Turkenburg, 2000).

3. Methodology, framework, scenarios and main assumptions

The geographical potential (G_i) is defined as the amount of primary biomass that can be produced for energy purposes at available land areas. The available land is land remaining after satisfying regular demand for food and forestry products, corrected for biodiversity losses, for nature development and land required for animal grazing or physically not suitable for energy crops. The latter competing land-use options are included in the land-claim exclusion factor (a_i). The geographical potential of biomass from energy crops can be expressed as (see also Figure 2):

$$G_i = \sum_{i=1}^{n} A_i \cdot a_i \cdot Y_i \cdot MF \qquad (1)$$

In which G_i is the geographical potential of biomass from energy crops in grid cell i (EJ y^{-1}); A_i is the area in grid cell i (km^2); a_i is the land-claim exclusion factor for energy crop production in grid cell i (-) which accounts for the competing land-use options; Y_i the harvested rainfed yield of energy crops in grid cell i (GJ $ha^{-1}y^{-1}$) and MF is the management factor representing the development of the management and technology (-). This management factor is similarly defined as the management factor for food crops used in the land-cover model of IMAGE 2.2.

Figure 2 indicates the approach to assess the geographical potential. The role of the IMAGE 2.2 model (Alcamo et al., 1998; IMAGEteam, 2001) is explicitly illustrated in Figure 2. The IMAGE 2.2 model is run assuming that there is no demand for energy crops to generate land-use patterns that apply for forestry demand and food demand over time. The available land for energy crops is derived from this run. Furthermore, the productivity of energy crops is simulated in the IMAGE 2.2 model. These two outcomes are combined outside the framework of the IMAGE 2.2 model to estimate the geographical and technical potential of biomass energy (see Figure 2). The IMAGE 2.2 model, the SRES scenarios, the land-claim exclusion factor and the management factor for energy crops are described below. The assumed efficiency for the assessment of the technical potential is given in Section 6.

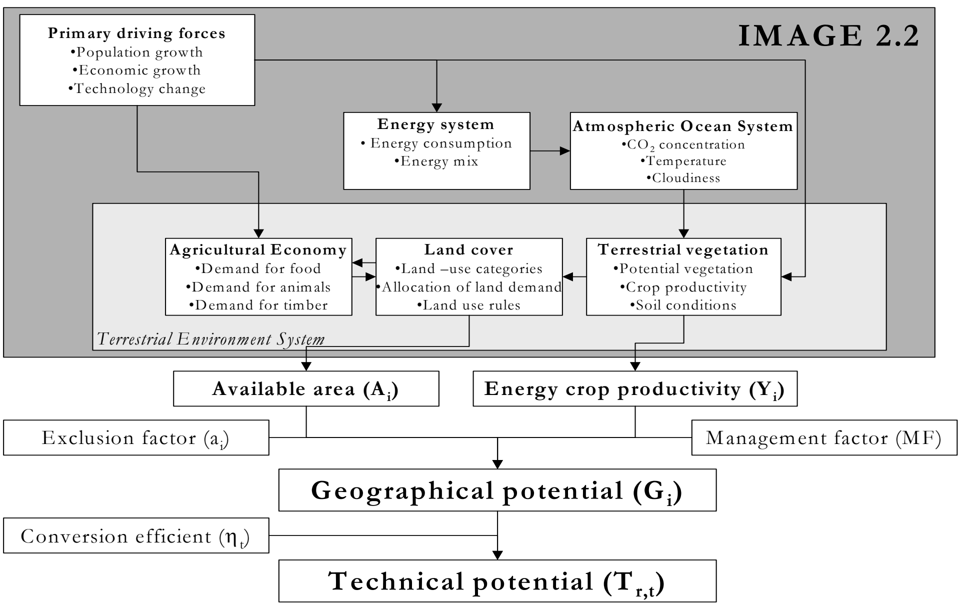

Figure 2: The key elements for the assessment of the geographical and technical potential of energy crops using the IMAGE 2.2 model.

3.1 The IMAGE 2.2 model: the Terrestrial Environment System (TES)

The objective of IMAGE 2.2 is to explore the long-term dynamics of global environmental change. The model consists of several linked modules. Within IMAGE 2.2 the world is divided in 17 regions: Canada, USA, Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, OECD Europe, Eastern Europe, Former USSR, Middle East, South Asia, East Asia, South East Asia, Oceania, Japan. As main driving forces economic and demographic trends for the 17 regions are used. Regional energy consumption, conversion of energy technological improvements, energy efficiency improvements, fuel substitution, supply and trade of fossil fuels and renewable and nuclear energy technologies determine energy production, energy use and emissions of greenhouse gases, ozone precursors and sulphur. Ecosystem, crop and land-use modules are used to compute land-use on the basis of regional consumption, production and trading of food, animal feed, fodder, grass and timber, and local climatic and soil properties. GHG emissions from land-use change, natural ecosystems and agricultural production systems and the exchange of CO_2 between terrestrial ecosystems and the atmosphere are simulated. The atmospheric and ocean models calculate changes in atmospheric composition by employing the emissions and by taking oceanic CO_2 uptake and atmospheric chemistry into consideration. Subsequently, changes in climatic properties are computed by resolving oceanic heat transport and changes in radiative forcing due to changing concentration of GHGs and aerosols. The impact models involve specific models for sea-level rise and land degradation risk and make use of specific features of the ecosystem and crop modules to depict impacts on vegetation.

Simulations by the IMAGE 2.2 model are conducted for the time frame 1970 – 2100. Historical figures (1971-1995) are used to calibrate the model. The model runs at a geographical grid cell level of 0.5° x 0.5°, longitude, latitude. A detailed description of the IMAGE 2.2 model can be found in Alcamo et al. (1998) and IMAGEteam (2001).

In this study we use the terrestrial system of IMAGE 2.2 (Leemans et al., 2002; Alcamo et al., 1998) that deals with the demand and production of land-use products like food and forestry products. The Terrestrial Environment System (TES) is included in Figure 2 and consists of three parts: the Agricultural Economy model, the Terrestrial Vegetation Model and the Land-Cover Model. The Land-cover model of IMAGE 2.2 simulates changes in land-cover on a terrestrial grid (0.5° x 0.5°) until regional demands for land-use are satisfied. The main input to the Land-cover model comes from the Agricultural Economy Model and the Terrestrial Vegetation Model.

1) **The Agricultural Economy part** simulates the regional demand for food (including meat and fodder) and timber. It is described in Strengers (2001). The demand for food and feed are based on the demand of 7 vegetable and 5 animal food products. As such,

about 70% to 80% of the food intake is covered. The remaining part of the diet (e.g. fish and fruit) is assumed to be a fixed fraction over time. Generally food consumption patterns change along with economic growth; with increasing incomes in developing countries, a higher share of animal products is assumed. In developed countries, more or less stable shares of animal products in the human diet are assumed. Population growth determines the total volume of the regional demand. The competition among food commodities in the model is not based on monetary units. Instead, the Agricultural Economy Model uses land-use intensities as a proxy for the food production costs. These intensities indicate the amount of land needed to supply 1 kcal of the vegetative or animal product. For animal products the 'feed efficiencies', i.e. the efficiency of the conversion of feed to meat, is taken into account. This depends on the type of feed that is fed to the animals, i.e. crop residues versus high quality crops. In the IMAGE 2.2 model the percentage of high quality crops in fodder is related to GDP. The Agricultural Economy model makes use of so-called 'utility functions', which return a utility-value for a given diet. This utility function is optimised and its maximum value is achieved at the point where the demands are equal to the so-called preference levels. These preference levels are determined by the calibration of the model over the years 1971-1995 using data of the FAO.

The level of food trade is determined in IMAGE 2.2 by exogenous Desired Self-Sufficiency-Ratios (DSSRs). DSSRs are defined for each region and each food product as the ratio between production and consumption[7]; for exporting regions the DSSR exceeds 1.0. Total exports are added to a 'global basket', which is available to the importing regions. The DSSR values of importing regions (DSSR < 1.0) are used as scaling factors to allocate food from this global basket, so that global exports equal global imports (IMAGEteam, 2001). The quantification of the DSSRs for the scenarios is described in Section 3.2. The final result of the Agricultural Economy model is the desired production of food crops and grass and fodder in each region in any year.

2) **The Terrestrial Vegetation part** simulates the consequences of changes in atmospheric CO_2 concentrations and climate on natural vegetation patterns, on the terrestrial carbon cycle, and most importantly on the crop productivity influencing the land-cover pattern. The productivities for 12 food crops are calculated in the crop growth model of IMAGE 2.2 as presented in Figure 3. The crop production model (Leemans and van den Born, 1994) is based on the FAO Agro-Ecological Zones Approach (FAO, 1981). This model calculates 'constraint-free rainfed crop yields' accounting for local climate and light attenuation by the canopy of the crop considered. The climate-related crop yields are adjusted for grid-specific conditions by a soil factor with values ranging from 0.1 to 1.0. This soil factor takes into account three soil quality indicators: (1) nutrient retention and availability; (2) level of salinity, alkalinity and toxicity; and, (3) rooting

[7] This approach is for instance also used in Leach (1995).

conditions for plants. The crop growth model is calibrated using historical productivity figures.

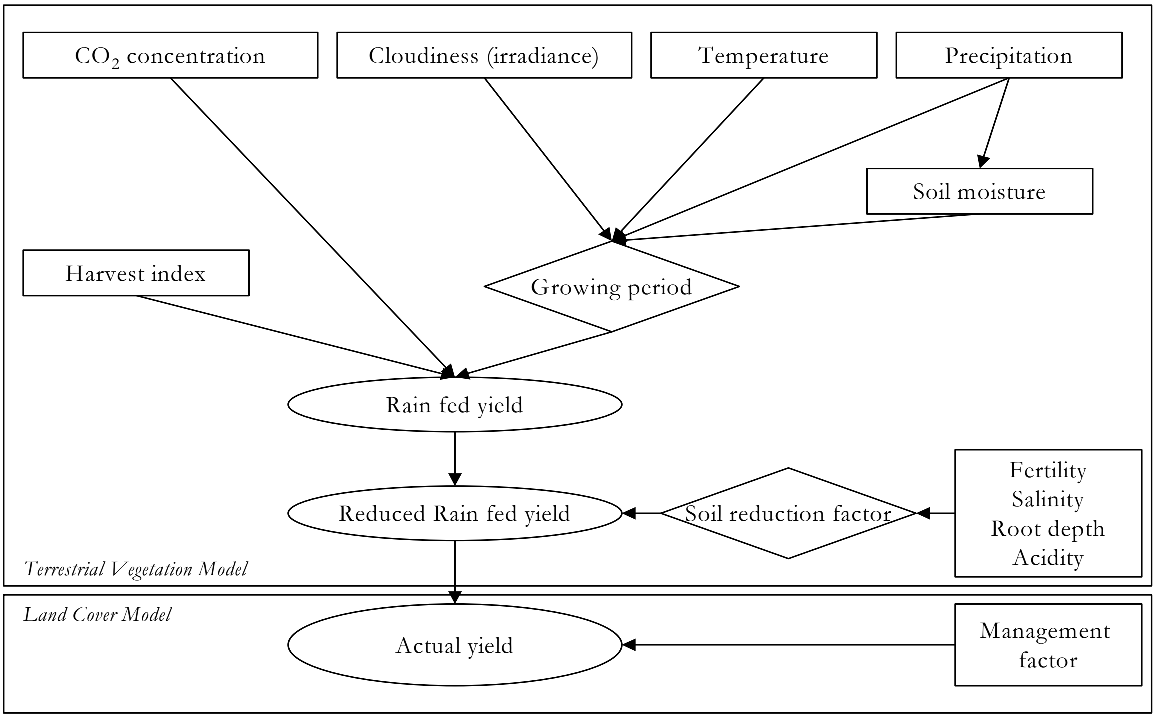

Figure 3: schematic representation of the simulation of land productivity within the IMAGE 2.2 model, based on (Leemans and van den Born, 1994).

3) **The Land-Cover part** simulates the spatial changes in land-cover transformation by reconciling the demands for land-use products (from the Agricultural Economy part) with the potential of land (from the Terrestrial Vegetation part). It differentiates 19 land-cover types [8] and allocates these land-cover types over the global terrestrial surface. A key aspect of the Land-cover model is that it uses a crop- and regionally-specific management factor (MF) to represent the gap between the theoretically feasible crop yields simulated by the Terrestrial Vegetation model, and the actual crop yield which is limited by less than optimal management practices, technology and know-how. If nutrients are applied optimally, there is sufficient weeding at the plantation and the harvest is optimal, the management factor reaches a value of 1. Irrigation, improvement in the harvest index (see Figure 3) and biotechnological developments can increase the management factor further to values above 1. Regional management factors are used to calibrate the model to regional estimates of crop yields and land-cover for the period 1970-1995 from FAO (FAO, 2003). For years after 1995 the management factor is a scenario variable, which is generally assumed to increase with time as an indication of the influence of technological development on crop yields. The allocation of land-use types is done at grid cell level.

[8] The land-use types distinguished in the IMAGE 2.2 model are: Agricultural land; Extensive grassland; Tundra; Temperate deciduous forest; Savannah; Wooded tundra; Warm mixed forest; Tropical woodland; Boreal forest; Grassland and steppe; Tropical forest; Cool coniferous forest; Hot desert; Temperate mixed forest; Scrubland; Ice; Regrowth forest (abandoning); Regrowth forest (timber)

Among these land-cover types are agricultural land and forest areas. Land-use transformations are in reality influenced by forces of a social, physical and economic origin. These forces are too complex to be integrated in a dynamic way in the IMAGE 2.2 model. As a proxy, the allocation of land-use types in the IMAGE 2.2 model is based on several criteria or logical rules. These are considered as simplifications of the complexity of the real forces that can be encountered due to the demand and supply of land. The Land-cover model explicitly deals with four land-cover transitions:

1. natural vegetation to agricultural land (either cropland or pasture) because of the need for additional agricultural land;
2. agricultural land to other land-cover types because of the abandonment or unsuitability (under climate change) of agricultural land;
3. forests to 'regrowth forests' because of timber and fuelwood extraction;
4. one type of natural vegetation to another because of climate change and/or increased water use efficiency.

The Land-cover model allocates the agricultural demand (including wood demand), grid cell by grid cell within each region, giving preference to cells with the highest crop production potential for satisfying this demand. The preference ranking of grid cells is based on 'land-use rules'. Grid cells are given a higher ranking for agricultural production if they:

1. are close to existing agricultural land or fallow forest land;
2. have high potential crop productivity;
3. are close to large rivers or other water bodies.

Furthermore, an extra factor is introduced that allocates a random value at grid cell level. For timber 'land-use rules' 1 and 3 are used. Instead of rule 2, IMAGE 2.2 uses the biomass production per unit area in the form of stems and branches, as computed by the Terrestrial Carbon model.

The food or feed crops are allocated to grid cells of the type agricultural land. In each grid cell, various types of crops can be allocated, with preference to the productivity levels. The specific crops are allocated within the agricultural cell according to their crop productivity (Alcamo et al., 1998). The land-cover model results in land-cover allocation of all 19 land-cover types at grid cell level.

3.2 The quantification of the SRES Scenarios of the IPCC

The assessment of the geographical potential of biomass for energy is conducted within the context of four different scenarios for the development of the society. We have chosen to use four scenarios published by the Intergovernmental Panel on Climate Change (IPCC) in the Special Report on Emissions Scenarios (SRES) (Nakicenovic, 2000) as implemented with the IMAGE 2.2 model (IMAGEteam, 2001). The four scenarios are constructed using four storylines. The storylines describe different social, economic, technological, environmental and policy developments. Basically the four scenarios ('stories') are constructed along two dimensions, i.e. the degree of globalisation versus regionalisation, and the degree of orientation on material versus social and ecological values (see Figure 4). The four scenarios do not have a particular order and are listed alphabetically and numerically, i.e. A1[9]; A2; B1; B2. Figure 4 shows the most important assumptions regarding food demand and supply made in each scenario.

Material/economic

	A1	**A2**
	Food trade: maximal	Food trade: low
	Consumption of meat: high	Consumption of meat: high
	Technology development: high	Technology development: low
	Average management factor for food crops: 2050: 0.82; 2100: 0.89	Average management factor for food crops: 2050: 0.78; 2100: 0.86
	Fertilisation of food crops: very high	Fertilisation of food crops: high
	Crop intensity growth: high	Crop intensity growth: low
	Population: 2050: 8.7 billion; 2100: 7.1 billion	Population: 2050: 11.3 billion; 2100: 15.1 billion
	GDP: 2050: 24.2 $\cdot 10^3$ billion $\$_{95}$ y^{-1}; 2100: 86.2 $\cdot 10^3$ billion $\$_{95}$ y^{-1}	GDP: 2050: 8.6 $\cdot 10^3$ billion $\$_{95}$ y^{-1}; 2100: 17.9 $\cdot 10^3$ billion $\$_{95}$ y^{-1}
Global oriented		***Regional oriented***
	B1	**B2**
	Food trade: high	Food trade: very low
	Consumption of meat: low	Consumption of meat: low
	Technology development: high	Technology development: low
	Average management factor for food crops: 2050: 0.82; 2100: 0.89	Average management factor for food crops: 2050: 0.78; 2100: 0.89
	Fertilisation of food crops: low	Fertilisation of food crops: low
	Crop intensity growth: high	Crop intensity growth: low
	Population: 2050: 8.7 billion; 2100: 7.1 billion	Population: 2050: 9.4 billion; 2100: 10.4 billion
	GDP: 2050: 18.4 $\cdot 10^3$ billion $\$_{95}$ y^{-1}; 2100: 53.9 $\cdot 10^3$ billion $\$_{95}$ y^{-1}	GDP: 2050: 13.6 $\cdot 10^3$ billion $\$_{95}$ y^{-1}; 2100: 27.7 $\cdot 10^3$ billion $\$_{95}$ y^{-1}

Environment/Social

Figure 4: The assumptions related to food demand and supply for the four scenarios considered in this study.

In Figure 5 the demand for food over time on a daily per capita basis used in the SRES scenarios is compared with figures from other sources (FAO, 2000;Sørensen, 1999; Rosegrant et al., 2001; Luyten, 1995; Döös and Shaw, 1999; Leach, 1995). The values found in these literature sources range widely, up to 35%. The variation between the scenarios is less significant, about 6%. Food intake assumed in our scenarios does not exceed the boundary levels found in the literature. This intake is assumed to increase about 20% (A2) to 28% (B1 and A1) over the 100-year period.

[9] We use the parameters of the A1b scenario; see (Nakicenovic, 2000)

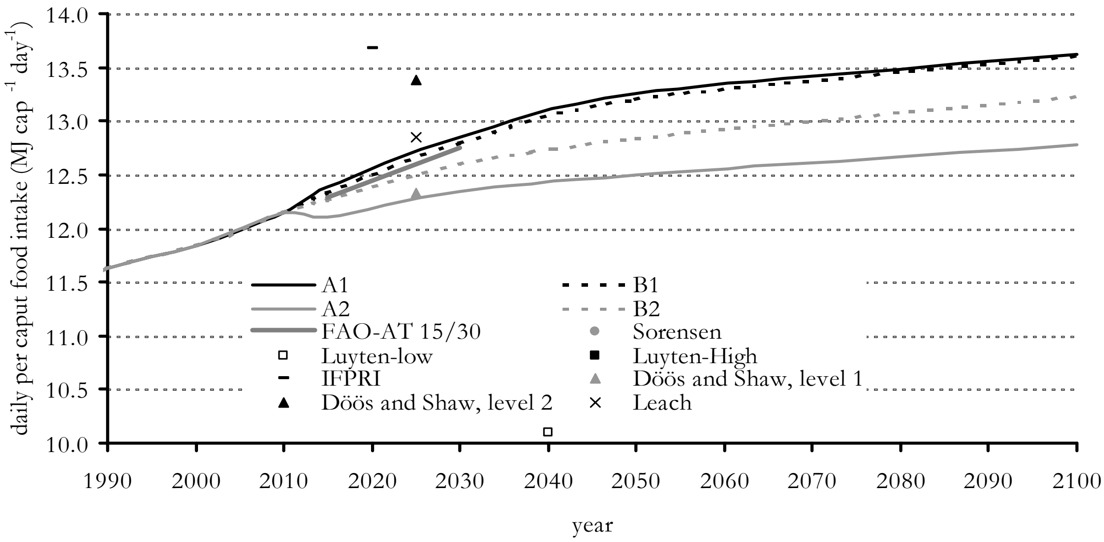

Figure 5: Estimates of the daily caloric food intake per capita over time used in this study compared with values suggested in the literature (for references, see text).

3.3 Land availability (A_i): different categories of land for energy plantations

At present many short-rotation energy forestry projects are - or are expected to be - implemented at land not required (anymore) for food. This can be degraded land or abandoned agricultural land (Rosenqvist et al., 2000; van den Broek et al., 2000; Perlack et al., 1995; Silva de la Maza, 1998). Furthermore, there are assessments of short rotation forestry on savannah land (Kgathi and Sekhwela, 1998). In this study we distinguish three categories of land available for energy plantations: 1. abandoned agricultural land, 2. low-productive land and 3. 'rest land' which is the remaining area further corrected for the grassland area, the forest land, the urban area and the bioreserves. This 'rest' land includes mainly savannah, shrubland, and grassland/steppe. These categories are based on the assumption that the production of energy crops should not effect food and forestry production, nature reserves or biodiversity and animal grazing. Furthermore tundra area is excluded as it is considered to be unsuitable for energy crop production. Dessert areas are not excluded, however as land productivity is about zero, it is not visible in the overall outcomes. This would not be the case for tundra areas.

To determine the geographical potential, IMAGE 2.2 is first run over time for the four SRES scenarios. In these runs the demand and production of food and forestry products are determined (see also Figure 2). The land available per category described above is taken from this run:

1) If within a scenario a grid cell is converted from agricultural land to natural vegetation in IMAGE 2.2 – agricultural land is abandoned – it is labelled 'abandoned' and assumed to be excluded for food production. This amount is added to a pool of abandoned agricultural land area for the rest of the timeframe (2100). Agricultural land can be abandoned because of surplus cropland or because of a decrease in suitability of the soil due to climate change.

2) We have assumed that low-productive areas have a productivity of energy crops below 3 ton ha^{-1} y^{-1}; about 5% of the maximum yield[10]. Before we include the area, we check if this area is not used for agricultural land in the IMAGE 2.2 model.
3) The final category is the area 'rest land' which includes the remaining land, excluding forest areas, bioreserves tundra and agricultural land.

3.4 The land-claim exclusion factor

Another factor determining the geographical potential, next to land availability is the land-claim exclusion factor (a_i in Equation 1). This factor indicates the percentage of land not available for biomass energy production. It is difficult to quantify the exclusion factor, as the empirical basis for various competing land-use options is weak, in addition these factors are judged differently for the four scenarios. This is comparable with assumptions regarding available land when estimating the geographical potential of wind turbines or of photovoltaic modules (Chapters 5 and 6). We have chosen to correct for the claims for which quantification was found in literature. We exclude land-use claims for a) nature development and b) urbanization; we introduce land-use specific exclusion factors as a reduction factor for c) cattle grazing on extensive grassland. Furthermore, d) we correct for remaining factors that are valid at rest land, like biodiversity and water resource distortion, losses of areas for nomads, etc. The consequences of this factor are addressed in the discussion.

a) Nature development:

At present, the amount of protected areas world-wide is almost 10% of the global terrestrial area (World Commission on Protected Areas (WCPA), 2000; Kemp-Benedict et al., 2002). The nature reserves included in the IMAGE 2.2 model amount 6% of the global terrestrial land area. There are initiatives to extend the protected areas, for instance via the establishment of a global network of protected areas. This would link various isolated areas to improve the vitality of the ecosystem (World Commission on Protected Areas (WCPA), 2000). At a global level the area required for nature conservation is assessed to be in the range of 10-20% of the world's land area (German Advisory Council on Global Change (WBGU), 1999). This means an increase of 0-10% compared to the present protected areas and an increase of about 5% to 15% compared to the values included in the IMAGE model at 6%. We assume 5% for the more economically oriented scenarios (A1 and A2) and 15% for the more ecologically oriented scenarios (B1 and B2). It is furthermore assumed that nature development occurs on each land-use category.

b) Urbanisation:

The built environment is at present about 2% of the global land area. Future increases are expected because of urbanisation and population growth (United Nations Population

[10] The maximum yield of woody biomass is set in IMAGE 2.2 at 55.8 ton $ha^{-1}y^{-1}$ based on optimal photosynthesis and respiration of the crop.

Division: Department of Economic and Social Affairs, 2002). The built environment has been simulated in the Global Environmental Outlook (UNEP, 2002). Results show figures of the built environment in the year 2030 ranging between 3% and 4% of the world's land area, with the highest levels in the developing regions (UNEP, 2002). We use these data from the Global Environmental Outlook at a regional level and assume a change of the built environment as a linear function of the population growth at a regional scale. Urban areas are assumed to be established at the land-use categories also available for biomass energy crops.

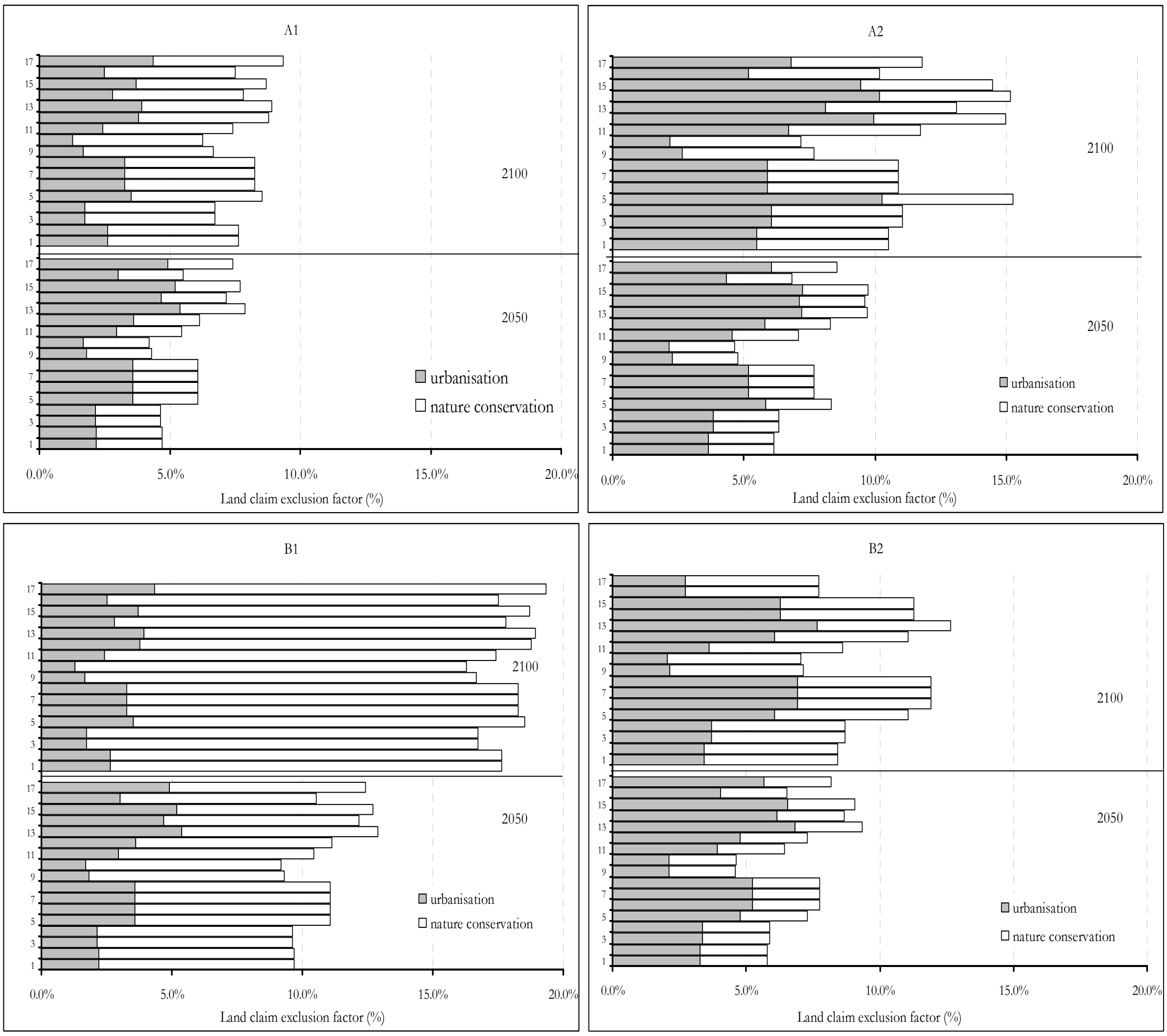

Figure 6: The estimated land-claim exclusion factor per region and scenario. These exclusion factors apply for all land-use types suitable for energy crops (1 = Canada, 2 = USA, 3 = Central America, 4 = South America, 5 = Northern Africa, 6 = Western Africa, 7 = Eastern Africa, 8 = Southern Africa, 9 = OECD Europe, 10 = Eastern Europe, 11 = Former USSR, 12 = Middle East, 13 = South Asia, 14 = East Asia, 15 = South East Asia, 16 = Oceania, 17 = Japan.).

In Figure 6, land-claim exclusion factors for urbanisation and nature development per region and scenario are given. It can be seen that the highest exclusion factor is found for

South and East Asia (India and China) due to high estimates for land required for urbanisation. The lowest exclusion factor is found for the Canada and Japan.

For the land-use specific exclusion factors following assumptions are made:
c) Cattle grazing on extensive grassland
Thus far, pasture areas have been far kept out of the analysis (included in agricultural land), as it is assumed that these areas are required for feed and cattle grazing. In the IMAGE 2.2 model, extensive grassland is also expected to be used for cattle grazing. The share is not further specified. The extensive grassland is included in the low-productive land category as well as in the rest land category. We use the results of Bouwman et al. (in prep) for the exclusion of the extensive grassland area required for cattle grazing. In their analysis they combined information on animal populations and production, feed conversion and the composition of animal feed, and geographical information on the distribution of grasslands. Their aim is to assess the use of different feed resources by ruminants and requirements of grazing land for two aggregated ruminant (cattle, buffaloes, and the small ruminants, i.e. sheep and goats) production systems, i.e. pastoral systems and mixed and landless systems on the basis of FAO (1996). The FAO (1996) provide data for animal populations and production for different production systems for the early 1990s and so on the production per ruminant category for each production system. The areas of grasslands distinguished by (IMAGEteam (2001) were subdivided into mixed and landless systems and pastoral systems. Pastoral systems depend almost exclusively on grazing, while in the mixed and landless systems the animals rely on cereals, other feed crops, crop residues, silage and grazing. Therefore, the efficiency of production (i.e., off-take rates and feed conversion) is generally lower in the pastoral systems than in the mixed and landless systems. Mixed and landless systems were assumed to occur in mosaics with arable land, while grid cells with pastoral systems have less or no arable land. The fraction of arable land in cells with mixed and landless production systems varies from one world region to another. This is to ensure that the production of feed crops and possibilities for disposal of animal waste as manure, required in mixed and landless systems, is available at short (<50 km) distance. This way pastoral systems are more remote from cities and densely populated areas, while the landless and mixed systems are closer to the markets and infrastructure needed to transport animal feedstuffs and livestock products. In most countries, part of the low-productive grasslands (with a rainfed productivity of <25% of the global maximum (IMAGEteam, 2001) was assigned to the pastoral systems. The remainder of the marginal grassland was considered to be natural grassland or grazing land with very low cattle densities, for example in nomadic systems. At a regional level, this results in an exclusion of all extensive grassland areas (OECD Europe, South Asia and Japan) to barely any exclusion of extensive grassland (Canada, USA, Central and South America, West and South Africa, East Europe and Oceania), in the other regions. Extensive grasslands are available for biomass production for 60 - 65% (North and East Africa, Former USSR and South East Asia) and 39% in East Asia and 17% in the Middle East.

d) Remaining exclusion factor for rest land

We have corrected the estimated available land for energy crops for nature development, urban area and animal grazing. However, it is expected that energy crops at the ' rest land' category have larger impact on vulnerable ecosystems and water resources and encounter more competing factors that limit the complete use of the area, like recreation and land required for indigenous population. The value of these land-claim exclusion factors is conceptually difficult to quantify because it cannot be measured, depends on personal values and is not generic over the world or the regions. The value is therefore to a large extent arbitrary. We propose scenario-dependent factors as the impact on biodiversity or water availability would be judged differently among the scenarios. A more stringent factor of 90% exclusion is proposed for the more ecological oriented scenarios (B1 and B2) and a land-claim exclusion factor of 50% is proposed for the more economically-oriented scenarios (A1 and A2). We will address this factor in the discussion again.

3.5 The management factor for energy crops

The productivity of energy crops is a function of environmental conditions like soil quality, water balance, and growing season, which in turn are dependent on climate conditions like temperature, precipitation and cloudiness. The rainfed productivity of energy crops is simulated in the IMAGE 2.2 model at grid cell level, shown in Figure 2 and 3. The technological improvement related to woody energy crops, like the use of fertilisations, is included in the management factor, shown in Figure 2 and 3 and incorporated by calculations outside the IMAGE 2.2 model (see Figure 2). Exogenously, the productivity can be improved in three ways: by an improvement of the photosynthetic efficiency (e.g. increasing the leaf area index), improvement of the harvest index, (e.g. the ratio of the total produced biomass and the harvested part), see Figure 3 and improvement of agricultural organisation and agricultural technology (Vleeshouwers, 2000). Vleeshouwers (2000) states that so far, the photosynthetic efficiency of food crops has not much improved over time. Since woody energy crops have already a high harvest index, the harvest index is also not expected to improve significantly. Vleeshouwers (2000) expects therefore that major improvements are to come from better management. In the literature, annual increases for global average yields for the time frame up to 2020 are estimated at about 1.1% to 2.6% and up to 2050 at about 1.2% to 1.6% (Vleeshouwers, 2000). For comparison, the global average annual increase from 1961 to 2002 for sugarcane, wheat, rice and coffee are respectively 0.66%, 2.26%, 1.82% and 0.94% (FAO, 2003). The average global management factor for woody biomass for the year 1995 was derived from the management factor of sugar cane assumed at 0.7 in the IMAGE 2.2 model. The assumed harvest index is 0.6, which is relatively low, compared to empirically values (e.g. Hoogwijk, 1998) The maximum average value of the management factor for agricultural crops in the IMAGE 2.2 model is about 1.3 for rice and maize for the B1 and A1 scenarios. Here, it is assumed that in the A1 scenario the technological development increases rapidly and also biotechnological developments are expected. We assume an upper limit of the management factor of 1.5 in this scenario. We assume an annual growth of 1.6%, which is the upper growth level assumed by Vleeshouwers (2000). The maximum management factor is reached in 2050. The B1 scenario is expected to reach levels that are lower as biotechnology is assumed to be less approved in this scenario. The upper level of the management factor is therefore assumed at 1.3. The growth rate is also assumed at 1.6%. For the B2 and A2 scenario, the technological development is expected to be less strong. We assume an upper level of the management factor of 1.1 and a growth rate of 1.2%, corresponding to the lowest growth rate found by Vleeshouwers (2000).

4. Results for land availability and energy crop productivity

4.1 Land availability

The results of the variation in the land-use pattern based on IMAGE 2.2 runs is given in Figure 7.

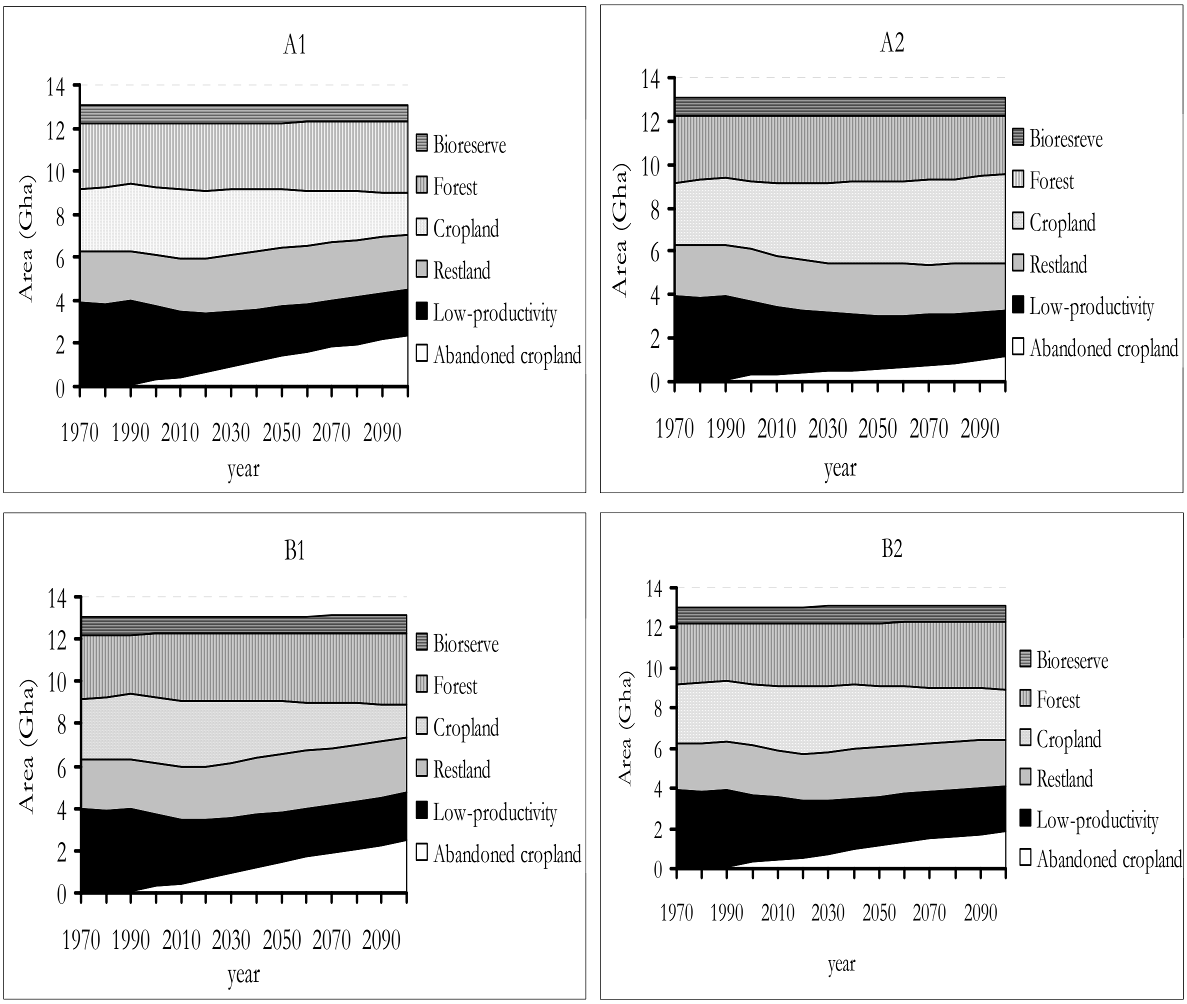

Figure 7: The simulated distribution of the land-use pattern, excluding the land-claim exclusion factor: agricultural land, forest land, grassland, low-productive land and rest land.

Category 1: Development of abandoned agricultural land

In all scenarios agricultural land is taken out of production, either because there is a surplus of agricultural land, or because of a decreased suitability due to climate change of land for food production. The abandoned agricultural land area is the highest in the B1 and A1 scenarios, mainly due to surplus agricultural land. In these scenarios population reaches its maximum in 2050 and technological advancement is assumed to increase relatively fast because of a high interchange of knowledge in the globalised world. The main difference between A1 and B1 is the higher meat consumption in A1 compared to B1 (about 16% points higher in A1 on a daily per capita basis in the year 2100), leading to slightly less abandoned land (2% in 2100). The high population growth and slow technological improvement in the A2 scenario clearly leads to the lowest estimate of available abandoned agricultural land.

Category 2: Development of low-productive land

The area of low-productive land is at least in the first half of the century much larger than the area of abandoned agricultural land. Most areas are extensive grassland and desert. Parts of these desert areas have very low productivity, down to zero. The extensive grassland is partly used for cattle grazing (see Section 3.4). The amount of low-productive land marginally decreases over time due to the increase in productivity as a result of the technological improvements (management factor) and of positive climate change feedbacks, e.g. by means of higher temperature and rainfall.

Category 3: Development of rest land

As can be seen from Figure 7, the category rest land, including savannah, extensive grassland, shrubland and (in this figure also) tundra land, is significant, amounting to about 2.5 Gha in the year 2000. The rest land category varies slightly over time. It increases slightly in the first half of the century and decreases slightly in the second half. Rest land can increase because low-productive land decreases in productivity and adds to the rest land category and tundra and savannah land is converted to forest area.

Summarising, the area from abandoned agricultural land in 2050 ranges between 10% of the total land surface of 13 Gha in the case of A1 (1.3 Gha) to 4% (about 0.6 Gha) in the case of A2. The high value is in the same order of magnitude as about 10% of the total terrestrial global area and the low value is about the area of the Middle East. For the year 2100, these areas are about doubled in all scenarios. The total rest land area is even larger, in the year 2050 around 2.3 Gha for the three scenarios, or about 18% of the total global area. What would be the impact on the land-use system if the abandoned agricultural land areas, the low-productivity and rest land is used for energy crop production? To get a feeling for the required area, we pictured the land-use pattern in the year 2050 of the world presenting these three areas in Figure 8 for four scenarios; A1, A2, B1 and B2.

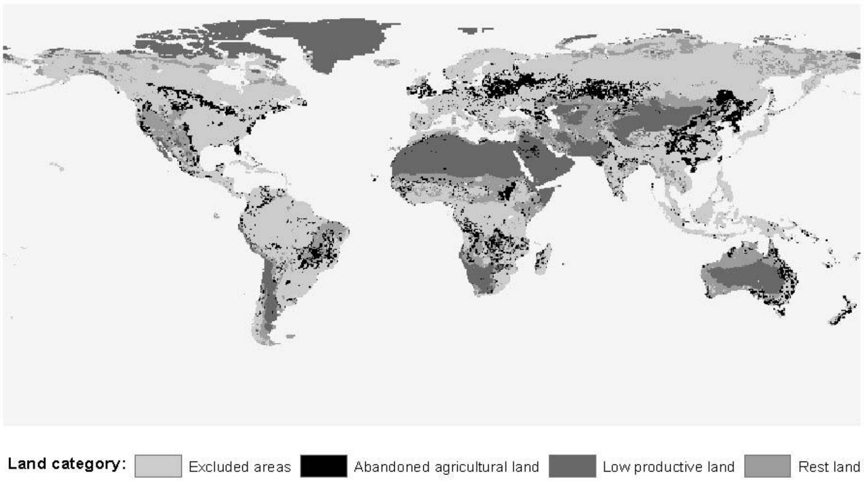

Figure 8: Scenario A1

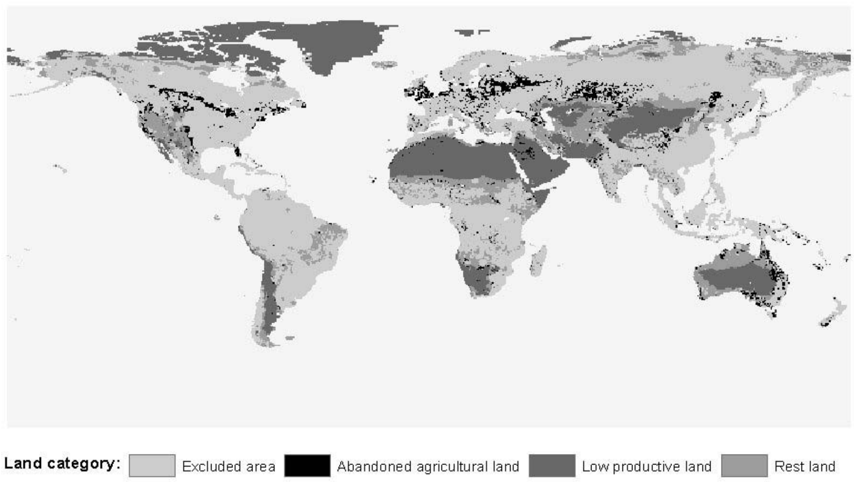

Figure 8: Scenario A2

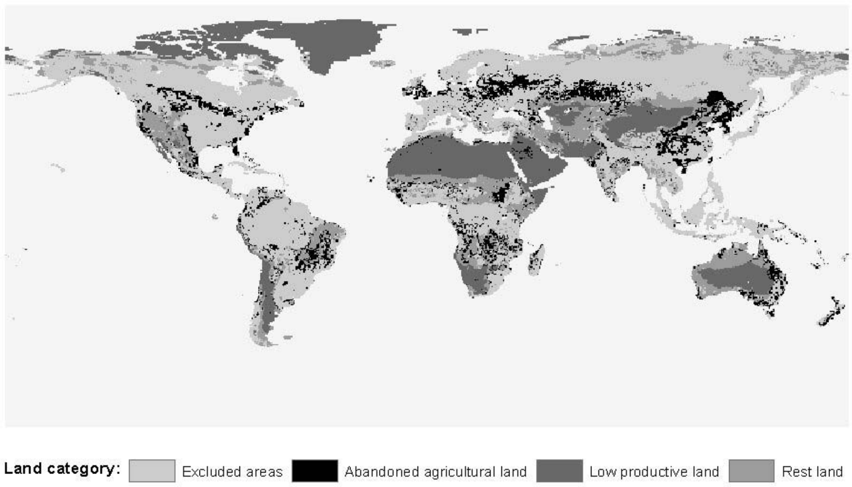

Figure 8: Scenario B1

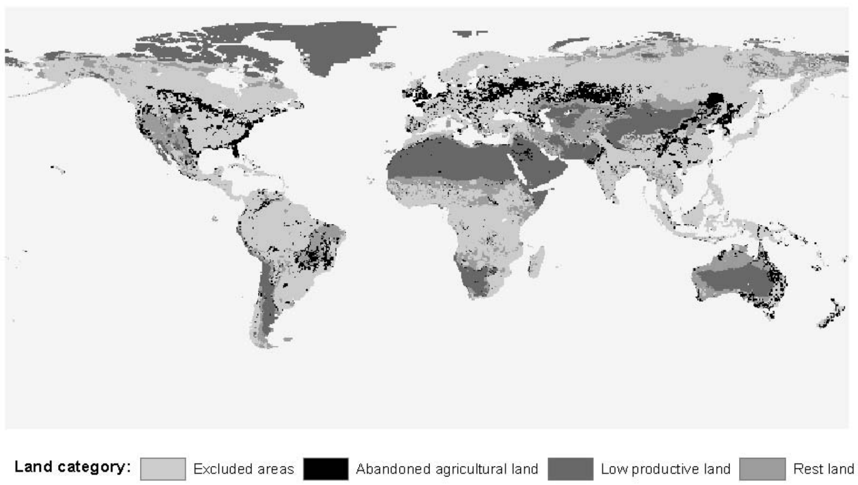

Figure 8: Scenario B2

Figure 8: The spatial distribution of the potentially available areas for energy crop as distinguished in this study: abandoned agricultural land, degraded land and rest land, for the A1, A2, B1 and B2 scenarios for the year 2050.

The forest area declines in the A2 scenario. As the abandoned agricultural land is assumed not to become available for agricultural or forest purposes after the area is abandoned, lost forest areas cannot be compensated. This does not occur in the other scenarios due to a lower demand for food and a higher food crop management factor compared to A2. In the A2 scenario, significant amount of forest area is cut down for the production of food or fodder (see Figure 9). The forest areas in the Middle East and Southern Africa completely disappear if abandoned agricultural land is not returned to forest land. The forest area in South America reduces significantly; about 45% in 100 year. Also a significant reduction is found in the default run (Figure 9). The forest areas in the Former USSR, Canada and Europe (East and OECD Europe) remain almost constant over time, which means that according to the IMAGE 2.2 simulations, the pressure on the land-use system, specifically forests does not increase significant in these regions. This should be seen in the context that in the A2 scenario the regions in Africa and South America have low shares of available abandoned cropland, as most abandoned cropland is found in the northern regions as OECD Europe, the Former USSR and the USA (see Figure 8).

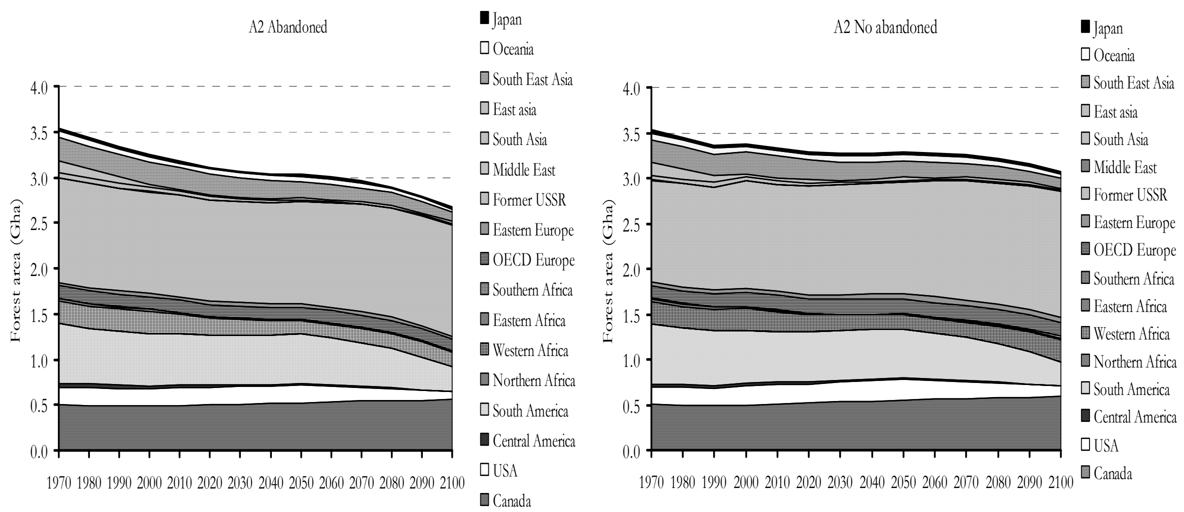

Figure 9: The forest area development over time as simulated by the IMAGE 2.2 model for the A2 scenario with and without the inclusion of abandoned agricultural land for energy plantation.

4.2 The productivity of energy crops

The productivity of energy crops for several land-use categories (land-claim exclusion factor is not applied) is shown in Figure 10. It is obvious that agricultural land results in overall higher productivity than low-productive land and to some extent rest land, as shown in Figure 10. Although the latter categories have a larger area, the geographical potential of growing biomass for energy purposes at these areas is less significant.

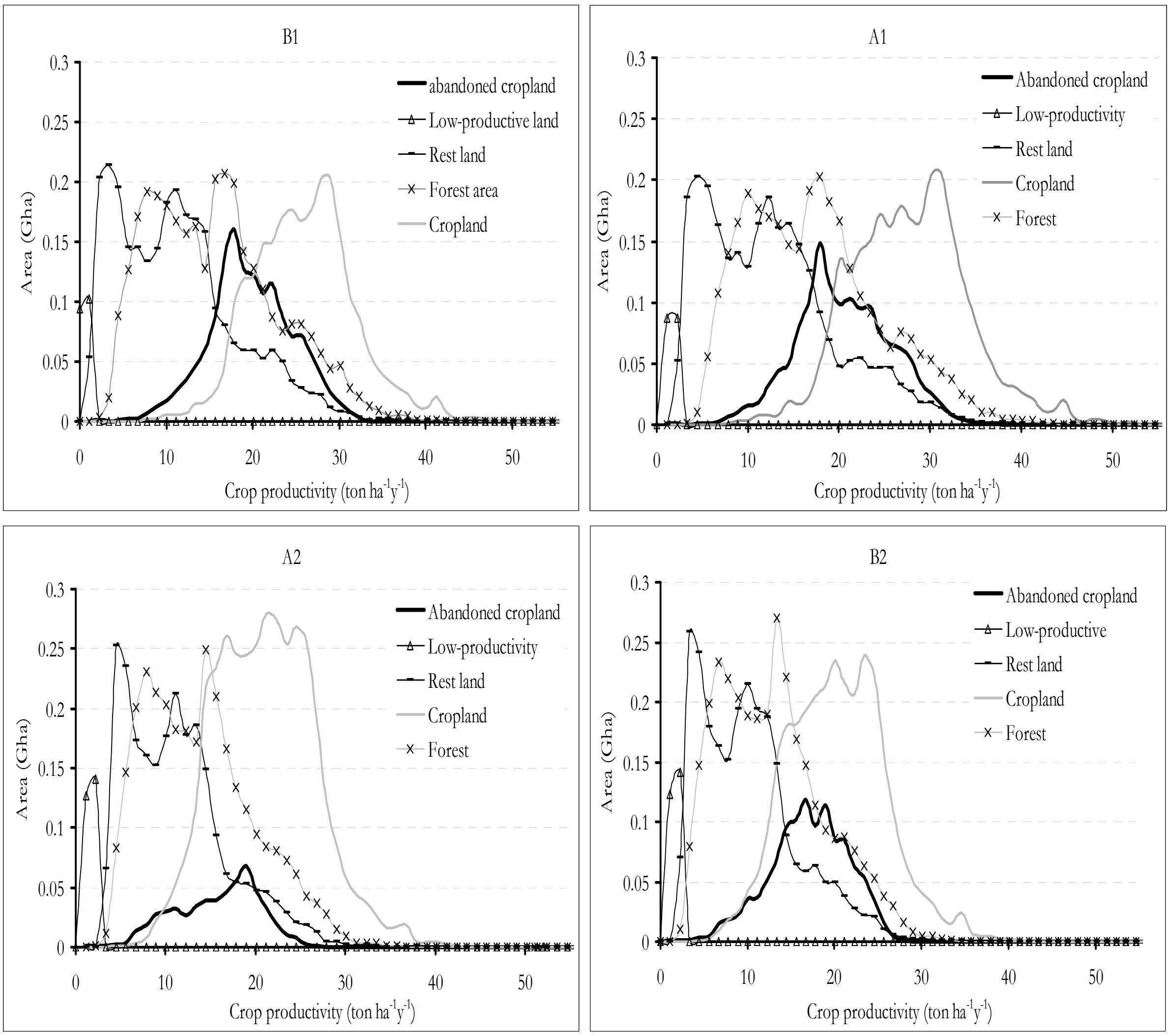

Figure 10: The simulated productivity (including the management factor) of woody biomass energy crops in 2050 at the total global terrestrial surface, excluding the land-claim exclusion factor, for four SRES scenarios per land-use category distinguished in our study[11].

The distribution of energy crop productivity over the globe (including agricultural land and forest areas) - as simulated by the IMAGE 2.2 model - is shown in Figure 11 for two scenarios: A1 and B2. The A1 scenario is chosen as it provides the highest productivity level and the B2 scenario as it provides the lowest one. The figure shows also the impact of CO_2 fertilisation in these scenarios on energy crop productivity. For the current situation, the two scenarios are identical. For the future situation productivity is simulated to increase significantly, although different for the two scenarios, mainly because of different assumptions regarding productivity improvement due to an improved management of the energy crop production system. The CO_2 fertilisation effect contributes only marginally.

[11] It should be noted that for illustrative reasons we have plotted the land productivity in the selected cells as a functional relationship with the area, whereas this is not correct. A more correct representation would have been a histogram.

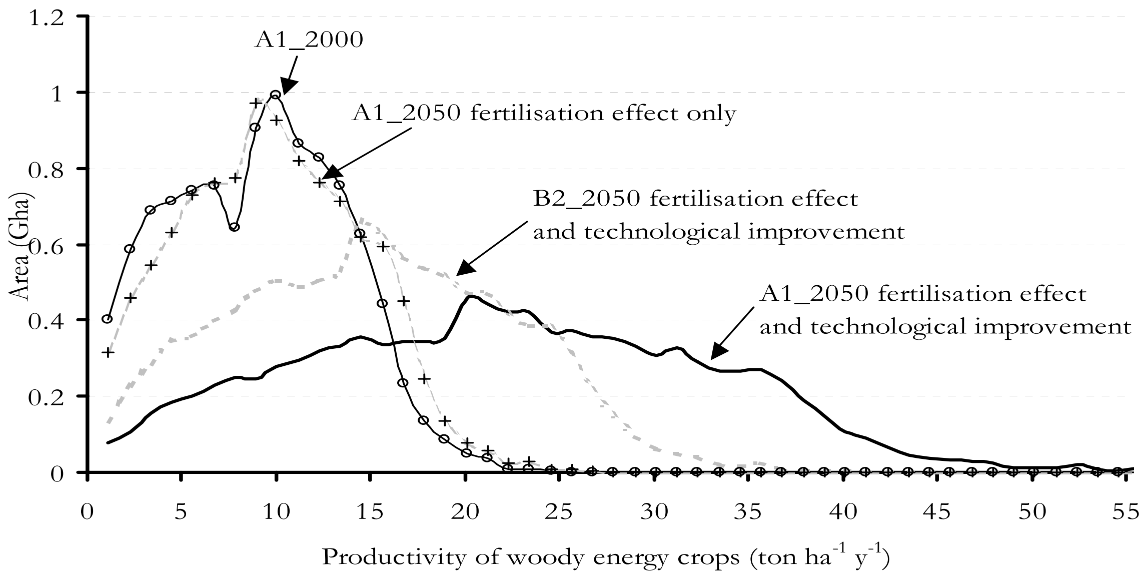

Figure 11: The simulated productivity of woody biomass energy crops at the total global terrestrial surface for two SRES scenarios (A1 and B2). A curve is given for both the current (2000) and future (2050) situation, with and without technological improvements taking into account CO_2 fertilisation effect.

5. Results for the theoretical and geographical potential

The results of the geographical potential are presented for all three categories of energy crops; however, we will elaborate mostly on energy crops at abandoned agricultural land.

5.1 The theoretical potential of biomass energy

The theoretical potential of biomass energy is assumed to equal the total amount of energy crops at the total land surface. Hence, the theoretical potential for the situation in 2050 of biomass for energy is taken from Figure 12. Using these data, the theoretical potential of biomass energy at the total terrestrial surface is about 3500 EJ y^{-1}. This is highly in line with the figure given by Hall et al. (1993), of about 3300 EJ y^{-1}, assuming a lower heating value of 15 GJ ton^{-1}.

5.2 The global geographical potential of energy crops

For the year 2050 and 2100, the geographical potential of growing biomass for energy purposes is given in Table II for each land-use type (abandoned agricultural land, low-productive land and rest land). The geographical potential at abandoned agricultural land is most significant. For the year 2050 the estimates of the geographical potential of energy crops at abandoned agricultural land for the A1 and B1 scenarios are in the same order as the current (2000) global primary energy consumption (~400 – 450 EJ y^{-1}) (Goldemberg, 2000). These even increase further in the second half of the century. Different figures are found for the A2 and B2 scenarios that result in significantly lower potentials of energy crops. The geographical potential of low-productive land is almost negligible compared to the other two categories. The potential at rest land is however significant (see Table II). This is mainly due to savannah areas at which high land productivities are found.

The development over time of the geographical potential as sum of the three categories is shown in Figure 12 for each scenario. The figure also shows the total simulated primary energy demand over time for the scenarios (IMAGEteam, 2001). The estimated geographical potential of B1 in 2100 is higher than the simulated total primary energy demand for that scenario. The A2 scenario is the scenario with the highest total energy demand and the lowest biomass energy geographical potential. If we consider the share of biomass in the total energy mixture, this would always be limited (22%) in an A2 world, but may reach 100% in a B1 scenario at the end of the century.

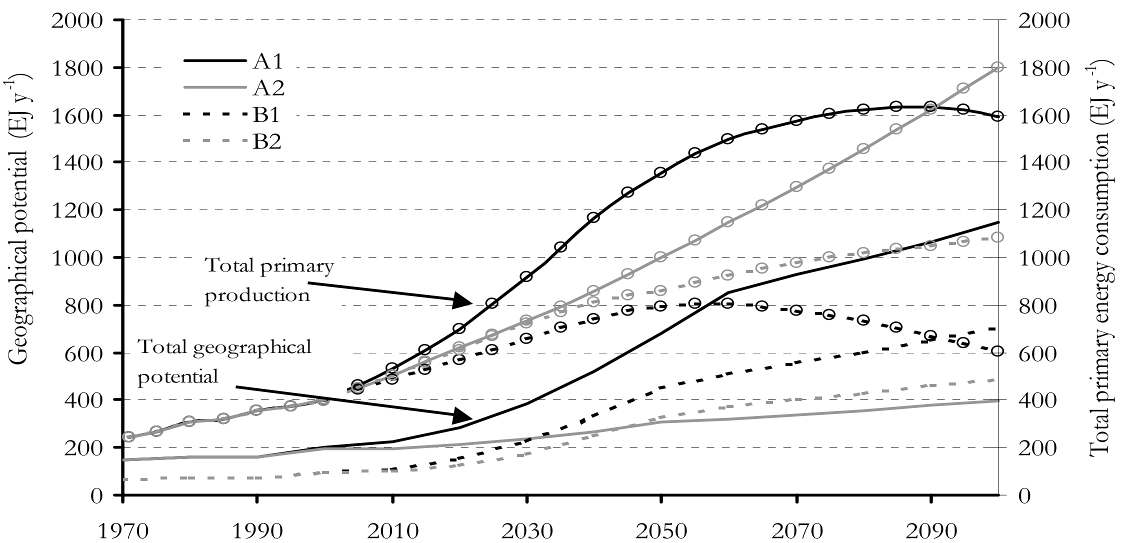

Figure 12: Geographical potential of woody biomass energy crops as assessed for the four SRES scenarios over time, as well as the simulated total primary energy consumption. The latter is differentiated from the graphs of the geographical potential by circles in the graphs.

5.3 Regional variation in geographical potential

Which regions have the highest geographical potential for energy crop production? Table II shows the geographical potential of energy crops at three land-use categories. The highest geographical potential in the first half of the century is found in the Former USSR (region 11). East Asia (China) is simulated to have the highest regional geographical in the second half of the century. Figure 13 shows the regional availability of abandoned agricultural land for the 8 most interesting regions: the regions with the highest abandoned agricultural land area. These regions are identical in all scenarios, however the variation in time differs by scenario. In the B1 and A1 scenario the abandoned agricultural land area in East Asia (mainly China) increases rapidly at the end of the century. This is mainly caused by the decrease in population growth in this region at the end of the century. Interesting are also the African regions. Simulations result in large surfaces of available area in Africa in the A1 and B1 scenarios. These are the scenarios with high levels of technological growth. As a result, food productivity is high. Subsequently, this results in a large share of abandoned agricultural land in these regions. In the A1 and B1 scenario, these regions are also assumed to increase their level of food import. This reduces the demand for agricultural land, so larger amounts of areas are assumed to become available for energy plantations in Africa.

Table II: The regional geographical potential of energy crops at three land-use categories for four scenarios, A1, A2, B1 and B2 for the year 2050 and 2100 (EJ y^{-1})

	Energy crops: abandoned agricultural land								Energy crops: low-productive								Energy crops: rest land							
	A1		A2		B1		B2		A1		A2		B1		B2		A1		A2		B1		B2	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Canada	14	17	9	10	13	12	12	15	2	1	3	2	2	2	3	2	4	3	3	2	1	0	1	0
USA	32	39	18	20	33	31	46	55	0	0	1	0	0	0	1	0	19	21	15	9	3	3	3	3
C.-America	8	22	1	1	10	19	4	10	0	0	0	0	0	0	0	0	9	10	4	2	2	2	1	1
S.-America	53	73	1	1	56	70	37	41	1	0	1	0	1	0	1	1	32	33	24	12	6	5	6	5
North-Africa	2	5	1	2	2	5	1	2	0	0	0	0	0	0	0	0	3	3	2	2	1	0	0	0
West- Africa	20	69	3	36	22	58	2	25	0	0	0	0	0	0	0	0	29	27	20	16	5	4	4	3
East- Africa	15	49	1	13	17	41	2	5	0	0	0	0	0	0	0	0	24	25	14	12	4	4	3	2
South- Africa	24	83	1	36	26	66	1	35	0	0	0	0	0	0	0	0	17	18	9	8	4	3	2	2
W. Europe	9	16	10	11	9	14	15	17	0	0	0	0	0	0	0	0	4	5	4	4	1	1	1	1
E.- Europe	9	12	8	10	8	10	9	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F. USSR	97	147	47	63	83	101	74	106	1	0	3	1	2	1	2	1	27	33	21	25	5	4	4	5
Middle East	2	13	1	2	2	10	1	2	0	0	0	0	0	0	0	0	11	11	7	7	2	2	2	1
South Asia	12	49	3	8	11	38	4	15	0	0	0	0	0	0	0	0	13	14	11	10	3	2	1	1
East Asia	79	181	7	11	74	127	43	61	1	1	1	1	1	1	1	1	22	35	16	23	4	4	3	4
S.- East Asia	1	28	1	1	1	19	2	10	0	0	0	0	0	0	0	0	8	6	6	2	2	1	1	1
Oceania	32	42	17	17	31	34	26	36	0	0	0	0	0	0	0	0	21	22	17	14	4	4	3	3
Japan	0	2	0	1	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
World	409	847	129	243	398	656	279	448	5	2	9	4	6	4	8	5	243	266	173	148	47	39	35	32

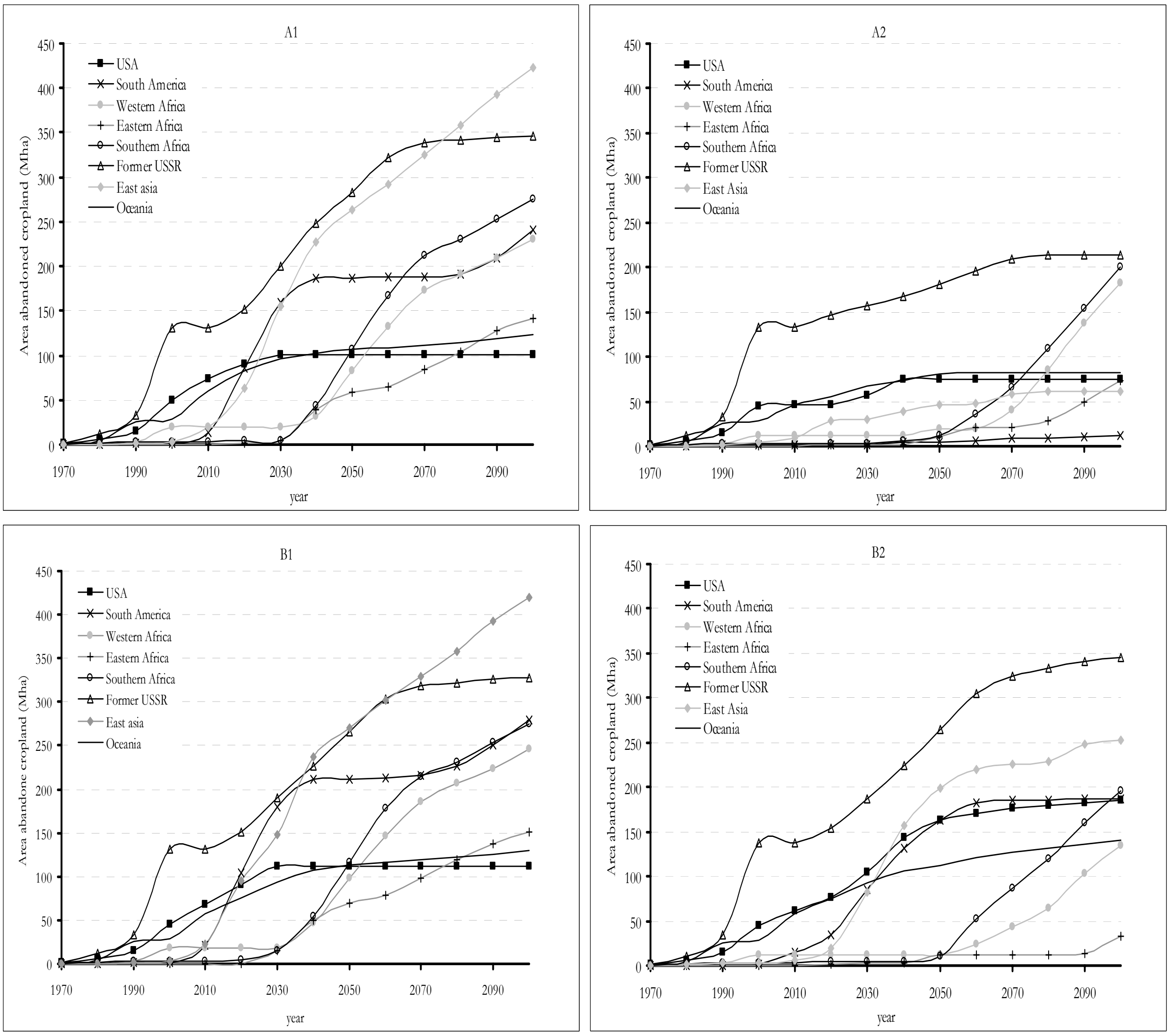

Figure 13: The regional variation over time of abandoned agricultural land area (Mha) as simulated by IMAGE 2.2 for four SRES scenarios. Only regions with high amounts of abandoned land are included.

The regional geographical potential of growing biomass (including all categories) in the year 2050 exceeds the present primary energy demand in various regions. However, compared to the future energy demand this is not the case. We have compared the geographical potential in the year 2050 estimated for the four scenarios with the projected primary energy demand by the IMAGE 2.2 model for these scenarios in the year 2050 (Table III). In none of the scenarios the estimated global geographical potential in the year 2050 exceeds the projected total primary energy demand in that year. At a regional level, this is different: e.g. the geographical potential in Oceania and the Former USSR exceeds its regional energy demand in the year 2050 in all scenarios.

Table III: The ratio of the regional geographical potential of growing biomass in 2050 compared to the projected primary energy consumption in the year 2050, taken from IMAGEteam (2001).

	A1	A2	B1	B2
Canada	1.1	0.8	1.4	1.2
USA	0.4	0.2	0.4	0.5
Central-America	0.4	0.1	0.3	0.2
South-America	0.9	0.3	1.0	0.7
North-Africa	0.1	0.1	0.1	0.1
West- Africa	1.3	1.1	1.0	0.3
East- Africa	1.7	1.4	1.3	0.4
South- Africa	1.1	0.4	1.1	0.1
OECD Europe	0.1	0.2	0.1	0.2
East- Europe	0.3	0.3	0.5	0.4
Former. USSR	1.4	1.1	1.9	1.4
Middle East	0.1	0.1	0.1	0.0
South Asia	0.1	0.1	0.1	0.0
East Asia	0.5	0.2	0.7	0.3
South. East Asia	0.1	0.2	0.1	0.1
Oceania	6.0	4.0	6.1	4.4
Japan	0.0	0.0	0.0	0.0
World	0.5	0.3	0.6	0.4

6. The technical potential of biomass energy

Up to this point, we have limited our analysis to primary production of energy crops only. The technical potential from the conversion to biomass fuel and biomass electricity is assessed in this section.

The technical potential of biomass energy is simply the product of the geographical potential and the conversion technology specific conversion efficiency (η). The conversion efficiencies for the conversion to electricity are based on values presented in the literature; for Biomass Integrated Gas Combined Cycle (BIG/CC) we used (Dornburg and Faaij, 2001) and (Faaij et al., 1998). For the transportation fuels we have based our estimates on (van Hooijdonk, 2002; Tijmensen et al., 2002; Hamelinck et al., 2003a). Table IV shows the efficiencies for the present and future situation of the technologies. For the future developments, ranges of exogenous technological improvements are assumed for the four SRES scenarios. The A1 and B1 scenarios are assumed to have large conversion plants that develop fast over time. The A2 and B2 scenarios are assumed to have a slower technological development, however reach the same upper level in 2050. The quantification of these assumptions is given in Table IV.

Table IV: Summary of the parameters required for the two conversion technologies.

	Electricity	Transport fuel
Conversion route/type of fuel	Gasification – combined cycle	Gasification / Hydrolyse-fermentation
Typical scale (MWth)	20 - 1000	100 - 2000
Status	Demonstration	Laboratory /Demonstration[a]
Conversion efficiency (%) (year 2000)	40	40
Conversion efficiency (%) (year 2050)	56	55

[a] Fischer Tropsch using biomass is in the pilot scale, however, the conversion of coal to Fischer Tropsch oil is commercial already. Several companies have or are developing positions in Fischer Tropsch technology, Sasol, BP, ExxonMobile, ENI and Shell.

The technical potential is estimated for the year 2050 as presented in Table V for the two conversion technologies and the four scenarios. The variation in the results over the scenarios reflects a similar pattern as the variation in the geographical potential over the scenarios.

Table V: The technical potential of biomass energy for the year 2050 for four SRES scenarios compared to the present consumption (IEA/OECD, 2001b) and (Goldemberg, 2000)

	A1		A2		B1		B2		Present (2000) global consumption
	2050	2100	2050	2100	2050	2100	2050	2100	
Geographical potential (EJ y^{-1})	657	1115	311	395	451	699	322	485	
Electricity (PWh y^{-1})	132	225	63	80	91	141	65	98	15 PWh y^{-1}
Fuel (EJ y^{-1})	361	613	171	217	248	384	177	267	142 EJ y^{-1} [a]

[a] This is the oil consumption for the year 1998.

7. Sensitivity analysis and discussion

The geographical potential at abandoned agricultural land has turned out to have the highest potential. Furthermore it is assumed to encounter less constraints regarding impact on vulnerable ecosystems and water resources, as these areas have previously been used for agricultural purposes. We therefore start with a sensitivity analysis on the availability of this land-use type at a regional level. We furthermore conduct a sensitivity analysis for the low-productive land and the rest land at a global level.

7.1 Sensitivity of the available area from abandoned agricultural land

The abandoned agricultural land estimated in this study varies widely for the four scenarios. The scenarios differ mainly according to:

- Population growth

- GDP development
- Technological development; i.e. the management factor for food production
- The degree of social/environmental prioritising; i.e. the diet
- The degree of globalisation; i.e. the trade level

All these factors influence the abandoned agricultural land. In the IMAGE 2.2 model, the following relations of these factors with the geographical potential are included:
- The population growth influences the demand for food or fodder crops.
- The GDP influences the type of crop that is used for fodder. If a large amount of capital is available, the animals are fed with high-quality food crops, whereas otherwise large shares of food residues are used. Furthermore, the GDP is included in the assessment of the ratio between affluent and basic types of food. An increase of GDP increases the share of affluent food intakes (e.g. animal intake and oil crops).
- The technical development of the production of food or fodder is determined by the management factor.
- If a world is more or less environmentally oriented is reflected in the amount of meat that is consumed in the diet; e.g. in the B1 scenario, the rate of increased meat consumption declines.
- The globalisation or regionalisation is reflected in the level of trade that is assumed in the scenario. The B1 and A1 scenarios have maximum trade, so the desired food demand can be imported from other regions; or regions extent their food production to higher levels, so it can be exported to other regions.

To analyse the effect of these factors on the geographical potential of biomass energy, we have taken the parameterisation of the B1 scenario and converted it to the A2 scenario by varying one factor each run. The B1 and A2 scenarios represent the outer boundaries of the food demand and the required agricultural land area and are therefore interesting to use for these analyses. The variations over time for the amount of required agricultural land area are shown in Figure 14. The agricultural area is directly related to the available abandoned and remaining area. From Figure 14, it can be seen that:

- The global agricultural land area in the B1 scenario reduces over time, from about 3.1 Gha in 2000 to 1.6 Gha in 2100. Whereas the agricultural land area in the A2 scenario slightly increases, from 3.1 Gha in 2000 to about 4.2 Gha in 2100.
- The agricultural land area of the B1 scenario increases highly if we use the population figures from the A2 scenario; to 4 Gha in 2100; this is an increase of 250% compared to B1.
- The agricultural land area reduces slightly again if the lower GDP values of the A2 scenario are used (still about 240 % higher than B1). A higher GDP increases the quality of the fodder and so improves the feed efficiency of the animal, however, more food crops are required. The agricultural land area is reduced because the food crops demand is less in the A2 scenario and the affluent food types demand decreased.

- The effect of the lower management factor for the food production influences the agricultural land area only in the beginning of the century, as the technological change is assumed to be saturated at the end of the century. The agricultural land area at the end of the century is similar to the situation using the management factor from the B1 scenario.
- When using the consumed diet from the A2 scenario, the agricultural land area increases highly again (to about 290% compared to B1). In the B1 scenario, the meat consumption is low, whereas it is high in the A2 scenario. This is reflected in the agricultural area required for the food and fodder crops.
- In the final run we also used the food trade balance of the A2 scenario. If trade is used in an optimal way, high trade levels would reduce the agricultural land area. However, as can be seen from Figure 14, the lower trade levels of the A2 scenario decrease the agricultural land area. This was not expected, but is caused by the exogenous setting of the trade balance in the IMAGE 2.2 model, which is mainly based on an extrapolation of the historical trend. Figure 14 shows that the final run is close to the A2 scenario, so other parameters, e.g. cropping intensity, are not of high importance for the results.

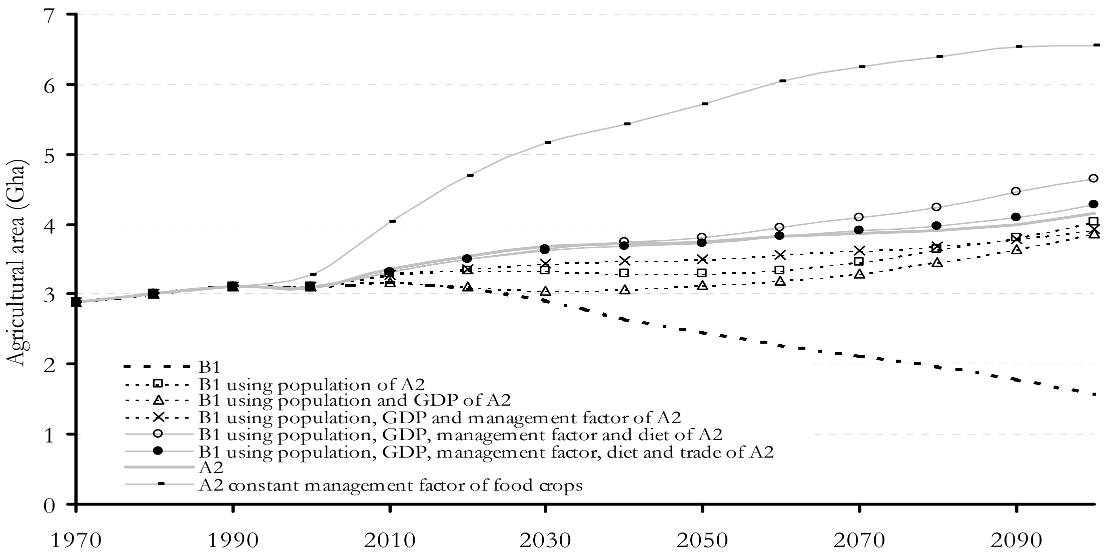

Figure 14: The global agricultural land area over time for several scenarios that convert the B1 scenario to A2 in various steps, as simulated by the IMAGE 2.2 model.

The used A2 scenario still includes the assumption of significant crop management improvements over time (see Figure 4). If there would be no technological improvements at all, the agricultural land area would rise to 5.7 – 6.5 Gha in respectively 2050 and 2100 (see Figure 14), compared to 3.7 and 4.2 Gha in 2050 and 2100 with the default management factor. This is seen as the upper boundary of the agricultural land area requirement. This would enhance the pressure on the land-use system significantly and would lead to marginal energy crop potentials, as the abandoned agricultural land for this situation is simulated to be 0.44 Gha (2050) – 0.71 Gha (2100).

In Table VI the results are shown of the sensitivity analysis on the geographical potential for abandoned agricultural land in the year 2050. We have also included the sensitivity to the productivity of the energy crop by varying the management factor of energy crops in the B1 scenario (± 25%). It can be seen that the population and the management factor of the food crops are of high importance for the geographical potential. Especially in regions like South America and the African regions the management factor of food crops, i.e. the technological development of the agriculture is of high importance for the geographical potential of energy crops. This is less important in more developed regions as Canada, Oceania, Europe and the Asian region. The latter encounter significant impact from variation in the population figures. In the OECD Europe the potential is even higher in the A2 scenario in the year 2050, because of the high trade levels assumed in the B1 scenario. The global results for all categories are shown in Table VII.

Table VI: Sensitivity of the geographical potential at abandoned agricultural land (in EJy^{-1}) for the year 2050 to various input parameters, the management factor (MF) of the energy crop and to scenario parameters, the population, GDP, food crop management factor, diet, trade and exclusion factor.

	B1 low MF	B1 High MF	*B1*	B1 using population A2	B1 using population and GDP A2	B1 using population, GDP and MF A2	B1 using population, GDP, MF and diet A2	B1 using population, GDP, MF, diet and trade A2	B1 using population, GDP, MF, diet, trade and exclusion factor A2	*A2*
Canada	10	16	13	12	12	9	8	9	9	**9**
USA	25	41	33	27	27	16	12	17	18	**18**
Central America	7	12	10	1	1	0	0	1	1	**1**
South America	42	71	56	26	26	0	0	0	0	**1**
Northern Africa	1	2	2	1	1	1	1	1	1	**1**
Western Africa	17	28	22	16	16	5	6	3	3	**3**
Eastern Africa	13	22	17	11	11	6	4	1	1	**1**
Southern Africa	19	32	26	17	17	2	1	2	2	**1**
OECD Europe	6	11	9	8	8	6	6	9	10	**10**
Eastern Europe	6	10	8	7	7	5	4	7	7	**8**
Former USSR	62	103	83	64	64	39	37	45	46	**47**
Middle East	1	2	2	2	2	1	1	1	1	**1**
South Asia	8	14	11	6	6	6	5	2	3	**3**
East Asia	55	92	74	27	27	29	20	11	11	**7**
South East Asia	1	2	1	1	1	1	1	1	1	**1**
Oceania	23	38	31	26	26	19	15	16	16	**17**
Japan	0	1	0	0	0	0	0	0	0	**0**
World	298	496	397	253	253	148	123	127	131	**129**

Table VII: The sensitivity of the geographical potential of energy crops for the year 2050 at abandoned agricultural land, low-productive land and 'rest land'

	B1 low MF	B1 High MF	*B1*	B1 using population A2	B1 using population and GDP A2	B1 using population, GDP and MF A2	B1 using population, GDP, MF and diet A2	B1 using population, GDP, MF, diet and trade A2	B1 using population, GDP, MF, diet, trade and exclusion factor A2	*A2*
Abandoned agricultural land	298	496	**397**	253	253	148	123	127	131	**129**
Low-productive	10	4	**6**	6	6	8	8	8	7	**8**
'Rest land'	34	58	**46**	42	46	36	34	34	175	**173**

The sensitivity analysis of the technical potential is straightforward as the technical potential is linearly dependent on the geographical potential via the conversion efficiency. For instance, a variation in the geographical potential from 342 to 618 EJ y^{-1} (i.e. total geographical potential of B1 scenario for low management factor and high management factor), the technical potential for electricity ranges from 56 to 101 PWh y^{-1}.

7.2 Comparison of the geographical potential with previous studies

Various studies have analysed the global potential of biomass energy. Berndes et al. (2003) have made an extensive overview of many of these studies. Except for the A2 scenario, we estimate the total geographical potential of biomass energy to be higher than previous studies for the year 2050. Found in the previous studies was that, for the first half of the century, energy crop potentials are estimated ranging from 14 EJ y^{-1} (Dessus et al., 1992) to 267 EJ y^{-1} (Hall et al., 1993). To understand the differences between the outcomes, we compare the results found for 2050 in this study with previous studies on the energy crop productivity and the available area (Figure 15). We only compare the area assumed to be available from abandoned agricultural land, as this dominates the geographical potential in previous studies as well as in ours.

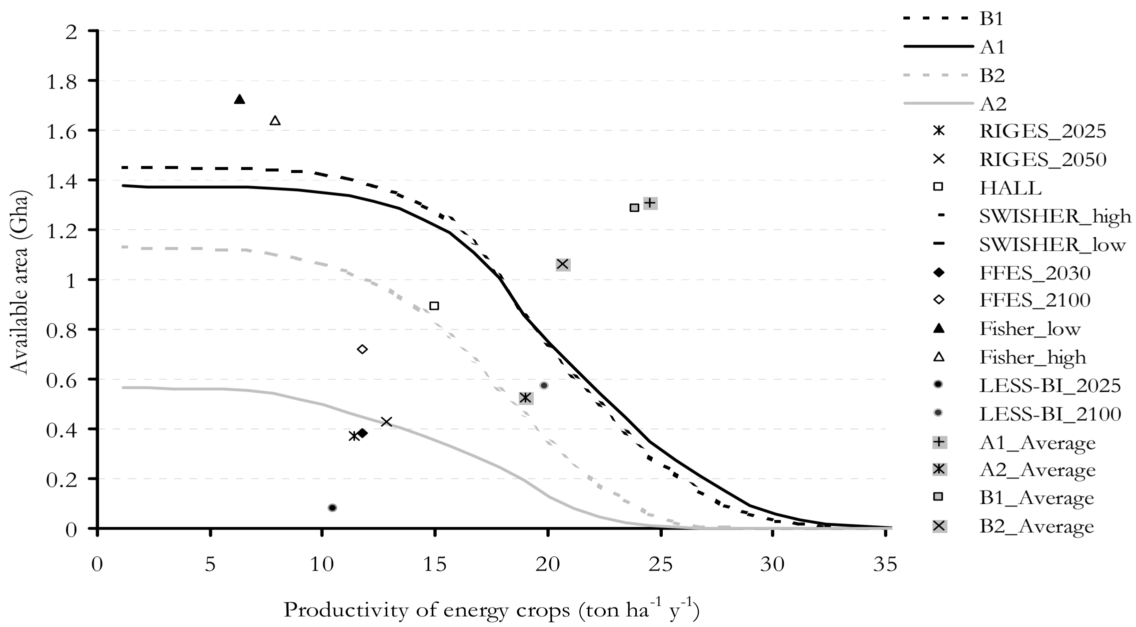

Figure 15: The estimated available abandoned agricultural land area (in the year 2050 for this study) and the corresponding average yields as simulated in this study and by previous biomass energy potential studies, (*RIGES*: (Johansson et al., 1993), *LESS-BI*: (Williams, 1995), *FFES*: (Lazarus, 1993), *Swisher*; (Swisher and Wilson, 1993), *HALL*: (Hall et al., 1993), *Fisher*: (Fischer and Schrattenholzer, 2001)) For Fisher and Schrattenholzer, land availability has been derived from their graphs and also given in (Berndes et al, 2003). Note that not all studies have been conducted for the year 2050, but range from 2025 - 2100.

From Figure 15 it can be seen that, except for the study conducted at IIASA (Fischer and Schrattenholzer, 2001), the estimated available area in this study is high compared to previous studies for the A1 and B1 scenarios. These scenarios simulate an optimistic situation for abandoned agricultural land, as the population growth slows down over time. Also there is an important role for technological improvement expected in these scenarios. Less optimistic scenarios, like B2 or A2 have outcomes in the same order as previous studies. Most studies have restricted the available land to abandoned agricultural land because of surplus or degraded cropland for energy crop production. For instance, Hall (1993) and Swisher (1993) assume that energy crops can be planted at only 10% of the abandoned agricultural land area in industrialised regions and at all degraded areas. This results in an available area of around 0.4 Gha to 1 Gha for the year 2025-2030. This is comparable to our abandoned agricultural land category, ranging from 0.5 Gha (A2) to 1.4 Gha (A1). The difference is however, that most of the available land in our study is found in developing regions, whereas Hall (1993) assumes abandoned agricultural land to become available in industrialised regions. (Fischer and Schrattenholzer, 2001) use a different assumption regarding the available land for energy crops, as they assume energy crop production at grassland only. If we apply this restriction to our figures (using the crop productivity at grassland/steppe), the geographical potential would be reduced to

195 to 200 EJ y^{-1}. This figure would be significantly higher if we apply the restriction to pasture land, part of agricultural land in the IMAGE 2.2 model. This is the same order of magnitude as the geographical potential mentioned by Fisher and Schrattenholzer of 154 to 205 EJ y^{-1} for energy crops in the year 2050. Both studies have estimated the energy crop productivity at grid cell level, this seems to give similar results. Other studies assume fixed productivity levels at a global scale (Hall et al., 1993; Swisher and Wilson, 1993; Lazarus, 1993). These productivities are lower than the (average) productivities computed in this study. The management factor for energy crops assumed in this study, seems high compared to assumptions in other studies. This is the case for all scenarios. Most studies have not incorporated significant productivity improvements over time. However, when comparing the improvements encountered for food crops, we consider these improvements to be attainable for energy crops too, although more research is required. Based on the comparison with the other studies we conclude that the results of A1 and B1 scenarios found in this study are high compared to other studies, mainly due to high amounts of available land and high productivity levels as the result of the assumed population reduction over time and high level of technological learning which increases the productivity rapidly. The B2 and A2 scenarios that are assumed to have higher population growth and less rapid technological learning result in geographical potentials that are in the same order of the figures found in the literature.

7.3 Discussion of results

Before discussing the results in detail, we stress that although the assessment of the geographical potential of energy crops has been conducted at grid cell level, the results are aggregated to regional level and it is this level that needs to be considered as the geographical level. To what extent the regional geographical or technical potential of biomass energy can become available depends on various factors outside the scope of this study, like the import and export of biomass energy and on the willingness to invest in energy plantations. Furthermore, it depends on factors that are included in this study and are weakly underpinned, e.g. the land-claim exclusion factor for 'rest land'. Finally it depends on factors that are not taken into account in this study due to limitations of the approach, e.g. the change in the pressure on the land-use system. The pressure on the land quality (e.g. the depletion of the water and nutrient resources) is not included in this study at grid cell level. This pressure can be significant if energy crops are implemented at large-scale. As woody energy crops have larger roots, their pressure on groundwater availability is higher than for food crops. Based on a scenario study regarding the introduction of about 304 EJ y^{-1} of biomass energy in the energy system, Berndes (2002) concludes that large-scale energy crop implementation would in some countries lead to a further enhancement of already stressed water situation (e.g. South Africa, Poland). In countries that currently do not experience water stress, a large-scale expansion of biomass energy could induce a more difficult situation (e.g. India, China). But there are also countries where such impacts are less likely to occur (e.g. USA, Canada, Brazil, Russia). Although Berndes' analysis is benign for the regions that have large geographical potential levels simulated in this study, it is highly recommended to include the water availability in a future analysis, preferable at regional level, especially when assuming land available at rest land types, e.g. savannah. The water availability is to be included in the IMAGE 2.2 model. Similar applies to nutrient availability in the soil, although this type of soil degradation depends highly on the management of the energy plantation, the amount and type of fertilisers applied and the use of the branches and leaves of the crop (e.g. van den Broek, (2000)). These limitations need to be taken into account when using the outcomes of this study, as the ranges of the geographical potential of energy crops may be broader than indicated here.

In this study we have corrected competing land-use claims with care. However, as mentioned before, the choice of the land-claim exclusion factor for 'rest land' area is rather arbitrary. The chosen value does have a significant impact on the geographical potential. Because the value for the future depends mainly on local factors and cannot be measured, no generic value over the world or at regional level can be estimated. The results of the geographical potential at 'rest land' area should therefore be considered with care.

Finally, it should be noted that using the total of the potential covering three types of land-use categories is extreme and theoretical, as it would imply an area of almost 30 - 40% of the total land area! Only including abandoned agricultural land and rest land (representing around or more than 99% of the sum of the potentials), the required area ranges from about 11 (B2) to 21% (A1) of the total terrestrial area in 2050, up to 16 to 28% in 2100. These values are in the same order of magnitude as the current agricultural land area.

8. Summary and conclusion

In this study we have estimated the geographical and technical potential of produced biomass for energy purposes (energy crops) at grid cell level for the four SRES scenarios: A1, A2, B1 and B2, using the IMAGE 2.2 model. These scenarios vary according to the population and economic growth, the technological change, social behaviour, the value that is given to environmental and ecological issues and the level of globalisation. The geographical potential is the product of the available area for energy crops and the productivity level. Three categories of potential available areas are distinguished: 1) abandoned agricultural land, 2) low-productive land and 3) rest land not required for food, forest or bioreserves. The potential at low-productive land is negligible. The global geographical potential at the three land-use categories for the year 2050 and 2100 for the four scenarios is summarised in Table VIII.

Table VIII: The global geographical potential for the years 2050 and 2100 for three land-use categories for the four scenarios (EJ y^{-1})

	A1		A2		B1		B2	
	2050	2100	2050	2100	2050	2100	2050	2100
At abandoned agricultural land								
Primary biomass	409	847	129	243	398	656	279	448
Biomass fuel	225	466	71	134	219	361	153	246
Biomass electricity (PWh y^{-1})	82	171	26	49	80	132	56	90
At low-productive land								
Primary biomass	5	2	9	4	6	4	8	5
Biomass fuel	3	1	5	2	3	2	4	3
Biomass electricity (PWh y^{-1})	1	0	2	1	1	1	2	1
At rest land								
Primary biomass	243	266	173	148	47	39	35	32
Biomass fuel	134	146	95	81	26	21	19	18
Biomass electricity (PWh y^{-1})	49	54	35	30	9	8	7	6

The geographical potential at abandoned agricultural land is found to be the largest for the A1 and B1 scenario. For these scenarios, the potentials are comparable to the present energy consumption of about 400 EJ y^{-1} (Goldemberg, 2000). The ratio between the total geographical potential and the future energy demand is in most regions below 1, which means that the regional potential does not exceed the regional projected primary energy demand. Oceania does have the largest relative geographical potential; e.g. the geographical potential in the year 2050 does exceed the energy demand in the year 2050 for all scenarios. For the B1 scenario, this ratio is about 6. In absolute terms, the Former USSR has the highest potential, reaching levels in 2050 of about 71 (A2) to 125 (A1) EJy^{-1}.For the year 2100, the available area, and so the geographical potential at abandoned agricultural land, is about doubled; at 'rest land', it remains almost constant.

The technical potential for biomass fuels is estimated for the year 2050 at levels of 71 (A2) to 225 EJ y^{-1} (A1), at abandoned cropland, 1 – 3 EJ y^{-1} at low-productive land and 19 (B2) to 134 (A1) EJ y^{-1} at rest land. The present oil consumption of 142 EJ y^{-1} lies within this range for 2050 (Goldemberg, 2000). For biomass electricity, the technical potential in the year 2050 is estimated at 26 (A2) to 82 PWh y^{-1} (A1) at abandoned agricultural land, 0 to 2 PWh y^{-1} at low-productive land and 7 (B2) to 49 PWh y^{-1} (A1) at 'rest land'. The present electricity consumption of 15 PWh y^{-1} lies within this range (IEA /OECD, 2001)

The results are most significant for the A1 and B1 scenarios. Both scenarios describe a world with decreasing population growth in the second half of the century and a world in which the technical development is high. The food productivity levels are high because of high management levels and high crop intensities. In the B1 scenario the world is highly oriented towards environmental, ecological and social values. Therefore, competing land-use options, like nature conservation, are higher than in the A1 scenario. However, there is still a high potential left in this scenario. The A2 scenario has the lowest geographical potential. It is a world with rapid population growth up to 15 billion people in the year 2100. It furthermore experiences less technical development, is region oriented and is market-based growth oriented towards economic development. As food trade is not assumed, the food supply needs to be produced within the region. In this world, the pressure on the land-use system is already high. In North Africa and the Middle East people have to adapt their food intake to lower levels, as the expected (high) demand cannot be satisfied within the region. Furthermore, large areas (~700 Mha) are deforested in this scenario for the establishment of agricultural land. As in scenario A2 the ecological values are not considered important, reforestation is not expected. However, if these areas would be reforested, the potential of biomass at abandoned agricultural land would decrease even further with about 140 EJ y^{-1}, assuming an average energy crop productivity of 13 ton ha^{-1} y^{-1}. Due to climate change, which is severe in this scenario, the land-use pattern changes and land is taken out of production not because of surplus agricultural land, but because of a shift towards more suitable areas. The remaining land is estimated in this study as abandoned agricultural land. Nevertheless, if the total geographical potential of biomass energy is produced in this scenario, the stress on the land-use system will even increase.

Except for the scenario driving forces, we have so far not included economic, social or political factors. These might be important. For instance large available areas are found in the African regions in the A1 and B1 scenarios, i.e. scenarios with significant technological growth. The sensitivity analysis shows that the assumption of the management factor for food crops is of high importance for this value of geographical potential in these regions. Significant technological and organisational improvements in the agricultural sector in these regions are required to reach this potential. This is only possible if the issue of food security and improvement of food production system increases on the international agenda and if the political situation in Africa improves the coming decades.

This study gives insight in the geographical potential of biomass energy using different land-dynamic scenarios. Interesting conclusions have been drawn in this study. However, also some more aspects are acknowledged that give rise to recommendations for further research:

- This study has focused on biomass from energy crops only. The inclusion of biomass from residues using the IPCC scenarios requires a dynamic model that includes the demand and supply of forestry products in an integrated and detailed manner. Such study can also include the effect of cascading.
- We have only included the impact of land degradation by means of climatic change, e.g. increase of temperature and rainfall. However, if land resources are used in an intensive way that reduces the organic content of the soil, the productivity reduces significantly. This feedback is not incorporated in this analysis. Inclusion of this

mechanism can reduce the land productivity and consequently the geographical potential.

- Related to the land degradation due to bad management, inclusion of more variation in the energy crop and food crop production systems is needed. One may think of varying the rotation length, the harvest index or the amount of nutrient applied. These different production systems result also in different yields of the food and energy crops and consequently in different geographical potentials.
- It is recommended to study the geographical potential at rest land in more detail. This study has shown that significant amounts of biomass can be produced at these areas. However, the reduction of the available land by means of impact on vulnerable ecosystems or water resources etc. is conceptually difficult to quantify and could only be roughly estimated in this study. Further research that for instance includes the required land for remaining the biodiversity or water security can be combined with studies on the available rest land area to get a more underpinned estimated of the land-claim exclusion factor.

CHAPTER FOUR

POTENTIAL OF BIOMASS ENERGY UNDER FOUR LAND-USE SCENARIOS. PART B: EXPLORATION OF REGIONAL AND GLOBAL COST-SUPPLY CURVES[#]

Abstract

For four global land-use scenarios, we have explored the regional and global cost-supply curves of energy crops at abandoned agricultural land and at remaining non-productive land over time (to 2050). In addition, cost-supply curves of biomass liquid fuel (synthetic diesel) and bio-electricity (BIGCC) are estimated. The cost factors of the former curves are divided into transportation, land, labour and capital costs that evolve differently over time. Land productivity improvements and cost reductions due to learning are assumed. Furthermore, capital-labour substitution is assumed over time. The land availability and energy crop productivity investigated at grid cell level determine the supply. It is estimated that in the long term about 130 to 270 EJ y^{-1} of energy crops may be produced at costs below 2 \$ GJ^{-1} (equivalent to the currently highest cost level of coal). Interesting regions, because of low production costs and significant potentials, are the Former USSR, Oceania, East and Western Africa and East Asia. Using these energy crop production costs, the production costs of biomass liquid fuels may come down to about 2 times the present diesel production costs. Bio-electricity may become competitive with baseload fossil fuel electricity production combined with CO_2 capture and storage. It is found that using biomass, the present world electricity consumption of 15.7 PWh y^{-1} may be generated in 2050 at costs between 0.04 – 0.05 \$ kWh^{-1}. At costs of 0.06 \$ kWh^{-1}, about 18 to 53 PWh y^{-1} can be produced.

[#] Submitted to Global Environmnetal Change. Co-authors are André Faaij, Bert de Vries, Wim Turkenburg. We are grateful to Richard van den Broek (Ecofys), who kindly supplied the background data on the production costs of Nicaragua, Ireland and the Netherlands, and to Bas Eickhout (RIVM) for the runs with the IMAGE 2.2 model. Furthermore, we would like to thank Håkan Rosenqvist (University of Luleå) for data supplied on Swedish costs, Carlo Hamelinck (Utrecht University) for data supply for the costs of liquid biomass fuels and transport costs and Karst Geurs (RIVM) for information on transport costs.

1. Introduction

In recent years, the interest in biomass energy has increased considerably worldwide. There are several reasons for this: biomass is widely available and it has the potential to produce modern energy carriers such as electricity and liquid transport fuels that are clean, convenient and easily used in the present energy supply system. Biomass energy can also be produced in a carbon neutral way and can contribute to (local) socio-economic development. The present contribution of modern biomass to the primary energy consumption is estimated at 6 or 7 EJ y^{-1}. Combined with traditional biomass, its share in the total primary energy supply is 9 - 13% (Turkenburg, 2000). Various scenario studies suggest potential market shares of modern biomass till the year 2050 of about 10% to 50% (Berndes et al., 2003). However, such high shares can only be achieved if biomass becomes available at competitive costs. At present, biomass energy competes in some places with conventional sources with the use of policy intervention, like a carbon tax. Examples are the production of ethanol in Brazil and the USA (Moreira and Goldemberg, 1999; Shapouri et al., 2000), district heating using biomass in Scandinavian countries, and the generation of electricity by (co-)combustion of biomass in power plants in various countries (AEA Technology, 2001; van den Broek et al., 2000; van den Broek et al., 2001; Turkenburg, 2000).

At present, biomass residues from the forestry or agricultural sector are mostly used to produce modern biomass energy carriers at low costs. However, biomass originating from energy crops has a much larger potential than biomass from residue flows (Berndes et al., 2003) and see Chapter 2 of this thesis. But specially cultivated biomass for energy purposes currently results in high fuel and electricity costs in most cases, particularly where land and labour costs are high. Therefore, insight in potential cost and supply developments of energy crops and biomass energy carriers is important. Cost-supply curves of biomass energy have been studied at a regional (Junginger et al., 2001) or national level (Graham et al., 1995; Walsh, 2000) but not at the global scale.

In this chapter we focus on the long-term regional and global cost-supply curves of short-rotation energy crops and liquid fuel and electricity produced from such biomass. These curves give insight in the long term economic and market potential of biomass energy. This endeavour is complicated by various reasons, see e.g. Roos and Rakos (2000). Firstly, there is limited experience with energy crop production. Moreover, the availability and cost of land for energy crop production as well as soil productivity and required labour and capital inputs are site-specific. For the assessment of regional cost-supply curves, data from detailed, geographical analysis are needed. These data are not available for all possible sites and have to be derived from more generic assumptions, which we do here.

This study is a sequel to an earlier assessment of the geographical and technical potential of energy crops as has been presented in Chapter 3. There, we used land-use scenarios to estimate the geographical and technical potential of energy crops for 17 world regions. This chapter estimates the production costs associated with the production of energy crops and the derived fuel or electricity for the same scenarios and geographical regions. By cumulating the geographical and technical potential as a function of the production costs, we construct the cost-supply curve of energy crops and of fuels and electricity derived from these crops.

We start with a description of the methodology used in this study to investigate biomass energy cost-supply curves (Section 2). Next, we focus on the quantification of the input parameters with an emphasis on cost parameters (Section 3). Section 4 deals with the results of the cost-supply curve of primary biomass, whereas the cost-supply curve including the conversion to secondary energy carriers in the form of electricity and fuels is presented in Section 5. A sensitivity analysis of the results and a discussion is given in Section 6 and Section 7. The final section presents a summary and the conclusions of this study.

2. Methodology

2.1 Crop choice and land-use scenarios

In this study we focus on the timeframe 2000 – 2050. To estimate the production cost of energy crops and biomass energy carriers, we take the same grid cell approach, assumptions and regional aggregation level as used in Chapter 3 to assess geographical and technical potential of biomass energy[12].

Of the many possible types of energy crops, we restrict ourselves to short rotation crops in commercial large-scale plantations. These are woody biomass crops that are harvested with rotation cycles of 4 - 10 years. Which species is preferred depends on climate conditions and soil quality. Examples of species used for short rotation forestry are poplar or willow in temperate climates, e.g. Sweden (Rosenqvist et al., 2000), and eucalyptus in more tropical climates, e.g. India (Sudha et al., 2003), Nicaragua (van den Broek, 2000) or Brazil (Larson and Williams, 1995). The focus on short rotation forestry implies that we do not take into account perennial crops like grasses or starch containing crops like sugar cane or maize. Arguments to confine the analysis to short rotation crops are that they can be grown under different conditions and can be efficiently converted to a number of biomass-derived energy carriers

[12] The IMAGE 2.2 geographical grid of 0.5° x 0.5°, about 55 x 55 km at the equator, has been used (IMAGEteam, 2001). The results are aggregated to 17 regions: Canada, USA, Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, OECD Europe, Eastern Europe, Former USSR, Middle East, South Asia, East Asia, South East Asia, Oceania, Japan.

We assume that only abandoned agricultural land and so-called rest land is available for energy crops. Both categories are calculated in the context of four land-use scenarios that are in turn based on IPCC-scenarios simulated with the IMAGE 2.2-model (IMAGEteam, 2001; Nakicenovic, 2000) and have been reported in detail in Chapter 3. Abandoned land is the land taken out of agricultural production due to less demand, higher land productivities elsewhere or both. Rest land includes all the remaining non-productive land that can be used for energy crop production. The rest land category excludes bioreserves, forest areas and agricultural area (Chapter 3).

2.2 The cost-supply curve of primary biomass energy from energy crops

The geographical potential of primary biomass energy for four land-use scenarios is taken from Chapter 3 (see Section 3.1). The production costs of energy crops are assessed based on regional data and assumptions about future developments. We aggregate the costs inputs in three parts: the labour costs, the capital costs and the land rental costs. These represent all costs that are made during the production chain which consists of establishment of the plantation (ploughing and weed control), planting of cuttings, management of the plantation e.g. by application of fertilizers, harvest of the crop and the break up of the plantation, e.g. Coelman (1996) and van den Broek (2000).

In the literature estimates have been made of the production costs of woody biomass from energy crops at project level. A broad range of costs is found, ranging from 2.5 to 16.4 $\$_{2000}$ GJ^{-1} in Europe, 2.1 to 7.4 $\$_{2000}$ GJ^{-1} in the USA, 1.0 to 5.0 $\$_{2000}$ GJ^{-1} in Latin America and 0.5 to 1.3 $\$_{2000}$ GJ^{-1} in Asia (Perlack and Wrights, 1995; Perlack et al., 1995; Perlack, 1995; van den Broek, 2000; Hillring, 1999; Venendaal et al., 1997; Biewinga and Bijl, 1996; de Jager et al., 1998; Walsh, 1998; Williams and Larson, 1993; Phillips et al., 1995; Marrison and Larson, 1995; Azar and Larson, 2000; Larson and Williams, 1995; Faundez, 2003). This large range can partly be explained by the wide variety of energy crops, locations and time horizons in these studies. Our purpose is to construct a generic cost estimate procedure that can be applied to conduct long-term regional and global cost-supply curves. This is done by following a more theoretical and generic approach.

To determine regional cost-supply curves of biomass from energy crops, we focus on the long-term dynamic factors in the production costs. We postulate three factors that are relevant:

a) land productivity;
b) relative cost of labour and capital;
c) innovations.

a) Land productivity:
The land productivity Y, in ton or GJ per hectare[13], is taken from Chapter 3 based on the IMAGE 2.2-scenarios. The regional distribution of the land productivity is given on the basis of 0.5° x 0.5° grid cells as a function of time. They are based upon theoretical upper limits of primary biomass rain-fed[14] productivity. These figures are therefore to be multiplied with a time-dependent management factor[15], accounting for the management as is discussed further on. We assume an increase in the operational and capital input with an increase of the management factor.

b) Relative cost of labour and capital:
We assume that all inputs for the production process, next to land, can be incorporated in only two so-called production factors: capital input K and labour input L. Economic production theory suggests that there is an 'optimal' ratio between the use of capital and labour, (e.g. Varian (1996)). It is given by:

$$\left(\frac{K}{L}\right)_{opt} = \left(\frac{\alpha}{1-\alpha}\right) \cdot \frac{p_L}{p_K} \tag{1}$$

Assuming that the output Y is a Cobb-Douglass function of the required capital K and labour L:

$$\frac{Y}{Y_0} = \left(\frac{K}{K_0}\right)^{\alpha} \cdot \left(\frac{L}{L_0}\right)^{1-\alpha} \tag{2}$$

with Y output per ha (i.e. land productivity) (GJ ha^{-1} y^{-1}); α the capital-labour factor substitution elasticity ($0 < \alpha < 1$); and p_i the price of the corresponding factor i. The initial situation is associated with index 0.

Thus, if the price of labour goes up – an increase in wages, that is – and the price of capital stays constant – a constant interest rate, that is – one would expect an increase in the capital-labour ratio as that would lower the total production costs. Behind such a process of substituting capital for labour is in fact a series of innovation and other change processes, mechanisation being the most familiar one. These innovations do not imply an increase in the overall productivity, but only a substitution of the labour and capital inputs.

[13] We assume a Lower Heating Value of 15 GJ ton^{-1}
[14] The rain-fed productivity is the theoretical productivity limited by water resources. The rain-fed productivity can therefore be increased by irrigation.
[15] The management factor (MF) is the ratio between the actual productivity and the potential rain-fed productivity. MF includes the harvest index. A management factor of 1.0 implies optimal availability of nutrients, no plagues, etc. An improvement of the harvest index, the use of irrigation, biotechnological improvements etc. can increase the management factor to levels above 1.0.

In the agricultural sector, substitution of capital for labour has been known for decades. Recent examples have been published for Zimbabwe (Dalton et al., 1997); South Africa (van Zyl et al., 1987) based on mechanisation of the harvesting; and South Korea, mainly due to the introduction of biochemical technology (Sharma, 1991). This substitution effect may have quite an impact on the future cost of biomass-derived energy if labour wages rise significantly – to be expected in low-income regions with a significant income growth – and the availability and price of capital remain unchanged. It is not easy to give empirical evidence of such substitution and to derive a typical substitution coefficient. Data are scarce and often ill-defined. Capital-labour ratios found in the literature are different for different energy or food crop plantations. Assuming that all projects are operated at minimum cost or 'optimally', one would expect lower capital-labour ratios in countries with lower wages. We estimate the value based on empirical data from three countries (Figure 1). Figure 1's left-hand graph shows the capital and labour costs for the production of energy crops expressed in Present Value per hectare of the production of energy crops in Ireland (willow), Nicaragua (eucalyptus) and the Netherlands (willow). Figure 1's right-hand graph shows the capital cost and labour cost shares of these energy crops (van den Broek et al., 2002). These data suggest that, if the projects are optimal in the minimum cost sense, K is the capital input, equal to α and L is equal to 1-α (see Equation 1), there is a tendency to larger capital costs, with α between 0.65 to 0.95.

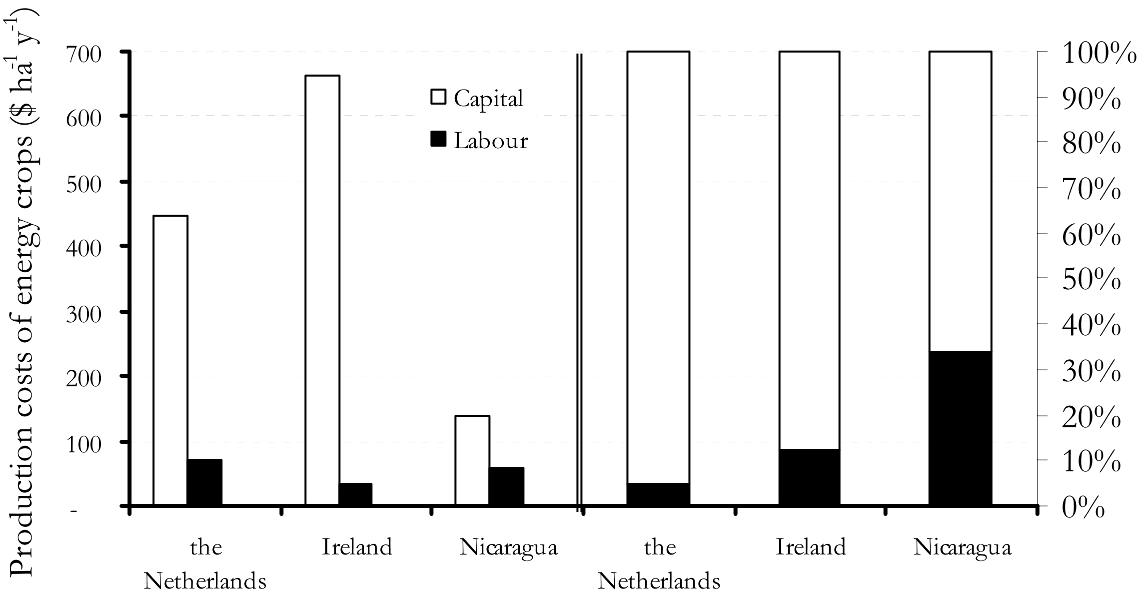

Figure 1: The capital cost and labour cost shares of the production of energy crops in Ireland (willow), Nicaragua (eucalyptus) and the Netherlands (willow) (on the right) and the production cost of energy crops per hectare (on the left). Source: (van den Broek et al., 2002).

c) Innovations:

If the market for energy crops develops, one may expect cost-reducing and productivity increasing innovations. The actual trajectory for such cost reductions is impossible to predict, but there is evidence that technological learning evolves according to a loglinear relationship of the form (see e.g. McDonald and Schrattenholzer (2002)):

$$\lambda = \left(\frac{\sum_{t=0}^{t} O}{O_0} \right)^{\pi} \tag{3}$$

with λ the cost reduction factor with which the input of labour and capital are reduced, π the learning coefficient ($\pi < 0$) and O the output, or produced commodity[16]. As we do not simulate actual but potential production over time, we assume that production has the same development as the geographical potential, i.e. we use the geographical potential for the output. This approach to technological learning reflects the finding that some representative cost factors, e.g. input required per unit of output, tends to evolve linearly with the logarithm of cumulative production. The coefficient π can also be expressed in the progress ratio[17] $PR = 2^{\pi}$.

For each grid cell i, with a land productivity Y_i (GJ ha^{-1} y^{-1}) and situated in region r, we propose the following expression for the cost calculation of the energy crop production costs C_i (\$ GJ^{-1}):

$$C_i = \frac{p_{Kr} \cdot \lambda_r \cdot K_r + p_{L_r} \cdot \lambda_r \cdot L_r + p_{Ar}}{Y_i} \tag{4}$$

with $p_{K,r}$ the interest rate (-) and $p_{L,r}$ the price of labour (wages) (\$ manyear^{-1} y^{-1}) in region r; p_{Ar} is the price of land in region r (\$ ha^{-1} y^{-1}); and λ_r the cost reduction factor due to technological learning in region r. L_r is the required labour (manyear ha^{-1} y^{-1}) and K_r the required capital (\$ ha^{-1} y^{-1}) in region r. It is assumed that labour and capital requirements are covering all the necessary operations and inputs in the production process.

From this formula it is seen that the local land productivity, the regional labour wages, interest rate, land prices, and cumulated production (geographical potential) are the determinants in our simple energy crop cost model. Note that as L and K are increased

[16] For simplicity we assume here so-called factor-neutral innovations, that is, it is not biased towards saving preferentially on the input of labour or capital as is the case in factor-substitution.

[17] A progress ratio of 0.9 implies that the costs are reduced with 0.1 for each doubling of the cumulative production; see e.g. OECD/IEA (2000).

with land productivity (intensification)[18], the main reason for reduction is innovation and a decreased share of land costs (due to the variation in the ratio of land costs to land productivity). Among regions the variation in production costs is caused by a difference in cost reduction factors and land costs.

Figure 2 illustrates the consequences of various assumptions with the example of a eucalyptus plantation in Nicaragua. The initial labour and capital inputs were derived from van den Broek (2000). The exact value is rather uncertain, amongst others because we have neglected the break-up costs. Curve 1 indicates the constant cost profile if cost inputs remain constant over time and no learning takes place. Let us first, for simplicity, assume that labour wages increase with 1% per timestep for a period of 100 timesteps. This leads to curve 2: an exponential rise in cost. If we include capital-labour substitution ($\alpha = 0.65$), curve 2 declines to curve 3, showing the effect of mechanisation and the like. Without capital-labour substitution but with factor-neutral innovations from technological learning, assuming 1% production increase per timestep and a progress ratio 0.9, costs will develop according to curve 4. Finally and still assuming the same 1% per timestep wage rise, curve 5 shows the cost trajectory with both substitution and learning. It is seen that one can postulate various mechanisms which influence future costs of energy crop derived energy – at least in theory.

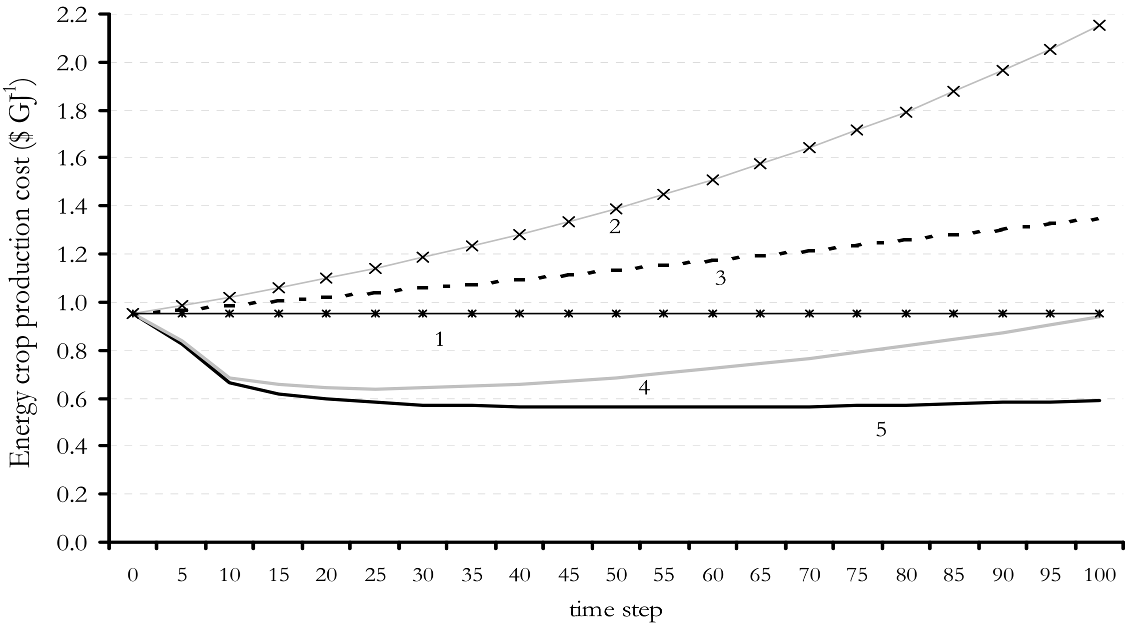

Figure 2: Development of energy crop production costs over time, applying different algorithms including; constant wages (1), a 1% wage rise per timestep (2) substitution to reduce cost increase (3), innovations (4) or both substitution and innovations (5). The data are based on estimates for a plantation in Nicaragua, see text.

[18] In theory, land productivity is a function of the input (K and L). However, as we use the land productivity from Chapter 3, here K and L are calculated from the land productivity results.

Finally, cost-supply curves are constructed by ranking the geographical potential as function of the estimated production costs in the grid cells.

2.3 The cost-supply of secondary biomass: liquid fuel and bio-electricity

The technical potential that accounts for the supply of secondary biomass is derived from Chapter 3. Here we focus on the costs of secondary biomass energy. There has not yet been large-scale experience with the use of woody biomass for liquid fuel production in all regions, but research is done to improve and develop various conversion routes in order to achieve large-scale use. Research is also done to produce biomass-derived electricity more efficiently. In this paper we investigate two distinct routes: conversion of woody biomass to liquid fuels (synthetic Fischer Tropsch diesel) and to electricity. Converting woody biomass into FT-diesel, is assumed to include a gasification step. For the production of electricity, we assume that biomass gasification and subsequent combustion in combined cycle power plants is the preferred route as it is expected to have high efficiency and low electricity production cost on the long-term (Williams and Larson, 1993; Faaij et al., 1998). These conversion technologies are not yet commercially available, but important technological improvements and commercialisation are expected by several authors (Tijmensen et al., 2002; Turkenburg, 2000; Larson and Jin, 1999; Chum and Overend, 2001).

To evaluate costs of liquid fuel or electricity derived from biomass in any given cell i. we postulate a standard conversion plant of technology t with capacity P (GJ h^{-1} or kW) and output E_t (GJ y^{-1}). The latter is the product of the load factor (LF), the capacity (P) and the amount of hours in a year. We have to account for four elements:

1. Primary biomass costs.

These costs are obtained from the cost-supply curve of primary biomass and indicated by p_{pb}.

2. Overall conversion efficiency.

In the process from biomass to liquid fuel or electricity, there will occur losses during transport and conversion resulting in an overall conversion efficiency η. As the transport losses at short distances are rather small (Hamelinck et al., 2003a), we take the plant conversion efficiency equal to the overall efficiency.

3. Transport from the harvesting area to the conversion plants.

These costs can be approximated as the sum of fixed costs for load/unloading overhead etc. of charter costs for trucks etc. and for fuel costs as a function of the efficiency.

4. Capital cost and non-fuel operation and maintenance costs of the conversion plant.

Unlike for biomass production, we neglect labour cost variation over time. Also we assume that operation and maintenance costs are a fixed fraction μ of the capital costs. The latter are annuitized in the usual way by multiplying the specific investment costs with capacity P and the annuity factor a[19]. Of course, the cost of the conversion plant will change over time and probably decrease with increasing scale and experience (see e.g. (Faaij et al., 1998; Dornburg, 1999; Dornburg and Faaij, 2001)). Technological developments have been incorporated using the same learning curve as applied to the production of energy crops. Using this learning curve, we differentiate the specific investment costs among the four scenarios (different learning rate), regions and over time.

An overview of the calculations and input parameters used in this study are summarised in Figure 3. The production cost of secondary biomass energy carriers produced in cell i $C_{sb,i}$ (\$ GJ^{-1}), either liquid fuel or electricity, can now be expressed as:

$$C_{sb,i} = \frac{E_t \cdot (p_{pb,i} + T + D \cdot \tau \cdot F_r \cdot \upsilon)}{\eta} + \frac{(a + \mu_t) \cdot I_t \cdot P_t}{E_t} \qquad (5)$$

with E_t the plant output (GJ y^{-1}); $p_{pb,i}$ the biomass feedstock cost, T the fixed transport costs (\$ GJ^{-1}); D the distance, set at 50 km; τ the transport or charter costs per unit of biomass, set at 0.0424 \$ GJ^{-1} km^{-1}; F_r the regional fuel costs (\$ m^{-3}); and υ the fuel efficiency, accounting also for the load factor, set at 0.002 m^3 GJ^{-1}

[19] Annuitizing is done in the usual way: $a = \dfrac{r}{1-(1+r)^{-L}}$ with r is the interest rate, set at 10%; and L is the economic lifetime, set at 20 y. We assume the interest rate and economic lifetime of the conversion plants to be equal over the world and constant over time.

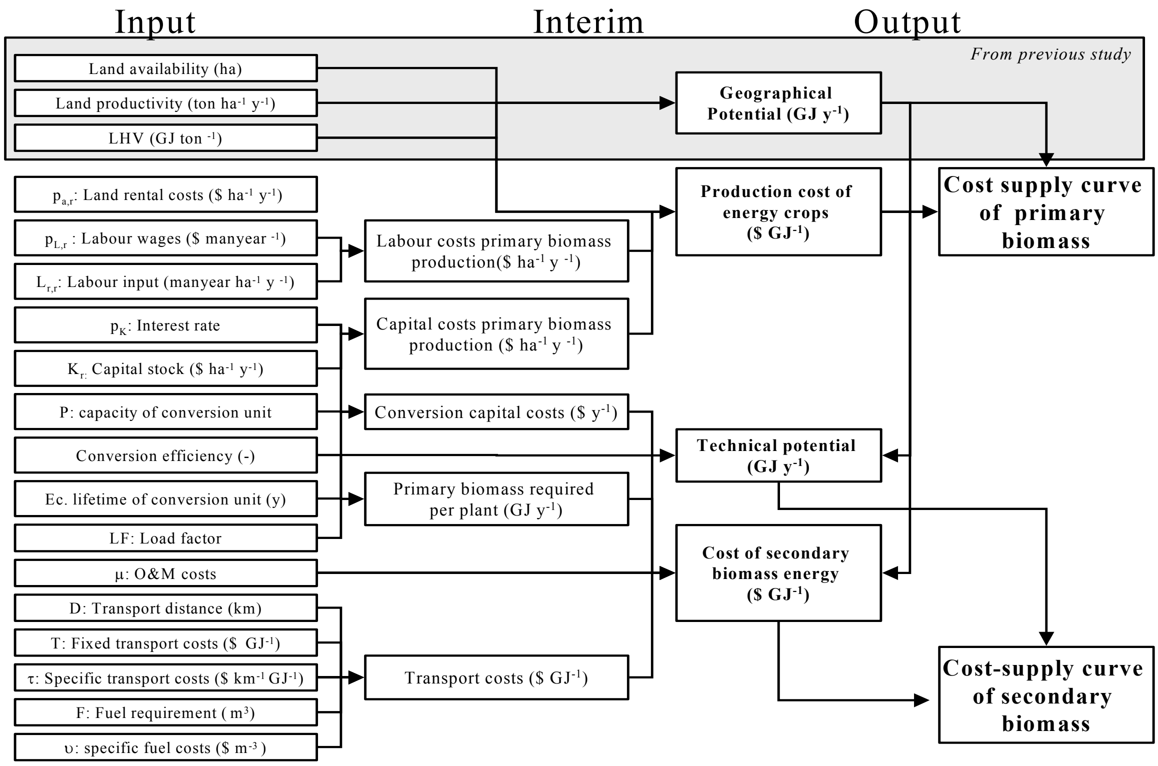

Figure 3: Overview of the approach to estimate the technical potential, the cost and the cost-supply curve of biomass for energy. This figure does not show the dynamics over time (capital-labour substitution and innovations).

3. Inputs to assess the production cost of energy crops

The application of the methodology described in the previous section is done using data from the IMAGE 2.2 model and from estimates based on a literature review. The input data are described below.

3.1 Land productivity and geographical potential

The land productivity – or yield – of energy crops was obtained from calculations using the IMAGE 2.2 model at a grid cell level for each of the four land-use scenarios (see Chapter 3), taking into account soil quality and climatic indicators as precipitation, temperature and CO_2 concentration. For the calculation of the land productivity in the various land-use scenarios, we have assumed in Chapter 3 that the management factor is the same in all regions and reach levels of 1.1 for the regionally oriented scenarios B2 and A2, 1.3 for the globally oriented, ecologically oriented, low food demand scenario B1 and 1.5 for the economic oriented globalised scenario A1.

Given the land-use scenarios and the resulting potential for energy crops at abandoned agricultural land and rest land, we have ranked the cells available for energy crops in any year of the scenario-period according to their productivity. In Figure 4 we present these distribution curves for the four scenarios for the year 2050. The curves show for instance that in the A2 scenario about 40 Mha of abandoned agricultural land with a land productivity of between 14.5 and 15.5 ton ha^{-1} y^{-1} can be maximally available for energy crop production in 2050. It is seen that in the scenarios A1 and B1 quite a large area of productive land may become available in principle; in the other two scenarios it is less. Clearly, the rest land area is large but its low productivity makes it much less attractive. Figure 5 shows the development of the calculated geographical potential between 2000 and 2050 for the four scenarios. The main difference between the A1, A2 scenarios and the B1, B2 scenarios concerning the geographical potential originates from the assumed availability of rest land.

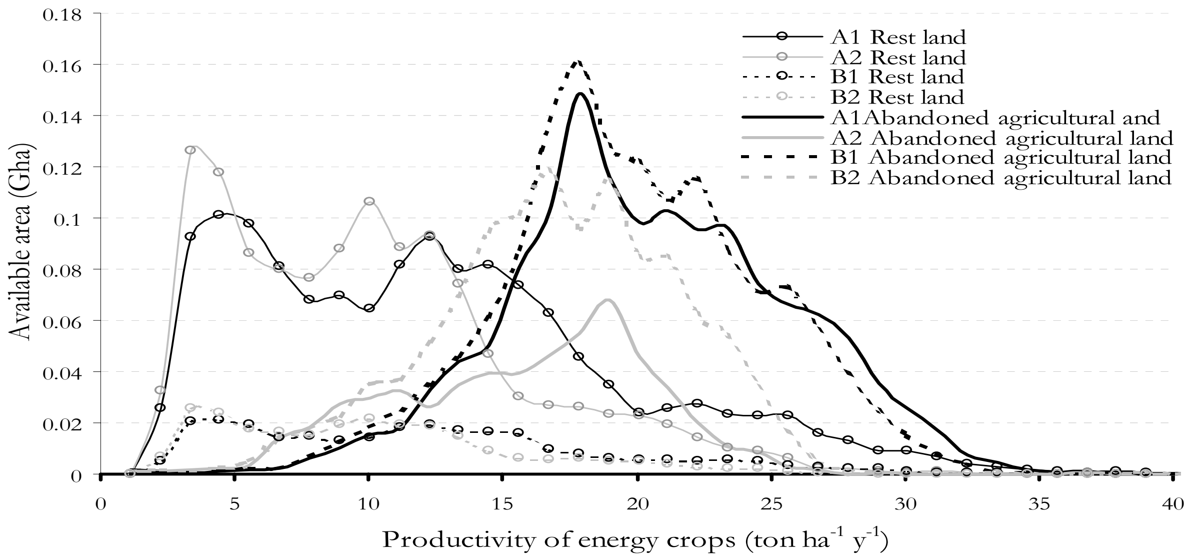

Figure 4: Available areas per land-use type for energy crop production and the distribution of the land productivity of energy crops at these areas for the four scenarios for the year 2050 (see Chapter 3).

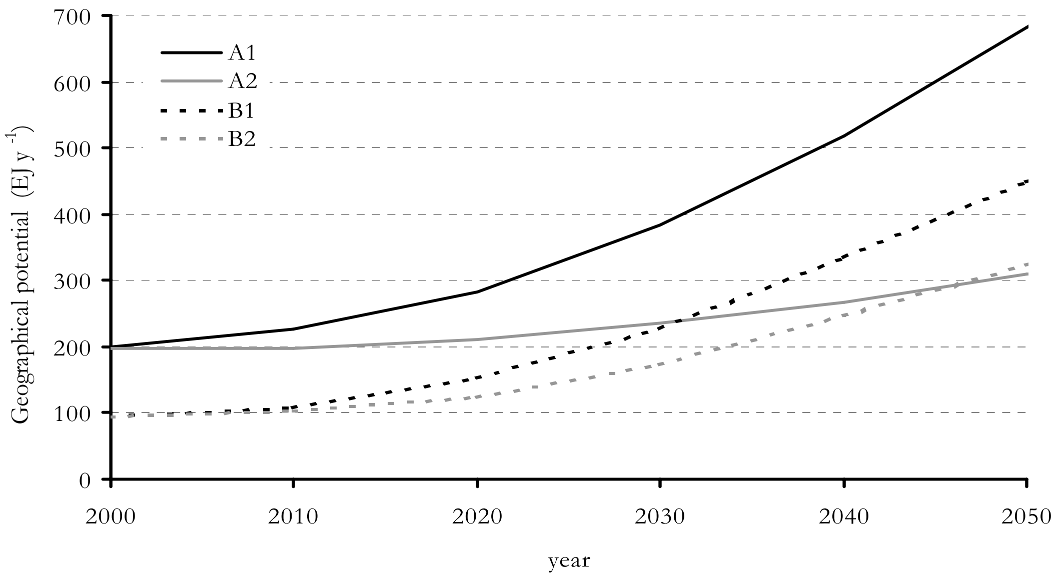

Figure 5: The global geographical potential of energy crops at abandoned agricultural land and rest land for four SRES scenarios between 2000 and 2050 (see Chapter 3)

3.2 Land rental cost

A second component in the calculation of primary biomass cost is the cost for land rental in region r, $p_{A,r}$ (\$ ha^{-1} y^{-1}). It depends on many local factors, such as the quality of land, the demand for land, subsidies and the distance to infrastructure. There is no unambiguous way of constructing a regional average from the – scarce – local data. The values mentioned in the literature (see below), give an indication of the ranges. Assuming a productivity of on average 150 GJ ha^{-1} y^{-1}, the land costs may range from 0.1 to 4 \$ GJ^{-1}.

We propose an estimation of the land rental costs based on data on the added value of land from the World Bank (Kunte et al., 1998). The added value of land is estimated as the difference between the (global) market value of the output crops and the crop-specific production costs, using market value and production cost of cereal, maize and rice. The data from Kunte et al. (1998) have been allocated to the regional division of IMAGE 2.2 and used to estimate also changes over time (Graveland et al., 2002). Because we assume biomass to be planted on land no (longer) required for food production and hence on relatively low productive land compared to agricultural land, the World Bank estimates will be too high. Therefore, Graveland et al (2002) have multiplied them with the ratio of the lowest productivity of the crop produced mostly in the region and the regional average productivity of that crop. These ratios are estimated in order of 0.2 – 0.6, varying among regions and changing over time if crop distribution changes. This ratio is in some regions low, assuming that land quality contributes significantly to the land price. This is a simplification that is expected to lead to an underestimation of land price. However, due to the complexity of the land price dynamics, we have only included this factor. The resulting estimated cost of land for the 17 IMAGE regions used in this study are shown in Table I. They are fairly similar to the values from literature for most developing regions and North America, however, low compared to OECD Europe. Land rental costs in the literature for agricultural or energy crop land are found ranging from 16 – 95 $\$_{2000}$ ha^{-1} y^{-1} in Africa (FAO, 1997), 27 – 150 $\$_{2000}$ ha^{-1} y^{-1} in Latin America (FAO, 1997; van den Broek, 2000; Marrison and Larson, 1995), 15 – 236 $\$_{2000}$ ha^{-1} y^{-1} in North America (Marrison and Larson, 1995; Perlack and Wrights, 1995; Williams and Larson, 1993; Walsh, 1998; Turhollow, 2000) and from 36 to 648 $\$_{2000}$ ha^{-1} y^{-1} in Europe (FAO, 1997; Rosenqvist, 2002; Toivonen and Tahvanainen, 1998; van den Broek et al., 1997; Dornburg, et al., 2003; de Jager et al., 1998).

Table I: The regional transport cost, the regional labour and the regional annual land cost estimated in this study, using the IMAGE 2.2 model based on land value figures from the World Bank (Kunte et al., 1998).

	Transport costs (C_t)	Labour cost (p_L)				Land cost (p_{Ar})			
	$ GJ^{-1}	$ h^{-1}				$ ha^{-1} y^{-1}			
		A1	**A2**	**B1**	**B2**	**A1**	**A2**	**B1**	**B2**
		2000-2050	**2000-2050**	**2000-2050**	**2000-2050**	**2025-2050**	**2025-2050**	**2025-2050**	**2025-2050**
Canada	0.33	12.6 – 26.4	12.5 – 18.2	12.6 – 26.4	12.5 – 21.9	64 – 68	65 – 67	64 – 65	65 – 67
USA	0.31	18.6 – 43.2	18.5 – 28.4	18.6-35.6	18.5 – 34.7	155 – 155	147 – 155	198 – 141	150 – 153
C America	0.29	1.7 – 15.5	1.6 – 5.9	1.7-13.7	1.7 – 7.0	137 – 119	145 – 123	137 – 119	144 – 124
S America	0.29	2.7 – 20.6	2.7 – 8.1	2.7-18.2	2.7 – 9.7	116 – 127	126 – 130	116 - 120	123 – 127
N Africa	0.4	0.8 – 9.4	0.8 – 3.3	0.8- 8.3	0.8 – 4.2	26 – 31	26 – 25	26 – 27	26 – 31
W Africa	0.4	0.2 – 2.6	0.2 – 0.8	0.2- 2.5	0.2 – 1.0	22 – 23	23 – 23	22 – 23	23 - 24
E Africa	0.4	0.1 – 2.2	0.1 – 0.7	0.1 – 2.2	0.1 – 0.8	20 – 21	22 – 21	21 – 22	22 – 21
S Africa	0.31	0.7 – 6.0	0.7 – 2.2	0.7 – 6.0	0.7 – 2.5	93 – 70	102 – 75	92 – 65	102 – 80
W. Europe	0.45	14.1–36.9	14.1 – 22.5	14.1 – 31.8	14.2 – 27.5	130 – 131	135 – 124	127 – 132	133 – 140
E Europe	0.38	2.0 – 23.9	1.9 – 7.0	2.0 – 14.0	2.0 – 12.5	72 – 66	73 – 71	72 – 70	73 – 71
F USSR	0.38	1.0 – 16.9	0.9 – 3.8	1.0 – 10.8	1.0 – 7.9	29 – 24	29 – 29	29 – 28	29 – 29
M. East	0.31	2.1 – 16.6	2.1 – 6.2	2.1 – 14.6	2.1 – 7.9	30 – 30	30 – 31	29 – 31	30 – 31
S Asia	0.31	0.3 – 6.4	0.2 – 1.0	0.3 – 4.3	0.3 – 3.1	111 – 147	109 – 148	107 – 147	118 – 114
E Asia	0.32	1.1 – 18.0	1.0 – 2.9	1.1 – 10.3	1.1 – 9.8	406 - 169	144 – 140	163 – 166	419 – 417
S-E Asia	0.26	0.9 – 11.0	0.9 – 2.6	0.9 – 7.1	0.9 – 7.8	155 – 149	181 – 149	153 – 151	156 – 150
Oceania	0.26	10.2–25.8	10.2 – 14.6	10.2 – 22.1	10.2 – 18.2	13 – 13	14 – 14	14 – 13	14 – 13
Japan	0.37	25.2–48.1	25.1 – 34.0	25.2 – 38.4	25.5 – 39.5	628 - 737	655 – 648	540 – 813	489 – 491
World		5.5 – 19.6	5.5 – 9.5	5.5 – 15.7	5.5 – 12.7	130 - 122	119 - 116	112 - 125	124 - 123

3.3 Capital, labour cost, substitution coefficient and learning

For the energy crop plantations, we assume that the expenses in the form of seeds or cuttings, machines required for planting, ploughing or harvesting and fertilizers and weed control can all be incorporated in a single cost figure: the annuitized capital costs. They reflect the prevailing production system used, e.g. intensive or extensive. Because of regional differences and differences in production system these costs can vary significantly. Currently observed costs of cuttings, for instance, range from 0.01 to 0.1 $ cutting^{-1}, with cutting densities for willow plantations at a level of 10 000 –16 000 cuttings ha^{-1} (van den Broek, 2000; De la Torre Ugarte et al., 2000). Operational costs during the production are to a large extent determined by the cost of fertilizer and fertilisation management. Pesticides and herbicides are less intensely used, mostly for the production of cuttings, e.g. van den Broek (2000). Because they depend strongly on the soil quality and literature shows not much experience yet with energy crop plantations, there is a wide range in estimates for the amount of fertilisation required. Estimates range from 9 –150 kg ha^{-1} y^{-1} for N, 2 – 90 kg ha^{-1} y^{-1} for P and 7 – 90 kg ha^{-1} yr^{-1} for K (Heilman and Norby, 1998; Coelman, 1996; de Jager et al., 1998; Turhollow, 1994; Lewandowski, 2001; Tuskan, 1998). The actually applied fertilizer can have a significant impact on land productivity. Fertiliser costs range from 0.4 to 1.6 $\$_{2000}$ kg^{-1} (Turhollow, 2000; Biewinga and Bijl, 1996). Using application levels as presented above, this results in costs per hectare of between 0.8 and 240 $\$_{2000}$ ha^{-1} y^{-1}. Assuming an average productivity of 150 GJ ha^{-1} y^{-1}, which might be overestimated for the low and underestimated for the high input case, results in a range of 0 to 1.6 $ GJ^{-1}. In our calculations we estimated the required capital from the labour costs and the capital-labour ratio, based on initial values of these labour and capital costs, based on van den Broek (2000).

Another important cost determinant is the price of capital, i.e. the interest rate. It is project-specific and depends on factors such as access to capital markets, project risk appraisal and credit facilities. We use a fixed interest rate of 10% for all regions, the same value as being used in the IMAGE 2.2 simulations (IMAGEteam, 2001).

The third important cost component is labour costs. These are a function of the required labour input and the labour wages. The wages differ for high-skilled and low-skilled labour. Average of high- and low-skilled labour wages per hour (assuming 8 hours of work per day) found in the literature are about 12 $\$_{2000}$ h^{-1} in Finland (Toivonen and Tahvanainen, 1998), about 13 $\$_{2000}$ h^{-1} in the USA (Strauss and Wright, 1990) and about 0.3 $\$_{2000}$ h^{-1} in Nicaragua and 12.8 $\$_{2000}$ h^{-1} in Ireland (van den Broek, 2000). In view of our model formulation, wage changes matter mostly and we use the development of regional GDP cap^{-1} as a proxy of the labour wages (see Table I).

For all regions, the capital-labour substitution elasticity is set at 0.65, based on the data presented in Figure 1. For the initial labour and capital input we use a cross-country analysis using data from the Netherlands, Ireland and Nicaragua (Figure 1). We have divided the regions in three groups according to their GDP value in the year 2000. The Netherlands is assumed to be representative for the regions with the highest GDP, Ireland for the middle class and Nicaragua for the lowest category.

For the assessment of the progress ratio, it is assumed that in the scenarios with a higher GWP and more global oriented (A1 and B1), the progress ratio is 0.9. For the other scenarios (A2 and B2), it is assumed that learning is less fast due to lack of investments and lower cross-country innovations; the progress ratio is set at 0.95. We assume the progress ratio to be constant over time. This is in contrast to what is suggested in the literature about decreasing progress ratios (e.g. McDonald and Schrattenholzer (2002)) but we found too little empirical evidence for time dependency of learning.

3.4 Transportation cost

Another cost component is transport. There are various aspects that determine the transport costs, at first the transport distance. The transport distance is a function of the size of the conversion unit and the supply around the conversion unit. This has been analysed in various studies, e.g. Marrison and Larson (1995) and Dornburg and Faaij (2001). The distance is the main reason for the choice of the type of transport medium. Truck transport is mostly favoured at short distances < 150 km (Hamelinck et al., 2003b; Ericsson and Nillson, 2003). Furthermore, the transport costs depend on the load that can be transported, also on the return trip (e.g. chips versus logs) and the car efficiency. The product of these factors and the fuel prices determines the fuel costs per transported commodity. For the USA it was shown that in the past 30 years the overall efficiency in MJ ton^{-1} km^{-1} has increased significantly, mainly due to an increase in transport load (Davis, 2001). In addition, there are costs for loading and unloading. These fixed costs depend on the type of biomass transported and the labour costs. Finally, there are charter costs, accounting for the truck rent. As the locations of the plants are not fixed and we do not have information on the distribution of the energy plantations within grid cells, such detailed analysis of transport distances cannot be conducted. Instead we use a fixed illustrative transportation distance of D = 50 km, which lies in the range found in the literature for national transportation of biomass (20 to 80 km) (Heller et al., 2003; de Jager et al., 1998; Walsh, 1998; Agterberg and Faaij, 1998). This distance implies an average distance to the plantation. We use a formulation for the transport costs C_t (\$ GJ^{-1}) and the parameters that is based on Northern European data (Hamelinck et al., 2003b) (see also Equation 5):

$$C_t = T + \tau \cdot D \cdot \tau \cdot F_r \cdot \upsilon \qquad (6)$$

Fuel costs are available for a large range of countries, the other parameters are more difficult to determine. One can argue that fixed and charter costs are lower in regions with relatively low wages. However, at the same time, the fuel requirement is often higher. We therefore calculated the transport costs by only varying the fuel costs as a first approach. Using data from (IEA/OECD, 2003), this results in a range in transport costs at a national level of 0.26 (New Zealand) to 0.6 \$ GJ^{-1} (U.K.). The fuel costs are for a significant share determined by taxes (Davis, 2001). No data for African countries are included in this range. We assume that the regions distinguished in this study have transport costs based on the averages of the national ranges. For African regions, we assumed similar costs as in the Former USSR and East Europe because of assumed low quality roads and low car efficiency. The transport costs at regional level are given in Table I. Due to lack of data, in the long term it is assumed that the transport cost remain constant.

Various studies conclude that international trade in biomass or energy carriers derived from biomass, such as liquid fuels, can be an interesting option, for instance between regions with limited resources but renewable energy targets and regions with ample supply of biomass (Agterberg and Faaij, 1998; Hamelinck et al., 2003b). At present biomass is also traded at significant levels, e.g. Ericsson and Nillson (2003). The cost of such interregional transport is excluded in this study.

3.5 Conversion to liquid fuel and bioelectricity

The cost-supply curve for the secondary biomass-derived liquid fuel and electricity requires data on the performance of the conversion plants such as the overall conversion efficiency (η_t), specific investment costs and the like. The assumptions regarding these variables are based on various sources, e.g. (Faaij et al., 1998; Tijmensen et al., 2002; Hamelinck et al., 2003a), and are given in Table II. They are taken as being equivalent across all regions. One can assume that similar technological learning takes place as was assumed for the production of energy crops. This reduces the specific investment costs. We therefore use the same cost reduction factors as calculated for energy crop production. The initial investment costs are based on figures as found in the literature, representative for a BIG CC plant of about 200 MW and a Fischer Tropsch plant of about 500 MW. One of the ways to achieve cost reductions is scaling up. The cost reductions assumed here can be reached using a scale of about 300 MW for BIGCC and about 1000 MW for Fischer Tropsch[20]. One may argue that further cost reduction is possible, e.g. by increasing the size of the conversion pant. However, as at present both technologies are not available at commercial basis, we rather use these, possibly more conservative figures.

Table II: Summary of the values of the parameters used in the cost calculations of different conversion technologies.

	Biomass electricity	Biomass transport fuel
Conversion route/type of fuel	Gasification – combined cycle	Gasification FT conversion
Typical scale (MWth)[b]	20-1000	100 - 2000
Status	Demonstration	Laboratory /Demonstration[a]
Conversion efficiency (%) (year 2000)	40	40
Conversion efficiency (%) (year 2050)	56	55
Availability (%)	95	95
Load factor[c]	0.7	0.8
Specific investment costs ($ kW^{-1}), (year 2000)	1370	1630
Specific investment costs ($ kW^{-1}), (year 2050)	A1, B1: 1120 A2, B2: 1300	A1, B1: 1180 A2, B2: 1380
Operational & maintenance costs (% of I)	4	4
Lifetime technology (year)	20	20

[a] The production of synthetic diesel by Fischer Tropsch technology using biomass is in the pilot scale, however, the conversion of coal to Fischer Tropsch oil is commercial already.
[b] We used typical scales mentioned in the literature for present plants and future plants.
[c] The load factor is defined as the ratio between the full-load hours per year and the total amount of hours in a year (8760).

[20] For BIG CC this estimate is based on a scale relation using a reference plant of 50 MW with an investment cost of 2400 $ kW^{-1} and a scaling factor of –0.4 (Faaij et al., 1998). For Fischer Tropsch, these investment costs are based on a scale relation using a reference plant of 400 MW with an investment cost of 1530 $ kW^{-1} and a scaling factor of –0.22 (Hamelinck et al., 2003).

4. The cost-supply curves of primary biomass energy

The production costs of energy crops develop over time. They may increase because of higher inputs required to obtain high productivity levels and increased labour costs. Over time, the production costs will fall due to productivity increases based on technological learning at a regional level. An example is given in Figure 6. Note the differences between the two scenarios (A1 and A2). The variation between the regions is comparable for the two scenarios, but the A1 scenario has larger reduction factors due to the larger geographical potential over time. In both scenarios, East Asia and Eastern Europe have the highest cost reduction potential. Note that technological learning is influenced by the overall geographical potentials as function of time and by the progress ratio, but also by the geographical potential in the initial situation, here chosen as the year 2000. This is the reason why for instance the Former USSR, the region with the highest potential, does not have the largest estimated cost reduction; this occurs in Eastern Africa for both scenarios.

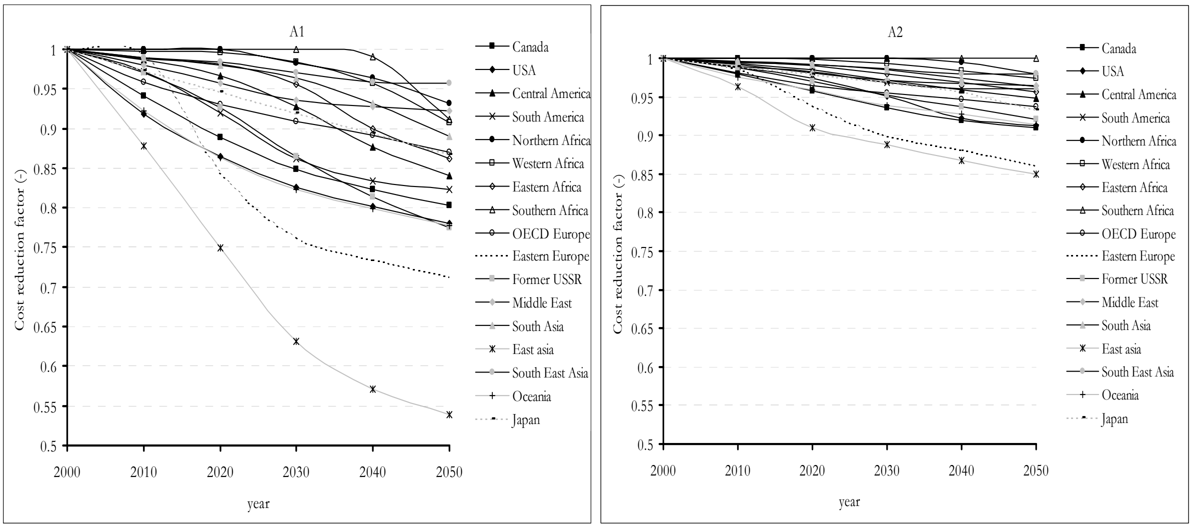

Figure 6: The cost reduction factor (λ) for capital and labour costs for the production of energy crops that takes into account the technological learning for the A1 and A2 scenario.

The global cost-supply curves of energy crops at abandoned agricultural land and at rest land for four SRES scenarios in the year 2050 are shown in Figure 7. Technological learning and capital-labour substitution in response to rising income c.q. wage levels are included. Also for the B1 scenario, the cost-supply curve for the year 2000 for abandoned agricultural land is shown. One should realise that these potentials not only depend on cost parameters, but also on the time-dependent geographical potential (Figure 5). Therefore, the two scenarios with the lowest value of the progress ratio (highest technology-induced cost-reductions) and the highest geographical potentials have the lowest energy crop production costs; A1 and B1. The cost-supply curves lie for a significant part, i.e. 130 (A2) - 270 (A1) EJ y^{-1} below 2 \$ GJ^{-1} which is considered the upper level of the present (1998) price for coal (Goldemberg, 2000). The lowest costs found for the year 2000 are 1 \$ GJ^{-1}. For 2050, the lowest costs are found at 0.8 \$ GJ^{-1}, in the A1 scenario in Eastern Africa.

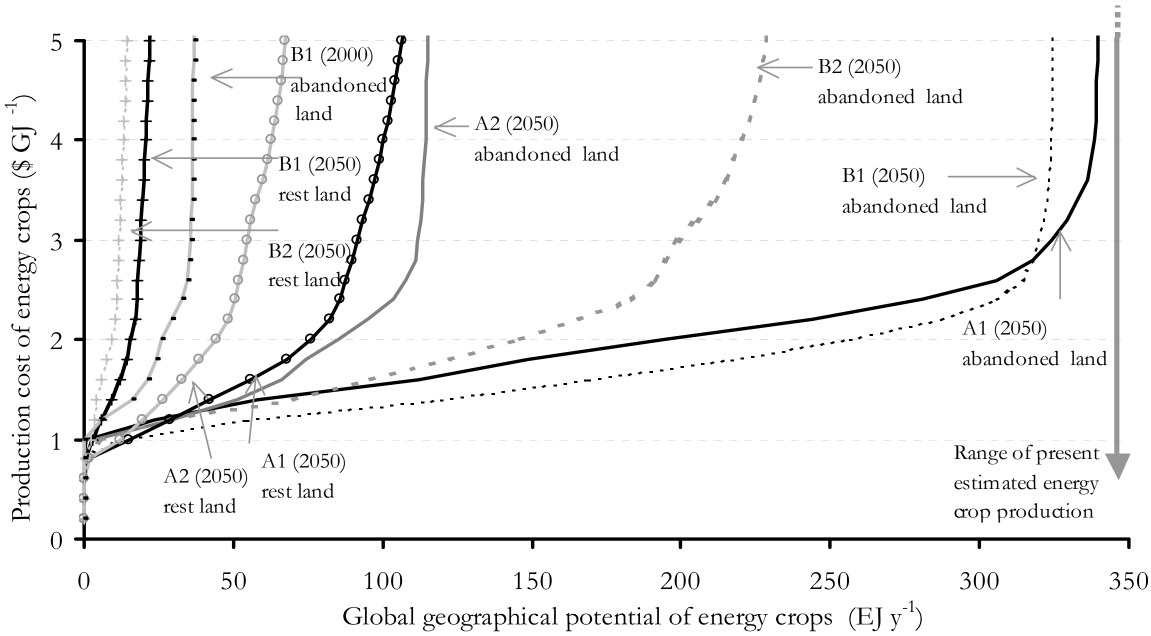

Figure 7: The global average cost-supply curve for the production of energy crops for four SRES scenarios for the year 2050 and the cost-supply curve at abandoned agricultural land for the year 2000 for the B1 scenario is also shown.

The results obtained for both land types together at the regional level are presented in Table III. It is found that Eastern and Western Africa has the lowest-cost largest potential (below 1 \$ GJ^{-1}). Regions that are assumed to be able to produce significantly at costs below 2 \$ GJ^{-1} are the Former USSR, Oceania, West and East Africa.

Table III: The total estimated geographical potential of energy crops for the year 2050, at abandoned agricultural land and rest land and the estimated geographical potential at various cut off costs for the four land-use scenarios, see also Figure 9b.

Region	A1				A2				B1				B2			
	Below 1 $ GJ^{-1}	Below 2 $ GJ^{-1}	Below 4 $ GJ^{-1}	Geographical potential (EJ y^{-1})	Below 1 $ GJ^{-1}	Below 2 $ GJ^{-1}	Below 4 $ GJ^{-1}	Geographical potential (EJ y^{-1})	Below 1 $ GJ^{-1}	Below 2 $ GJ^{-1}	Below 4 $ GJ^{-1}	Geographical potential (EJ y^{-1})	Below 1 $ GJ^{-1}	Below 2 $ GJ^{-1}	Below 4 $ GJ^{-1}	Geographical potential (EJ y^{-1})
Canada	0	11	14	18	0	8	9	12	0	11	12	14	0	10	11	13
USA	0	18	34	53	0	7	19	33	0	25	33	36	0	28	39	49
Central America	0	7	13	17	0	2	3	4	0	4	8	11	0	2	3	5
South America	0	12	74	87	0	5	15	24	0	28	61	63	0	6	33	43
Northern Africa	0	1	2	5	0	1	1	4	0	1	2	3	0	1	1	2
Western Africa	7	26	28	50	8	15	15	23	1	13	14	27	1	4	5	6
Eastern Africa	8	24	24	41	4	6	6	16	3	14	14	22	1	2	2	5
Southern Africa	0	13	17	43	0	0	1	10	0	12	13	29	0	0	0	2
OECD Europe	0	3	12	14	0	6	12	14	0	3	9	9	0	7	15	16
Eastern Europe	0	7	9	9	0	6	6	8	0	8	8	8	0	8	8	9
Former USSR	0	79	85	127	1	42	47	68	0	67	69	88	0	60	62	78
Middle East	0	0	3	13	0	0	1	8	0	0	2	4	0	0	1	3
South Asia	0	12	15	27	1	8	10	14	0	6	8	14	0	1	3	6
East Asia	0	16	64	107	0	0	6	23	0	50	61	77	0	0	21	46
South East Asia	0	9	10	10	0	7	7	7	0	3	3	3	0	2	4	4
Oceania	1	33	35	55	2	17	18	34	10	28	29	35	6	24	25	30
Japan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Global	16	271	438	675	15	129	177	302	14	272	344	443	8	155	234	316

Figure 8 shows for the A1 scenario the lowest regional energy crop production costs and their cost breakdown for the year 2050. The transport cost has a relatively high share in the delivered production costs in some African regions and in Oceania. Except for Japan, land costs do not contribute significantly to the overall production costs of energy crops. The capital and the labour costs are relatively high in the Middle East, due to a low cost reduction factor (Figure 6).

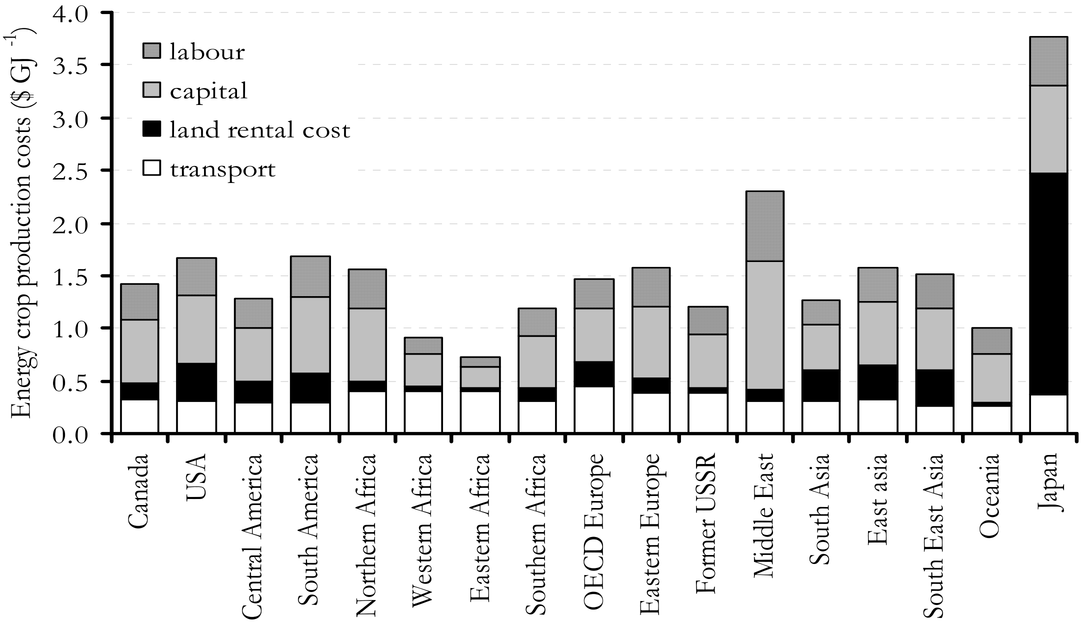

Figure 8: Cost breakdown for energy crop production costs in the grid cells with the lowest production costs within each region for the A1 scenario in year 2050.

Figure 9 shows the map of the world for the A1 scenario for the year 2000 and 2050, indicating where, according to our calculation, energy crops may be produced at costs below or equal to 2, 4 and 8 \$ GJ $^{-1}$ in the long-term. The figure shows that there are large areas in the Former USSR where energy crops may be produced at costs below 2 \$ GJ $^{-1}$. In Eastern Asia large areas are estimated where energy crops may be produced at costs below 4 \$ GJ $^{-1}$.

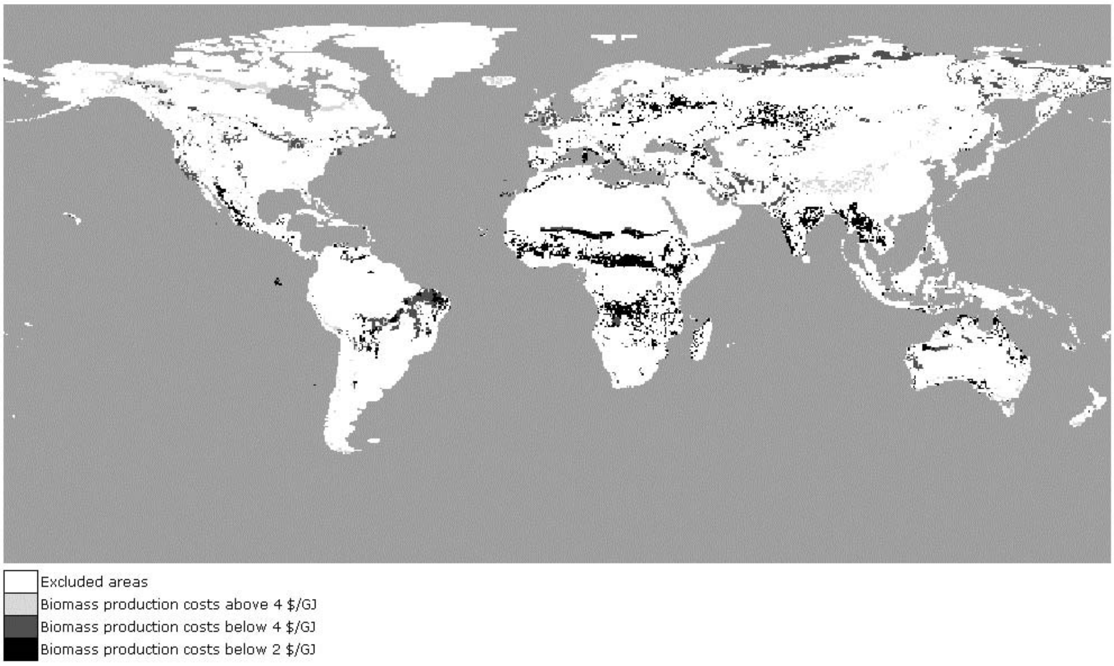

Figure 9a: Spatial distribution of production cost of energy crops for abandoned and rest land category in the year 2010 for the A1 scenario at abandoned and rest land area.

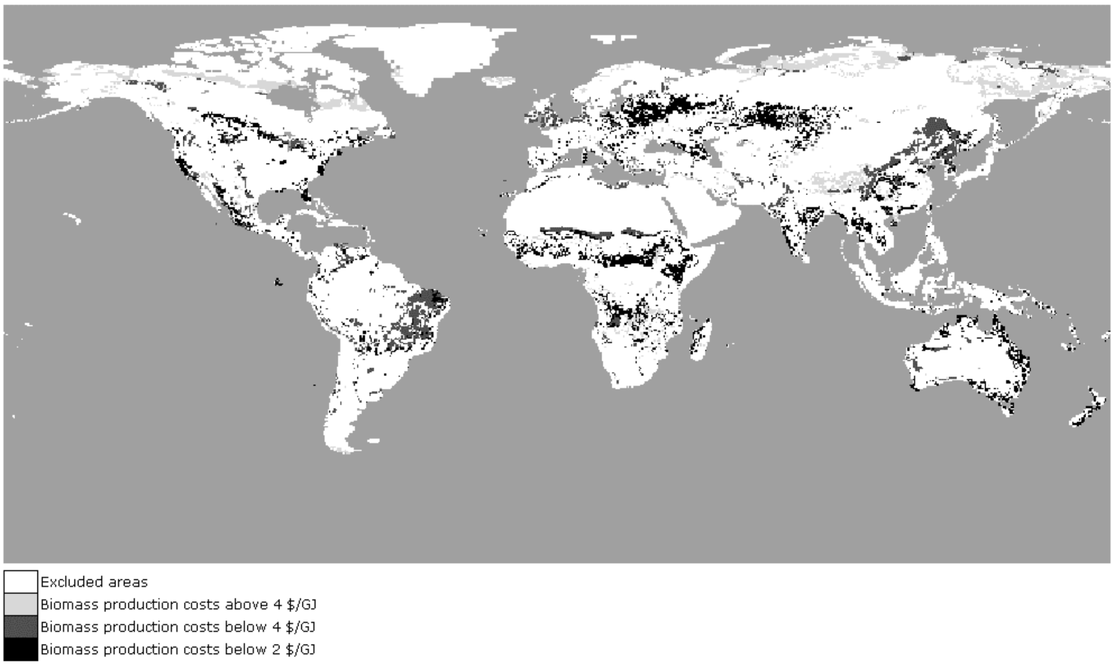

Figure 9b: Spatial distribution of production cost of energy crops for abandoned and rest land category in the year 2050 for the A1 scenario at abandoned and rest land area.

5. The cost-supply curve of secondary biomass energy

Figure 10 shows the global cost supply curve of biomass liquid fuel in the year 2050 using the primary biomass at abandoned agricultural land and at rest land for the four scenarios. Compared to the present production cost of diesel of about 5 \$ GJ^{-1} (Tijmensen et al., 2002), the costs of FT-diesel are high. As diesel costs fluctuate with the oil prices, the comparison is different for the long-term. Studies indicate that the world conventional oil production might peak in the timeframe we consider here, which may increase the diesel price in the long term, see e.g. Hakes (2000). The lowest production costs for biomass fuel are found in the A1 and B1 scenario, at a level of 9 \$ GJ^{-1}. For the A2 and B2 scenario, the lowest costs are found at about 10 \$ GJ^{-1}. The main differences between the two sets of scenarios are caused by the lower geographical potential development over time for A2 and B2, which leads to less technology-induced cost reductions.

The cost-supply curve of biomass electricity is shown in Figure 11. For comparison, we also indicate the future costs of electricity produced from fossil fuel with carbon capture and storage for various fuels and conversion plants, estimated to range from about 0.04 to 0.08 \$ kWh (David and Herzog, 2000) and present electricity production costs, at an average value for baseload plants of about 0.04 \$ kWh^{-1} (Goldemberg, 2000). These results show that biomass electricity may become able to compete with electricity from fossil fuel-powered plants with carbon capture and storage. It is found that in large-scale biomass fuelled power plants, the present world electricity consumption of 15.7 PWh y^{-1} (BP, 2002) may be generated in 2050 at costs between 0.04 – 0.045 \$ kWh^{-1} in A1 and B1 and at costs below 0.05 \$ kWh^{-1} for the other scenarios. At costs of 0.06 \$ kWh^{-1}, about 18 (A2) to 53 (A1) PWh y^{-1} can be produced. This is about 1.2 to 3.5 times the present electricity production.

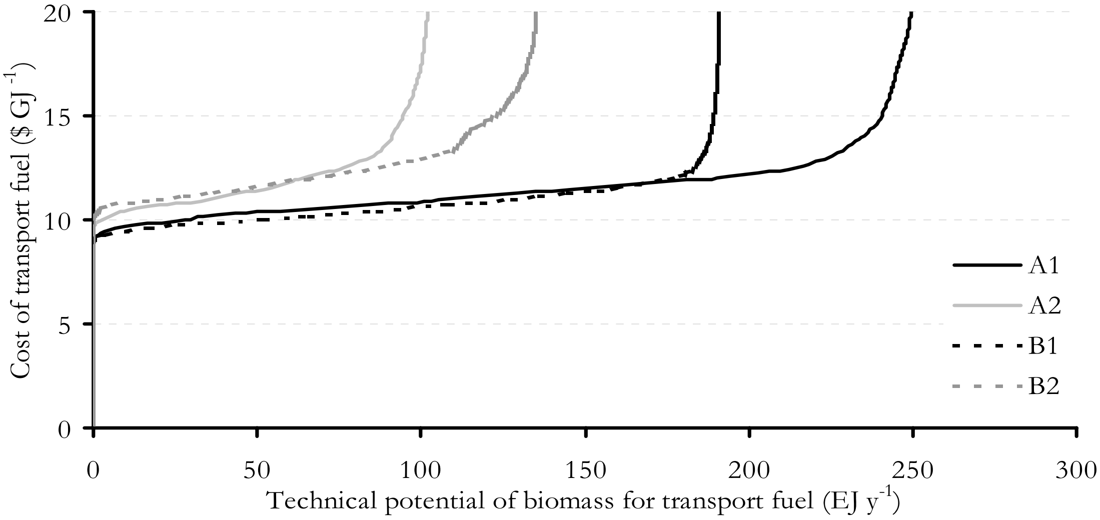

Figure 10: The cost supply curve for the year 2050 of biomass liquid fuel (synthetic FT diesel) using energy crop produced at abandoned agricultural land and rest land as feedstock for the four SRES scenarios

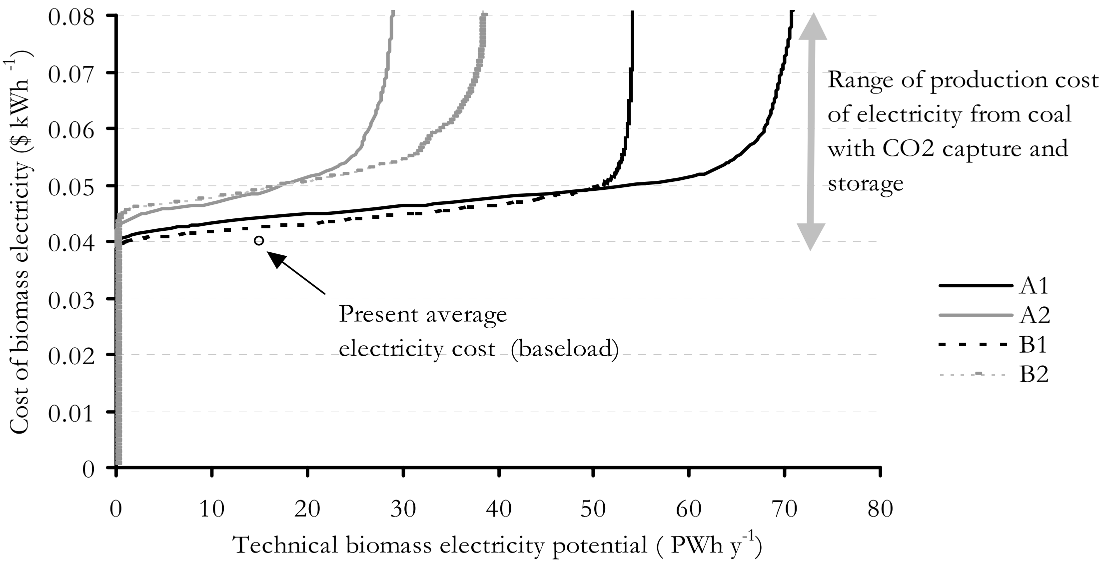

Figure 11: The cost-supply curve for the year 2050 of electricity using BIGCC conversion technology using energy crop produced at abandoned agricultural land and rest land as feedstock for the four SRES scenarios compared to present average baseload electricity production costs and estimates of future electricity production cost from coal-fired plants with CO_2 capture and storage.

6. Sensitivity analysis

In this study, the cost distribution of secondary biomass energy within and among regions is only determined by the costs of primary biomass. Therefore we investigate the sensitivity of the production costs of primary biomass for the various input parameters (Figure 12a and 12b), restricting ourselves to primary biomass from abandoned agricultural land for the A1 and A2 scenario. A1 and A2 are chosen as they represent the extreme ranges of the cost-supply curves. For one scenario (A1) we calculate the sensitivity of the cost-supply curve of electricity for the assumptions on conversion technology and costs (Figure 12c). To this purpose, we have varied the capital-labour substitution coefficient, the management factor, the interest rate, the initial capital and labour inputs, the conversion efficiency, the economic lifetime of the plants and the investment costs within a range of 25%. The progress ratio has been varied between 0.8 – 0.95 (A1) and 0.85 – 0.99 (A2). Figure 12a, 12b and 12c show that:

- The production costs of energy crops are most sensitive to the capital labour substitution. This implies that if e.g. mechanisation, and so capital-labour substitution stagnates (low α), the production costs in the year 2050 is almost doubled for the A1 scenario.
- Variation in the land productivity, incorporated by the management factor (MF), causes large variations in the production cost of primary biomass. Land productivity increase causes a lower relative land rental cost and an increase of the cost reduction factor due to technological learning.
- The cost-supply curve of energy crops is less sensitive to the other parameters.
- Primary biomass cost in A2 is less sensitive to variations in the input parameters, because the productivity and also labour wages increase over time are less in the A2 scenario compared to A1.
- The variation in the biomass-derived electricity cost varies similar as the production cost of energy crops. However, additional technical parameters are also important, as are the investment costs, resulting in a wide range of biomass-derived electricity costs.

Note that in practice not one but all parameters could have a value different from the default numbers used in this study. Consequently, the total variation can be larger than shown here.

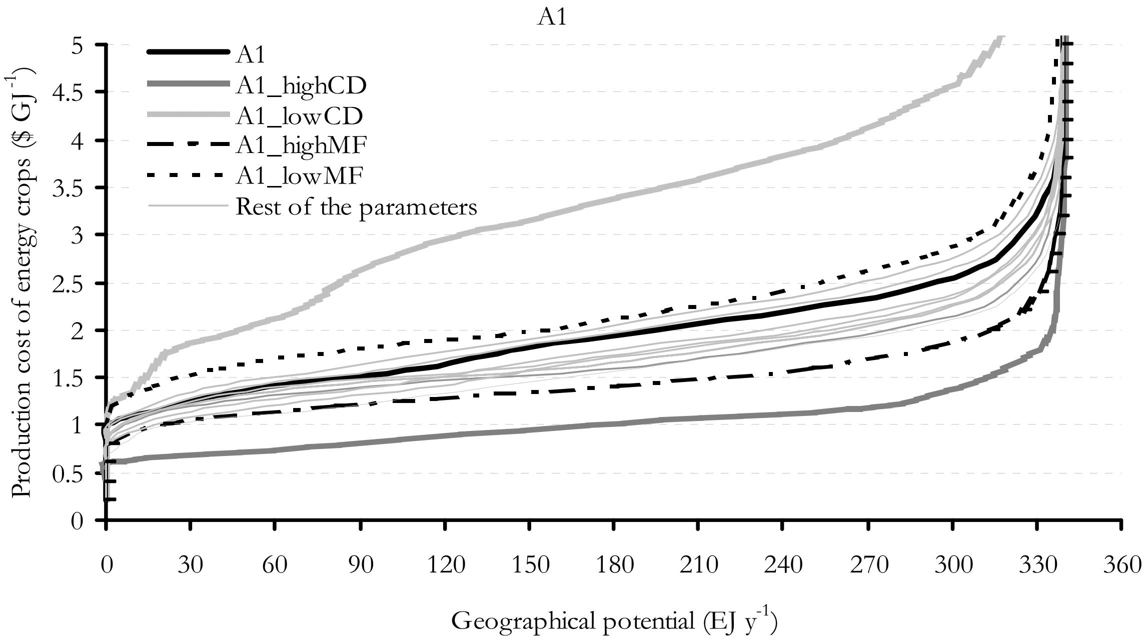

Figure 12a: Sensitivity analysis of the cost-supply curve of energy crops at abandoned agricultural land for the year 2050 within the A1 scenario by varying most important input parameters with ± 25%. The progress ratio has been varied between 0.8 and 0.95.

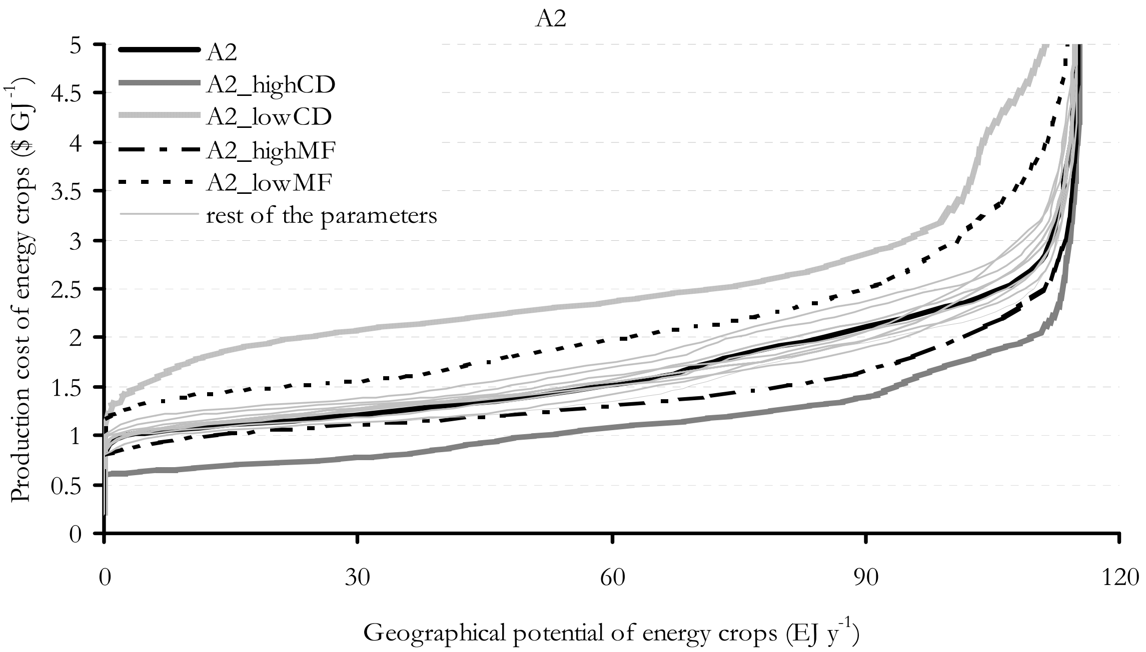

Figure 12b: Sensitivity analysis of the cost-supply curve of energy crops at abandoned agricultural land for the year 2050 within the A2 scenario by varying most important input parameters with ± 25%. The progress ratio has been varied between 0.85 and 0.99.

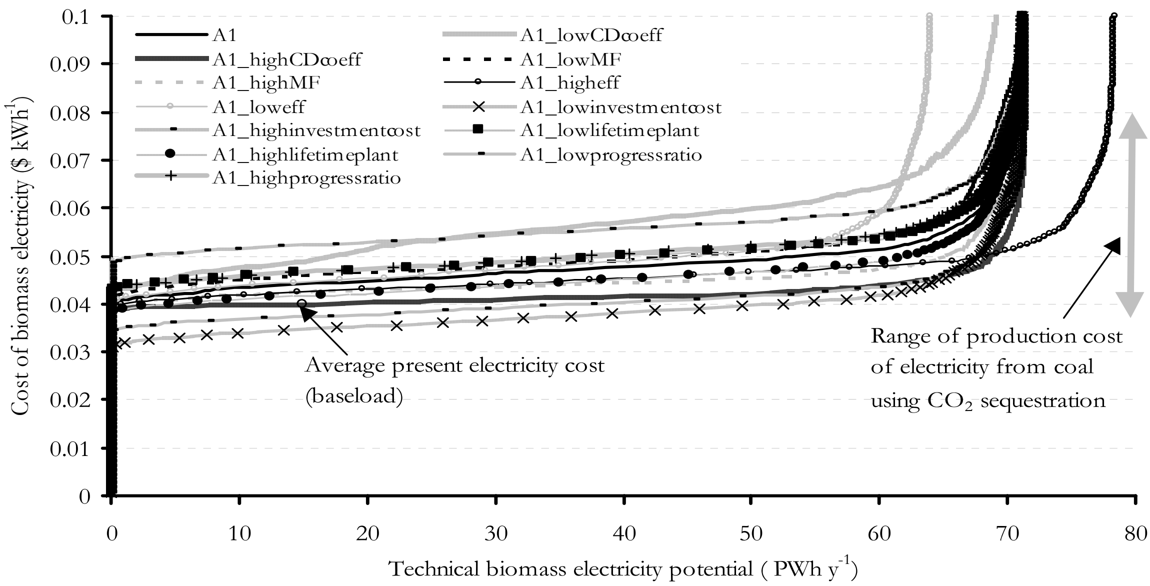

Figure 12c: Sensitivity analysis of the cost-supply curve of biomass electricity for the year 2050 for the A1 scenario by varying most important input parameters with ± 25%. (In the legend, *CD* means substitution elasticity, *MF* means management factor, *eff* means conversion efficiency.)

7. Discussion

7.1 Comparison with other studies

As this is the first attempt to estimate regional and global cost-supply curves of energy crops on the longer term in a systematic way, we cannot compare our results with previously published global supply curves. However, we can compare the results with production cost estimates for specific cases at project or national level for the present and future situation, although previous studies are based on different mechanisms compared to our estimates, e.g. (Hughes and Wiltsee, 1995; Walsh and Graham, 1995; Graham et al., 1995; de Jager et al., 1998). This comparison indicates that:

- Most literature sources on future energy crop costs assume that the capital and labour costs remain constant over time, and the costs reduce only due to autonomous land productivity increase. In our approach, with increasing land productivity inputs increase proportionally.
- In the literature, values for the future (2010-2020) woody primary biomass energy crop costs in the US are found ranging from 1.5 to 3.3 [21] $\$_{2000}$ GJ^{-1} (Hughes and Wiltsee, 1995; Hall et al., 1993; Graham et al., 1995). We assess comparable costs, but are on the low side. This is mainly explained as we assumed higher land productivity compared to other studies. This reduces the land costs to land productivity ratio.

[21] For this figure, Hall et al. have used a HHV of 17.9 GJ ton^{-1}, the cost value we present here is based on a LHV of 15 GJ ton^{-1} consistent with our estimates and converted to $\$_{2000}$.

- In the literature cost reductions are assumed to range from 35% to 60% in 10-20 years (Hughes and Wiltsee, 1995; Walsh and Graham, 1995; Graham et al., 1995). This is more optimistic than considered in this study. In our approach, cost reduction of primary biomass energy is assumed to be a function of the planted energy crops instead of an autonomous reduction resulting in cost reductions of primary biomass in 50 years of about 10 to 45 % for the A1 and B1 scenarios, 0 to 25 % for B2 and 0 to 15 % for the A2 scenario.

Cost levels of biomass electricity are also comparable with literature, e.g. (Graham et al., 1995) estimate cost-supply of biomass electricity from woody biomass for the USA. They conclude that 0.7 PWh y^{-1} can be generated in 2020 at costs below 0.045 $\$_{2000}$ kWh^{-1}. In our study, for the year 2050, in the USA, it is estimated that 3.3 PWh y^{-1} can be generated at costs below 0.045 $\$_{2000}$ kWh^{-1}. The main difference is that we focus on the year 2050 with higher land productivity levels compared to the year 2020.

For Fischer Tropsch diesel, detailed analysis on the conversion efficiency and production costs have been conducted by Hamelinck et al. (2003a). They state that on the longer term (~ 15 years) due to cost improvements, the production costs of Fischer Tropsch diesel may come down to about 10 $\$_{2002}$ GJ^{-1}, assuming primary biomass costs of about 2 $\$_{2002}$ GJ^{-1}. This is about equal to our lowest cost figures. We have assumed higher investment costs of the conversion plant, however, have used lower values of the energy crop production costs in the long term.

7.2 Limitations of this study

Our results of the cost estimates for the production of primary and secondary biomass fuels are in line with estimates conducted in other studies. Nevertheless, the approach used in this study is simplified from reality at various points, which limits the possibility to make firm statements about the future economics of biomass energy in different regions.

Several studies conclude that if one takes into account the ecological impact and the economics of the production system, woody short rotation crops are more interesting in the long term, see e.g. Kaltschmitt et al. (1997). However, alternative crops, like biomass waste streams or agricultural crops as sugar beet and perennial grasses can become competitive with short rotation crops studied here. Biomass liquid fuels and biomass electricity may therefore be available at lower costs than estimated here.

Our approach simplifies various economic and ecological aspects of primary biomass energy production. We aggregate cost components to four categories: capital, labour, land and transport costs and have not differentiated between different production systems, e.g. a high input system with irrigation and fertilisation and a more extensive system without irrigation or fertilisation. No extensive production system has been included. More information on the response of land productivity to e.g. irrigation and fertilisation could increase the accuracy of our results and of possible ecological impacts, as we have not conducted an ecological assessment of the energy crops. High land productivity levels may imply high inputs of water or fertilisers. We also do not include the possible cost increase as a result of possible negative ecological impacts, e.g. salinity of the soil or an increase in N_2O emissions. But neither do we consider potential ecological benefits such as erosion prevention or improvements of the C-content in the soil, see e.g. (Hall et al. (1993) and van den Broek (2000).

Various cost parameters are included at a global level, e.g. the interest rate, transportation cost and cost inputs of secondary biomass energy are dealt with in a simplified way. Cost estimates in this study show therefore less regional variety than is to be expected in reality. This is also the case for the estimation of the land costs. These are estimated at a regional level, but considerable differences in soil quality and competing options may exist within a region. More importantly, we have not included feedback mechanisms that take into account the impact on land costs from increased competition between food and energy crop supply. This mechanism can affect the land costs as the prices of food crops as well as energy crop increase with an increased demand of biomass for energy, see e.g. Azar and Berndes (1999). For a better understanding of these mechanisms more effort should be put in integrating the food system and the land costs.

Finally, it is to be noticed that the assumption on capital-labour substitution imply a reduced socio-economic benefit of employment often mentioned in the context of large-scale biomass production. To what extent this is a desirable in terms of sustainable development is not addressed here.

8. Summary and conclusion

We have explored the production cost of energy crops at abandoned agricultural land and at rest land at a regional and a global level to the year 2050. The estimations have been based on grid cell data on the productivity of short rotation crops on the available land over time and assumptions regarding the capital and the labour input required to reach these productivity levels. It can be concluded that large amounts of grown biomass at abandoned agricultural land and rest land, 130 to 270 EJ y^{-1} (about 40 to 70% of the present energy consumption) may be produced at costs below 2 \$ GJ^{-1} by 2050 (present upper limit of cost of coal). Interesting regions because of their low production cost and significant potentials are the Former USSR, Oceania, East and Western Africa and East Asia. Such low costs presume significant land productivity improvements over time and cost reductions due to learning and capital-labour substitution. An assessment of biomass fuel cost, using the primary biomass energy costs, shows that the future costs of biomass liquid fuels may be about twice the present diesel production costs, although this may change in the long term. Biomass derived electricity costs are at present slightly higher than electricity baseload costs and may directly compete with estimated future production costs of fossil fuel electricity with CO_2 sequestration (0.04 to 0.08 \$ kWh^{-1}). The present world electricity consumption of 15.7 PWh y^{-1} may be generated in 2050 at costs between 0.04 – 0.045 \$ kWh^{-1} in A1 and B1 and below 0.05 \$ kWh^{-1} in A2 and B2. At costs of 0.06 \$ kWh^{-1}, about 18 (A2) to 53 (A1) PWh y^{-1} can be produced.

The global curve that consists of all regional curves is found to be relatively flat, but this is highly sensitive to various input parameters, e.g. the elasticity that accounts for the substitution of capital for labour. If mechanisation, and so capital-labour substitution stagnates (low α), the production costs in the year 2050 is almost doubled for the A1 scenario. To enhance the insight in the future economic potential and competitive position of biomass energy, more research and more input data are required. It is recommended to focus future research on:

- The dynamics of the capital-labour substitution between the two production factors, to understand the impact of rising incomes.
- The technology development of the energy crop productivity for several production systems.
- The impact of large energy crop production on e.g. food production and agricultural land availability.
- The ecological impact of large-scale energy plantations.
- The possibilities of energy crops under more extensive production systems in comparison with intensive production systems as assumed here.

PART 2

WIND ENERGY

CHAPTER FIVE

ASSESSMENT OF THE GLOBAL AND REGIONAL TECHNICAL AND ECONOMIC POTENTIAL OF ONSHORE WIND-ENERGY#

Abstract

The regional and global geographical technical and economic potential of onshore wind energy is assessed using a grid cell approach. To assess the economic potential, the regional supply cost curves of wind electricity are presented. The global technical potential of wind electricity is estimated to be 96 PWh y^{-1}: about 6 times the present (2001) world electricity consumption at cut off costs of about 1 \$ kWh^{-1}. To realise this potential, an area of 1.1 Gha is required when the wind turbines are installed at an average power density of 4 MW km^{-2}. This is similar to the total global grassland area or to an area with the size of about China. The regionally highest technical potential of onshore wind energy is found for the USA: 21 PWh y^{-1}. Lowest figures are found for South East Asia, Southern and Western Africa and Japan. With present day technology, roughly an amount equal to the present (2001) world electricity consumption can be generated at a cost between 0.05 - 0.07 \$ kWh^{-1}, mainly in Canada, USA, South America, OECD Europe and the Former USSR.

Submitted to Energy Economics, co-authors are Bert de Vries and Wim Turkenburg. We are grateful to Jan Coelingh, Paul Smulders and Erik Lysen for commenting on draft versions and suggestions during the process.

1. Introduction

The power in the wind has been utilised for many centuries. The first windmills were used mainly for grinding grain and pumping water in Persia about 500-900 A.D. These were vertical-axis systems (Dodge, 2001). There is proof that in China and Tibet horizontal-axis windmills were used about 1000 A.D. By 1800 A.D. about 20,000 modern windmills were in operation in France alone and in the Netherlands about 90% of the power used in industry was based on wind energy (Ackermann and Soeder, 2002). In 1891, the pioneering Dane Poul LaCour built the first wind-energy turbine that generated electricity. The large-scale development of wind energy began after the oil crises in the 1970's, with wind farms being installed in California under an attractive tax scheme. At the beginning of the 1990's the US was leading in installed wind energy capacity. Germany took over around the mid 1990's due to effective government intervention. At the start of 2003, the installed capacity of wind energy in the world was 31.162 GW[22] against 2 GW in 1991. The main countries involved are Germany, USA, Spain, Denmark and India. In the last five years, the capacity increased annually by about 30%. The largest annual increase at country level (48%), in the period 1991-2001 was in Germany.

The rapid growth in wind capacity is reflected in the development of wind turbine technology. A significant trend is the up-scaling of the size of the turbines, increasing their output and reducing the generation costs and the visual impact on the landscape (Beurskens, 1999). The average size of installed commercial turbines has increased from about 30 kW in the mid-1970's (rotor diameter about 10 m) (Beurskens, 1999) to 1 MW at present (rotor diameter about 80 m) (Ackermann and Soeder, 2002). The largest commercial wind turbines now available are 2 MW. Wind turbines of 3 MW or more are under development. Other developments over the last few decades are better control and power regulation systems and focus on direct drive turbines. The latter involve higher investment costs (Bundesverband WindEnergie, 2001), but the direct drive turbine cost may be lower because no gearbox is needed. Furthermore, the energy conversion efficiency is improved (BTM, 2001; European Commission, 1999).

As is illustrated, there is recently a large policy interest in wind energy based on various arguments. First, wind energy reduces dependency on and payments for imported fuels. Second, it diversifies energy carriers for the production of electricity. Furthermore, it can increase the flexibility of the electricity system as demand changes and it saves fossil fuels for other applications and future generations. Finally, wind electricity reduces pollution and emissions, such as NO_x and CO_2 that are produced by conventional energy systems (Turkenburg, 2000). As wind energy becomes more and more competitive, many authors expect that a strong growth of installed wind turbines continues for a number of decades

[22] The figures of the global installed wind energy capacity is kept up to date by the 'Windicator', see http://www.wpm.co.nz/windicat.htm

(BTM, 2001; Nakicenovic, 2000; Johansson et al., 1993; Lazarus, 1993; Shell, 1995; World Energy Council, 1994; EWEA and Greenpeace, 2002; Turkenburg, 2000).

The global potential of wind energy has been assessed in previous studies. All have concluded that its (onshore) technical potential is sufficient to supply several times the total world electricity demand (e.g. Grubb and Meyer, 1993; World Energy Council, 1994; Fellows, 2000). However, a new evaluation of the potential of onshore wind electricity is useful for three reasons:

- The studies (except Fellows (2000)) have resulted in aggregate estimations of the theoretical and technical potential and have dealt in only a limited way with the spatial distribution of wind turbine applications. The assessment can be improved by using spatial data on average wind speed, land-use and land-cover data.
- Only two studies (World Energy Council, 1994 and Fellows, 2000) have included economic factors in the assessment. However, the cost data of the WEC are now out of date and the Fellows (2000) only focuses in detail on four regions. The assessment can be improved using recent knowledge on wind electricity production costs around the world.
- The methodological approach in previous studies has been applied on wind energy only. We have also applied a similar approach to assess the potential of biomass energy and photovoltaic electricity using the same background data for the spatial distribution of land-use and population as in Chapter 3, 4 and 6. This enables to compare the potentials and simulate the future role of different renewable energy sources in the electricity market, using an energy model like TIMER 1.0 (de Vries et al., 2002).

Therefore, this study analyses the potential of onshore wind electricity. First, we assess the world-wide theoretical, geographical and technical potential of onshore wind energy for electricity generation based on present day technology. Second, we estimate the production cost of wind electricity and construct wind energy cost curves as a function of the technical potential. The study is conducted at a global level, using a 0.5° x 0.5° (longitude, latitude) land-use grid and a division of the world into 17 regions. We evaluate the major uncertainties and assess the sensitivity for key assumptions.

We first describe the approach and definitions used (Section 2), by defining four categories of wind energy potential and by describing how the cost supply curves are constructed. Next we present the methodology used and the results found for each potential category (Sections 3, 4, 5 and 6). Section 7 contains a discussion of the results and a sensitivity analysis. We compare our study with other studies and evaluate the approach and input parameters. The final section presents conclusions that can be drawn from this study.

2. Approach and definitions

Consistent with the approach developed at Utrecht University (van Wijk and Coelingh, 1993) and published by the WEC (World Energy Council, 1994), we define four categories of wind energy potential: the theoretical, the geographical, the technical and the economic potential. Each category narrows down the previous one because it includes certain limitations and obstacles:

- Theoretical potential: The total global energy content of the wind (kWh y^{-1}).
- Geographical potential: The total global amount of land area available for wind turbine installation taking geographical constraints into account (km^2).
- Technical potential: The wind power generated at the geographical potential including energy losses due to the power density of the wind turbines and the process of generating electricity using wind turbines (kWh y^{-1}).
- Economic potential: The technical potential that can be realised economically given the cost of alternative energy sources (kWh y^{-1}).

We realise that the separate categories are not strictly defined and may be interpreted in different ways. However, the sequence included in the categories allows us to study the constraints that reduce the potential of wind energy. This gains insight in the factors important for the potential of wind energy.

For completeness, we also mention an additional category defined by van Wijk (1993); the implementation potential. Although the factors that are introduced in this type of potential are partly taken into account in this study in the geographical potential, the implementation potential is not studied in here:

- Implementation potential: the amount of economic potential that can be implemented within a certain timeframe, taking (institutional) constraints and incentives into account (kWh y^{-1}).

To analyse the implementation potential one needs a quantification of important social values and institutional interventions like subsidies, investment risks, local preferences, etc. These cannot be evaluated unless one defines a specific quantitative scenario based on population and economic dynamics. Possible barriers to implementation are visual and financial constraints or competition with other power generation options. However, it should be noticed that various social factors may already be encountered when estimating the geographical and technical potential. The assessment of the potentials is done at geographical grid cell level (0.5° x 0.5°), the results being aggregated to 17 regions: Canada, USA, Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, OECD Europe, Eastern Europe, Former USSR, Middle East, South Asia, East Asia, South East Asia, Oceania, Japan. These are consistent with the regions defined in the IMAGE 2.2 model (Integrated Model to Assess the Global

Environment) IMAGEteam (2001). For an overview of the approach, the reader is referred to Figure 1.

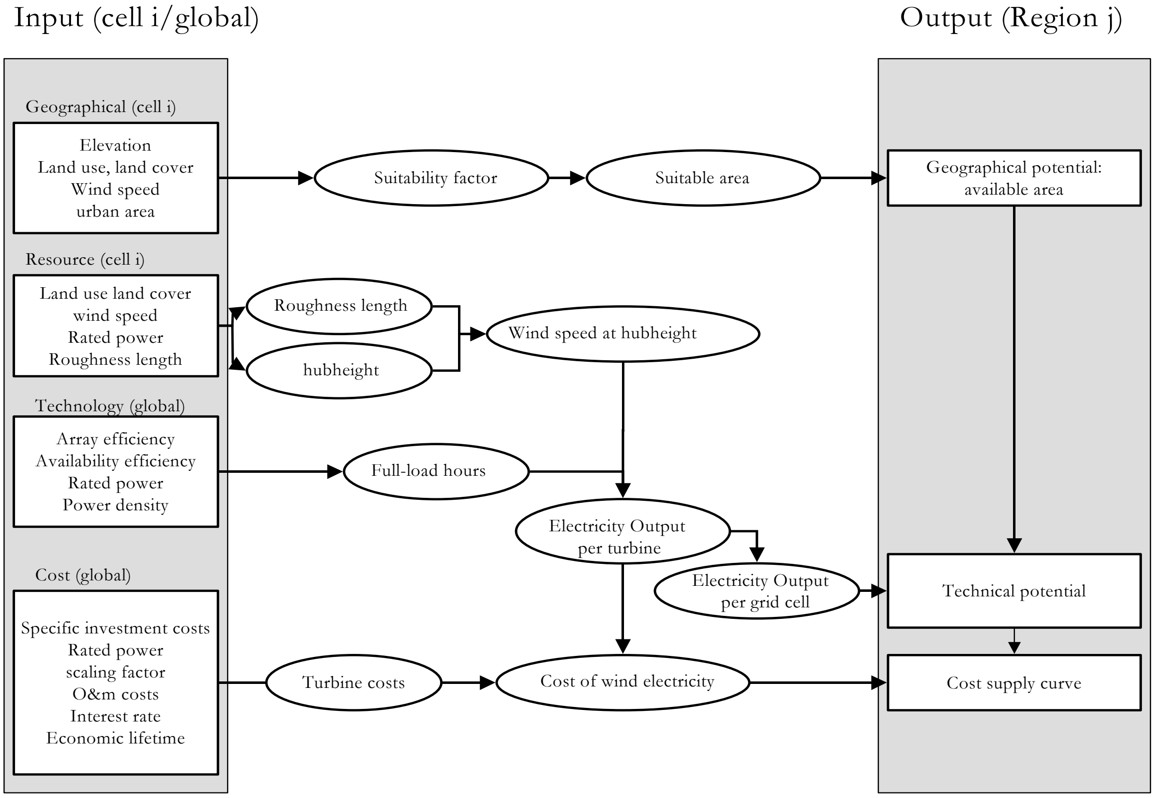

Figure 1: Outline of the calculation of the wind energy geographical, technical and economic potential.

3. Theoretical potential

Wind originates from temperature differences on earth that cause pressure differences in the earth's atmosphere. The rotation of the earth contributes to the speed and direction of the wind. The wind contains an amount of kinetic energy that can be expressed in terms of the mass of the air and the speed of this mass[23]. At grid cell level, it is conceptually difficult to calculate the power in the wind. The theoretical potential is rather derived from the theoretical solar energy reaching the atmosphere. King Hubbert (1971) estimated that the total wind power on earth is roughly equivalent to 2% of the solar energy reaching the atmosphere, which is about $3.5 \cdot 10^{15}$ W. Expressed in energy terms, this equals 110 ZJ; about 290 times the present world energy consumption of about 400 EJ (Goldemberg, 2000).

[23] The kinetic potential from wind energy is expressed as: $P = \frac{1}{2} \cdot \rho \cdot v^3$, where P is the power (W) per m^2 swept area; ρ is the air density in (kg m^{-3}) and v is the wind speed (m s^{-1}).

4. The geographical potential

The first reduction in the theoretical potential in this study is the restriction to onshore areas only. At present the wind energy indu4stry is showing much interest in offshore wind energy applications. The future of wind energy might be significantly offshore, in countries with a sizeable coastal region and land scarcity like the UK and the Netherlands. The technical potential of offshore wind electricity production is considered to be large and generation costs may decrease to cost-effective levels (Matthies et al., 1995; de Noord, 1999). However, offshore wind energy is excluded in this study because insufficient wind speed data are available to justify a proper analysis of the global offshore wind energy potential. Studies on the global wind energy offshore potential estimate its value at 37 PWh y^{-1} at 50 m depth, requiring 5.5 million km^2, with the largest potential found in Europe (8.5 PWh y^{-1}) (Leutz et al., 2001).

The onshore area available for wind power is further restricted to areas that are suitable for wind turbine installation. At the level of detail we are working on in this study, it is impossible to quantify all factors involved. We consider only constraints due to the wind regime, the land-use function of the area (including bioreserves), altitude (i.e. elevation), and the urban area (percentage of settlements within a geographical grid cell). These constraints are visualised in Figure 2. The area left after these constraints have been taken into account and is expressed as a fraction of the total area in each grid cell: the suitability factor f_i. This fraction ranges from 0 to 1. Hence, the geographical potential in each cell i (Gp_i) can be formulated as follows[24]:

$$Gp_i = A_i \cdot f_i \tag{1}$$

where Gp_i is the geographical potential in grid cell i (km^2); A_i is the total **onshore** area (km^2) in cell i and f_i is the suitability factor for socio-geographical constraints in cell i (-). The f_i is calculated from the following expression, using data from the IMAGE database (IMAGEteam, 2001) as:

$$f_i = \frac{(A_i - u_i) \cdot a_i \cdot w_i \cdot b_i \cdot r_i}{A_i} \tag{2}$$

with u_i the urban area in cell i (km^2); a_i the binary weighting factor for altitude (-); b_i the suitability factor for bioreserves being 0 if there are protected areas or areas with high

[24] As the theoretical potential could not be estimated in every grid cell, we express the geographical potential as the suitability factor f_i multiplied with the area. It would have been more logical to express the geographical potential in energy terms.

natural values and 1 for all other areas (-); w_i the suitability factor for land-use and land-cover function of cell i (-) and r_i is the suitability factor for wind regime restrictions (-).

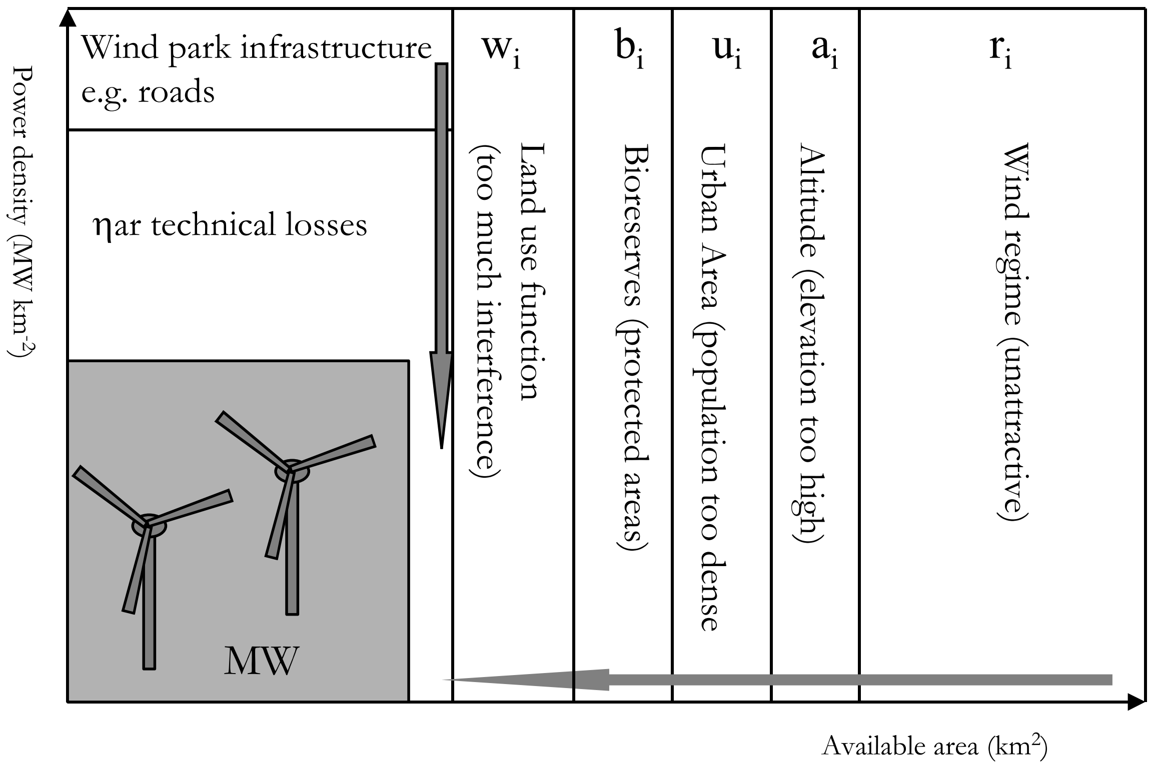

Figure 2: The constraints reducing the area available for wind turbine installation: altitude, urban area, bioreserves and other land-use functions, along the vertical axis are the constraints reducing the power density (see Section 5). The size of the boxes is illustrative.

Constraint 1: wind regime (r_i)

The wind turbines built at present have power curves[25] that can be parameterised for any wind regime: when the distribution in the wind (see Section 5) and the average wind speed are taken into account, it is technically possible to develop a wind turbine for situations with marginal wind resources. However, in reality, at these marginal sites no wind turbines will be installed since the output of a turbine in such a situation would be low, and so the wind electricity production costs high. Therefore, in this study we restrict the area to wind regimes with an average wind speed higher than 4 m s^{-1} at a height of 10 m at the specified resolution of 0.5° x 0.5° based on the available CRU database (the database is described in Section 5). Although this wind speed value is based on arguments concerning the output of a turbine and not on geographical constraints, it is included in the geographical potential since it restricts the available area.

[25] The power curve of a wind turbine indicates the electric output of a turbine (kW) at various wind speeds (m s^{-1}). It is determined by the cut-in speed (v_i) (minimum wind speed for power generation), the rated wind speed (v_r) (wind speed with output at rated power) and cut-out wind speed (v_o) (maximum wind speed until the generator is turned off) (see also Section 5).

The criterion might be considered too loose, since other studies have assumed stricter criteria, e.g. a wind regime above 6.0 m s^{-1}, or 5.1 m s^{-1} at 10 m (Grubb and Meyer, 1993; World Energy Council, 1994), based on the assumption that wind turbines at locations with an average speed below 5.1 m s^{-1} at 10 m of height cannot generate wind electricity at economically viable levels. There are two justifications for our choice. First, we introduce a wind electricity kWh - cost curve as a function of the supply (technical potential). Hence sites with a low average wind speed, end up in the upper - less attractive - part of the curve. Secondly, the database used in this study supplies one figure for the average wind speed at the specified resolution of 0.5° x 0.5°. The value of these figures is relatively low (see Section 5). For instance, about 80% of the global area has an annual average wind speed lower than 4 m s^{-1} at 10 m in the CRU database (e.g. Sub Saharan Africa and the total Indian continent). If we confine the estimate to an area with an average wind speed higher than 5.1 m s^{-1}, large areas that are known as areas where wind turbines are installed at present would have been cut off (92% as a global yearly average!).

Constraint 2: Altitude (a_i)

We restrict the suitable area to grid cells with an average altitude below 2000 m. Data on altitude are taken from the IMAGE 2.2 model, which assigns one value per grid cell (IMAGEteam, 2001). It is assumed that if a cell has an average altitude above this value, access would be too difficult and hardly any turbine could be installed. Furthermore, the air density – and thus the power in the wind – falls with height. The air density at 2000 m is reduced to a value of about 0.95 kg m^{-3}, compared to 1.29 kg m^{-3} at sea level at 20° (Lysen, 1982). This means 25% less power according to the expression of the power in the wind. On the other hand, however, the wind speed mostly increases with increasing altitudes. The value of 2000 m is rather arbitrary. It is known that wind turbines have been installed at altitudes of 1835 m (Oberzeiring, Austria; EWEA, 2001). Some turbines are found at higher altitudes in Latin America; however they are not installed on a large scale.

Constraint 3: Urban area (u_i)

We exclude urban area in our assessment because highly urbanised or otherwise densely populated regions are severely constrained as is evident in potential assessment and planning studies at national level (British Wind Energy Association, 2000; Elliot and Schwartz, 1993; EIA, 1999; Cabooter et al., 1997). Data on the urban area are obtained from the IMAGE 2.2 model. They are based on the DIScover database that supplies detailed data at 1 x 1 km cells, with urban area defined as land covered by buildings and other man-made structures (Loveland and Belward, 1997; Belward and Loveland, 1995). The data have been converted to 0.5° x 0.5° grid cells in order to construct a database that gives the fraction of urban area in each cell. This fraction is calculated by dividing the number of original 1 x 1 km cells classified as 'urban and built-up' by the total number of 1 x 1 km cells included in the 0.5° x 0.5° cell considered.

Constraint 4: Other land-use function (w_i)

The suitability of an area for wind turbine installation also depends on the current land-use function. This constraint is included using a suitability factor for land-use functions (w_i) at grid cell level, defined as the fraction (between 0 and 1) of the land that is suitable for wind energy applications at a certain power density. The land-use land-cover functions as well as the data on bioreserves at grid cell level are taken from the IMAGE 2.2 database (IMAGEteam, 2001). The data are allocated to the whole grid cell, as is the factor w_i. It is assumed that with installed turbines this part of the cell area will fulfil the same land-use function as before and no additional cost have to be made.

Siting constraints depend on land-use and land-cover functions; in most cases installing wind turbines means dual land-use. This is best illustrated with agricultural land, where the installation of wind turbines can easily be combined with the production of vegetables or with keeping cattle (Pimentel et al., 1994). When wind turbines are planned, urban areas, bioreserves, lakes and other water bodies are often excluded (British Wind Energy Association, 2000; Elliot and Schwartz, 1993; EIA, 1999; Cabooter et al., 1997). Some studies have also investigated restrictions applicable to forest areas (EIA, 1999; National Wind Coordinating Committee, 1997; Elliot and Schwartz, 1993).

Elliot and Schwartz (1993) include in their assessment of the technical potential of wind energy in the U.S. three different scenarios for site exclusion. The environment scenario excludes only environmental areas designated as nature and wildlife parks. The severe scenario restricts the available area to 10% of rangeland. The so-called moderate or realistic scenario assumes that 90% of range and barren lands, 70% of the agricultural area, and 50% of the forest area is available for wind turbine installation (Elliot and Schwartz, 1993).

We base our estimate of siting constraints on these studies (Table I). High suitability factors are given to land-use land-cover categories that facilitate dual use; lower factors or even zero to categories where this is not possible. Nature reserves are totally excluded (b_i = 0). Forest areas are categorised into tropical forests and non-tropical forest (e.g. temperate, boreal). The former is excluded entirely, whereas 10% of other forest types are assumed to be available.

Table I: Suitability factors and roughness lengths (see Section 5) that are assumed in this study for land-use categories. The roughness lengths are based on (Wieringa and Rijkoort, 1983) and (Lysen, 1982).

Land-use category taken from IMAGE 2.2	Suitability factor (-)				Roughness length[a] z_o (m)
	This study	U.K[b]	U.S.A[c]	Belgium[d]	
Bioreserve (b_i)	0	0	0	0	-
Agricultural land (w_i)	0.7		0 – 0.7		0.25
Extensive grassland (w_i)	0.8		0.1 - 0.9		1
Forest (boreal) (w_i)	0.1		0 – 0.5		1
Tropical forest (w_i)	0				1
Tundra (w_i)	0.8				0.25
Wooded tundra (w_i)	0.5				0.25
Grassland/steppe (w_i)	0.8		0.1 - 0.9		0.03
Hot desert (w_i)	1				0.005
Shrubland (w_i)	0.5				0.1
Savannah (w_i)	0.9				0.25

[a] The roughness length as a function of the land-use category is used in Section 5

[b] British Wind Energy Association (2000)

[c] Elliot and Schwartz (1993)

[d] Cabooter et al. (1999)

We have applied these restrictions to the grid cell data from the IMAGE 2.2 database. The regional average contribution of the constraints to the geographical potential is shown in Figure 3. It can be seen that the constraint for the suitable wind regime is most severe; in some regions it even reduces the suitability factor to nearly zero (South East Asia and Southern and Western Africa). The USA, Canada and Oceania have the highest suitability factor, respectively 27%, 21% and 24%. The global average value of f_i of the total onshore area is 9%.

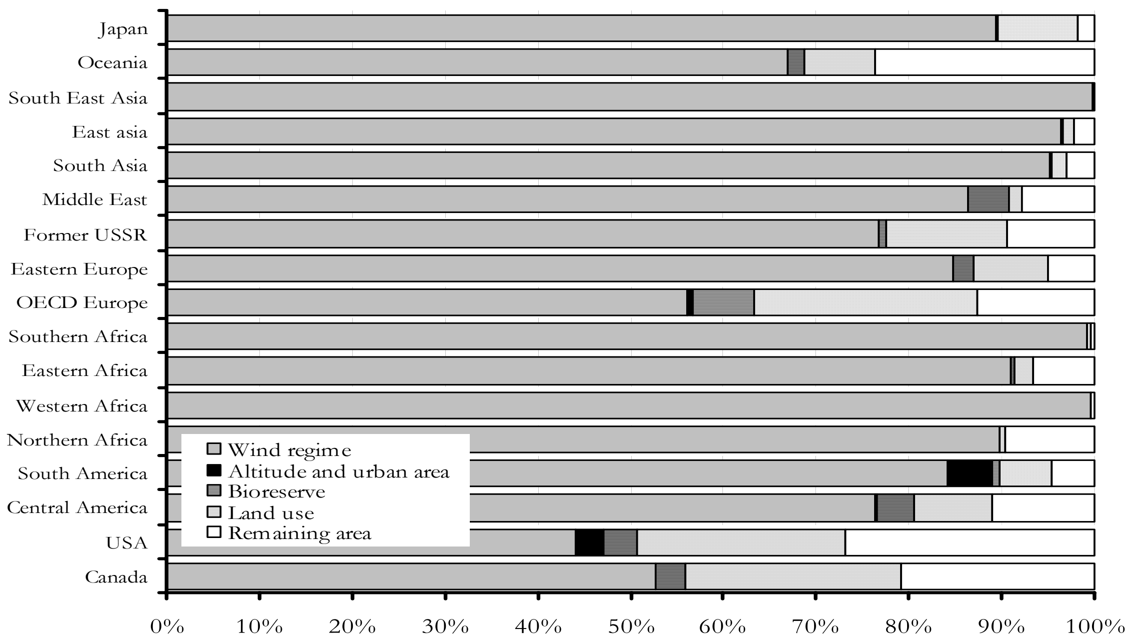

Figure 3: The regional siting constraints for the installation of wind turbines. In this figure, the remaining category equals the suitability factor, f_i.

5. The technical potential

The next step is to determine the technical potential, which is in this study the wind power that can be generated at the suitable area. The technical potential in a grid cell i is expressed as:

$$E_i = f_i \cdot A_i \cdot \eta_a \cdot \eta_{ar} \cdot D \cdot h_{f,i} \tag{3}$$

with E_i the wind energy output in grid cell i (kWh y^{-1}); η_a the average availability of the wind turbine (-) and η_{ar} the wind farm array efficiency (-); D is the power density (MW km^{-2}) and $h_{f,i}$ the full-load hours in grid cell i (h). Only the suitability factor f_i (described above), and the full-load hours $h_{f,i}$ differ at grid cell level. The global technical potential in kWh y^{-1} (E_i) is expressed as the sum over all grid cells.

5.1 Wind regime

Wind speed database

We use the average monthly wind speed at grid cell level at 10 m of height (V_{10}) but have aggregated the results to annual averages. The wind speed data for cells are taken from the digital database at grid cell level (0.5° x 0.5°) constructed by the Climate Research Unit (CRU) (New et al., 1997; New et al., 1999)[26]. The wind speed is presented in m s^{-1} at a height of 10 m. The dataset is constructed from climatic average measured values (1961-1990) from 3615 stations, covering the world. The coverage of the stations is highest in Europe and lowest in Oceania (New et al., 1999). The original measured values come from national meteorological agencies and the World Meteorological Organisation (WMO). The data at grid cell level are constructed by interpolation of the measured data; uncertainties are not specified. CRU[27] mentions errors in the data originating from the confusion of units, i.e. between metres per second and miles per hour and knots per hour. Furthermore, it was mentioned that the anemometer heights can vary greatly from the desired 10 m (e.g. between 2 m and 20 m.). Errors of these kinds are known to have occurred in Peru, Bolivia, Honduras, Sudan, Sierra Leone and Greece. In Latin America (Peru/Bolivia) unrealistic high values were found for the average wind speed (e.g. 25 m s^{-1} at 10 m). These figures are not used. Instead we have used a value adjusted to the neighbouring grid cells.

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[26] The geographical co-ordinates of the wind speed data from CRU do not match completely with the grid cell definition of the IMAGE 2.2 database. The CRU database has been converted to the raster of the IMAGE 2.2 database from which all the land-use data are taken. Furthermore differences existed in the definition of land cells versus sea cells. This was the case for 4200 (border) grid cells. These data have been converted by means of linear interpolation. Cells that border the shore are included in this study if more than 10% is defined as land. We have included only the onshore area fraction in these cells.

[27] All errors are mentioned on their web page http://ipcc-ddc.cru.uea.ac.uk/

No digital databases or atlases providing monthly or annual average wind speed values at grid cell level for the world have been published. Therefore a detailed comparison of our wind speed data with other studies could not be made. To explore the quality of the data we have done a visual comparison with maps from the European wind atlas (Petersen et al., 1981), the Wind Atlas for the U.S.A (Elliot et al., 1986), the wind atlas of India constructed by the Indian Institute of Tropical Meteorology (Rangarajan, 1998) and a wind atlas for South East Asia (TueWind Solutions, 2001). These comparisons show that the data are fairly consistent. Similar patterns are found and values are of the same order of magnitude, although the figures from the CRU database seem to be slightly lower than those in the wind atlases. In particular the comparison with the wind atlas of India (Rangarajan, 1998) showed that the wind speed data may regionally be rather low. While the CRU data give for India a regional annual average of 2.3 m s^{-1} at a height of 10 m, Rangarajan gives the lowest value as 2.5 m s^{-1} at 10 m. (Rangarajan, 1998).

Extrapolation to hub height

The wind speed (v) changes with altitude because of frictional effects at the surface of the earth. We therefore have to correct for the wind speed at the presumed average hub height of the installed wind turbines. Assuming a stable situation and a measured wind speed at 10 m, the average wind speed at height H can be calculated according to Lysen (1982):

$$V_H = V_{10}\left(\frac{\ln(H / z_0)}{\ln(10 / z_0)}\right) \tag{4}$$

where H is the height (m); V_H is the wind speed at height H (m s^{-1}) and z_0 is the roughness length of the surface (m).

We adjust the average wind speed V from the CRU database by estimating the roughness length (z_0) (Table I), using data on land-cover land-use taken from the IMAGE 2.2 database (IMAGEteam, 2001). The hub height, as part of the turbine design, is a function of the wind regime, the rotor diameter and the rated power of the turbine. To obtain a generic relation, we have analysed the hub height as a function of the rated power for a number of turbines commercially available in Germany (Bundesverband WindEnergie, 2001) in 2000. The data have been plotted as a function of the rated power (Pr) (Figure 4). A linear regression applied to these data yields the following empirically derived expression:

$$H = C \cdot \mathrm{P_r}^{w} \tag{5}$$

where C and w are constants at 10 and 0.28 resp. For the default turbine with a rated power *Pr* of 1000 kW, a hub height of 69 m is found.

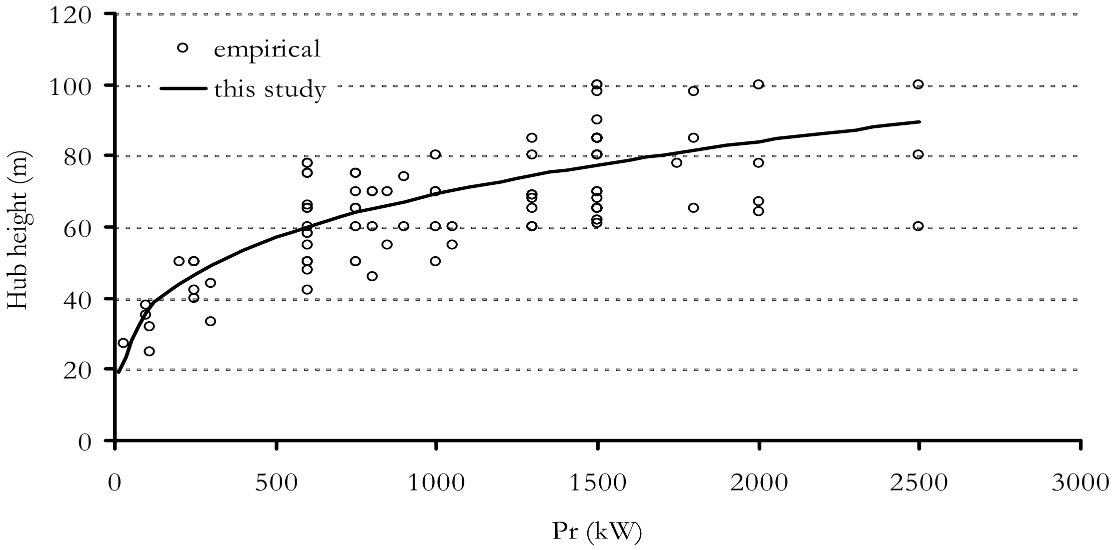


Figure 4: The relation between the rated power of a wind turbine, Pr (kW) and the hub height (m), as derived from data from existing wind turbines of the German market (Bundesverband WindEnergie, 2001).

5.2 Wind turbine output; amount of full-load hours

The electricity output per turbine depends on the wind regime. In most regions this can be described by a Weibull distribution function (see e.g. Stevens and Smulders (1979)[28]). The output also depends on the rated power of the wind turbine generator (Pr), the swept area (*Ar*) and the power curve of the turbine. Various combinations are possible between the generator and the rotor diameter, leading to different full-load hours (h_f)[29] for the wind turbine. The aim is to achieve a cost-effective optimum, which is attained at full-load hours around 2000 (BTM, 2001).

However, this optimum is attainable only if one can choose out of a large set of turbines for every type of wind regime. In reality this is not the case. Only a restricted number of turbines are commercially available. We therefore follow a more realistic approach in which the turbine is not optimal for the wind regime. Data on the yearly output and the yearly average wind speed of various wind turbines at 7 locations (wind farms)[30] (Windstats, 2000) show that there is a correlation between full-load hours and average wind speed (Figure 5). The full-load hours vary between 550 and 3400. Abed and El-

[28] The Weibull distribution function is a probability function of the form $f(v) = \frac{k}{a}\left(\frac{v}{a}\right)^{k-1} \cdot \exp\left(\frac{-v}{a}\right)^{k}$ in which k is the Weibull shape factor (generally ranging between 1 and 3), a the scaling parameter and v the wind speed.

[29] Full-load hours are the number of hours a year that the wind turbine operates at rated power (kWh y^{-1} kW^{-1}). The capacity factor (C_f) is defined as the ratio of the full-load hours and the total amount of hours in a year.

[30] We have included reported output of wind farms that supplied all required information. The farms are situated in Belgium and the US.

Mallah (1997) studied the capacity factor of wind turbines for several wind regimes. Their analysis results in a general mathematical expression for the full-load hours as a function of the cut-in and cut-out wind speed and rated wind speed as well as the Weibull parameters. We have simplified this expression to a linear relation determined by two factors; α_1 and α_2. These factors include information on the power curve and the Weibull parameters. The factors α_1 and α_2 are derived from theoretical performance of available wind turbines (Figure 5). The full-load hours as a function of the average annual wind speed are calculated using a Weibull distribution and the power curve of six commercially available wind turbines (adapted from (Danish wind turbine manufactures association, 2001).

$$h_{f,i} = \alpha_1 \cdot V_{h,i} - \alpha_2 \qquad (6)$$

where $h_{f,i}$ is the amount of full-load hours in grid cell i. The value of α_1 is found at 565 s.h $^{-1}$ m^{-1} y^{-1} and α_2 at 1745 kWh kW^{-1} y^{-1} for the Weibull function with k = 2. The relation taken in this study (k = 2) lies within the range of the empirical data supplied, although the latter seem to be slightly lower (Figure 5). We have assumed the maximum full-load hours at 4000 for the present situation.

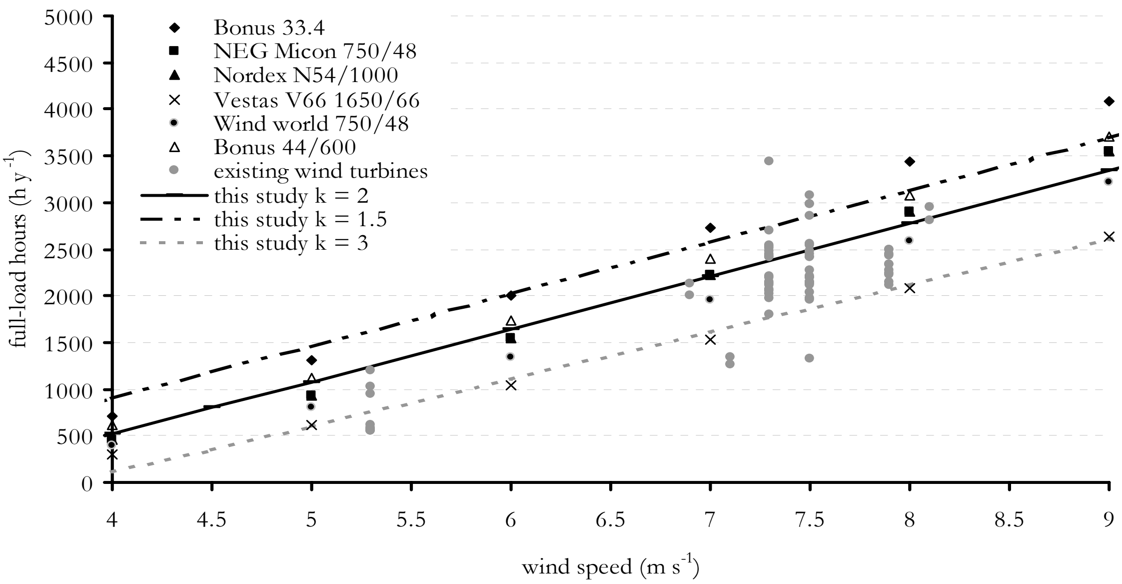


Figure 5: The full-load hours as a function of the average annual wind speed for a set of seven commercially available turbines operating at various average wind speeds and Weibull factors (k = 1.5; k = 2.0 (default); k = 3.0). Wind turbine output data of 7 wind farms are included for comparison.

5.3 Wind power density per km²

From the output of a turbine, we move on to the potential output of wind turbines in a grid cell. The available area per grid cell has been determined in the previous section. For the assessment of the specific energy output in the grid cell, the power density (D_i) is a crucial variable. We introduce the power density in the suitable area:

$$D_i = N_{t,i} \cdot \Pr \tag{7}$$

with D_i the average installed power density (kW km^{-2}) in the grid cell at the suitable area; $N_{t,i}$ the number of turbines per km^2 in grid cell i; and Pr the average rated power of a turbine with a default value of 1000 kW.

The literature reports current values for power densities at wind farm level varying from around 17 MW km^{-2} for dense arrays in California to 5-8 MW km^{-2} for European wind farms (ABB, 1998). The power density of a wind farm is determined by various factors, e.g. the infrastructure required for the turbines, the acceptable losses from interference, the available area and even visual constraints (not included in this study). Similar constraints are valid for the suitable area in a grid cell. However, we cannot quantify one of these constraints or considerations at this level of detail. As an upper level, therefore, we argue that the power density at the **suitable** area in a grid cell is just below the value of a wind farm, at a level of 4 MW km^{-2}. This figure includes the reduction of the power density because of the installation of single turbines instead of wind farms, e.g. in the year 2000 only 53% of the installed wind turbines were located in wind farms (BTM, 2001).

Assuming a power density of 4 MW km^{-2} in the suitable area in a grid cell, we get an upper limit for the technical potential at grid cell level, since power density values at national or provincial level are at present below 4 MW km^{-2} as shown in Table II. At the national level the highest power densities are found in Denmark, namely 0.05 MW km^{-2}. At provincial level, Schleswig-Holstein has the highest power density: 0.09 MW km^{-2}. For correct comparisons, we have estimated the country or regionally average suitability factor based on the land-use, land-cover, and altitude and wind speed data used in this study. This resulted in an estimate of the power density at the **suitable** area as is shown in Table II. This value corresponds to the power density assumed in this study. The highest power density in a suitable area (0.28 MW km^{-2} for Schleswig-Holstein) is still far below the value of 4 MW km^{-2} assumed in this study.

Table II: Power densities in a suitable area calculated using the country average suitability factor derived from this study. The power density at the suitable area can be compared with the power density used in this study.

Country/region	Installed capacity in MW (2001)	Power density ($MW\ km^{-2}$)	Average suitability factor (derived from this study)	Power density at suitable area ($MW\ km^{-2}$)
Denmark	2297	0.05	0.2	0.27
Germany	6113	0.02	0.15	0.12
Schleswig-Holstein (Germany)	1342	0.09	0.3	0.28
The Netherlands	448	0.01	0.1	0.13
The Netherlands target	1500[a]	0.04	0.1	0.44

[a] This is the national onshore target for 2020.

Equation 3 also introduces two efficiency factors. The availability factor (η_a) is the fraction of the full-load hours in a year that the wind turbine is actually available and is set at 0.95 (allowing for repair, breakdowns etc.). This is a low value in view of literature values up to 0.98 (Neij, 1999; Chapman and Wise, 1998). However, as a global average it is assumed to be realistic, since we also include several regions with less experience at present.

The array efficiency (η_{ar}) is the efficiency of a total wind farm, which decreases with closer spacing due to the interference of wind turbines. Its value is a function of the turbine spacing, configuration and size of wind farms. Indicative empirically derived values in the literature vary between 0.49 and 0.96 (Grubb and Meyer, 1993); 0.49 for high densities (a matrix of 10 x 10 and a spacing of 4 x diameter) and 0.96 for low density wind farms (a matrix of 4 x 4 and a spacing of 10 x diameter). We assume a fixed array efficiency of 0.90. Using the array efficiency values supplied by Grubb and Meyer (1993), 0.90 is consistent with a power density of 4 $MW\ km^{-2}$, a Pr of 1000 kW and a 2 x 2 matrix placing with a spacing 5 times the turbine diameter.

5.4 Results

A large number of grid cells have no technical potential, due to a suitability factor of 0. The highest figure for the technical potential in a grid cell is calculated at 55 $TWh\ y^{-1}$. We have ranked the technical potential E_i (Equation 3) for all cells (Figure 6). It is shown that most grid cells have a technical potential around 2 - 3 $TWh\ y^{-1}$. The global technical potential is calculated by summing over all grid cells (surface under the curve in Figure 6). It is estimated to be 96 $PWh\ y^{-1}$, about 6 to 7 times the present (2001) electricity consumption of 15 $PWh\ y^{-1}$ (BP, 2002). The regional technical potential is calculated by summing over all grid cells by region. High values are found in the USA the Former USSR and Oceania. The regional results are summarised in Table III. The highest regional technical potential is found in the USA with a large suitable area and a relatively high average wind speed.

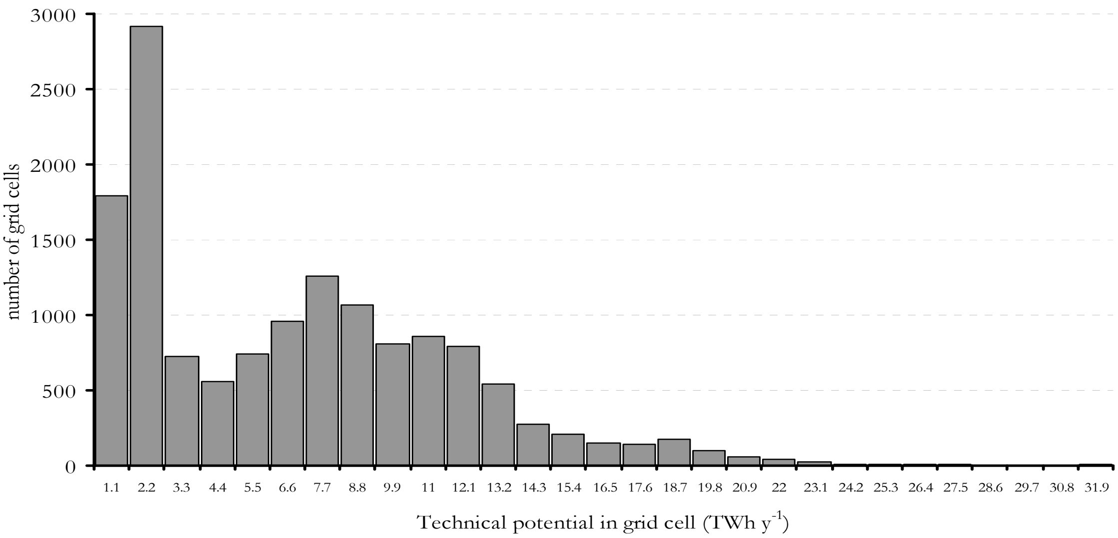


Figure 6: The global distribution of the technical potential over the grid cells as calculated in this study (N.B. 17 cells exceed 30 TWh y^{-1}).

Table III: The regional distribution of the total terrestrial area, suitable area, the regional average wind speed, technical potential, technical potential at three different cut off costs and the ratio of the technical potential and the current regional electricity consumed.

	Area (Mha)	Suitable area (Mha)	Average wind speed ($m\ s^{-1}$)	Average power density ($MW\ km^{-2}$)	Techn. Pot. PWh y^{-1}	Techn. pot. Cut off 0.07 \$ kWh^{-1} PWh y^{-1}	Techn. pot. Cut off 0.10 \$ kWh^{-1} PWh y^{-1}	Ratio techn. pot and pres electricity consumption[a]
Canada	950	199	4.1	1.08	19	8	16	33
USA	925	248	4.3	1.02	21	3	13	6
C-America	269	29	3.3	0.40	2	1	1	11
S-America	1761	82	3.0	0.26	8	4	6	13
N-Africa	574	55	2.9	0.42	3	0	0	23
W-Africa	1127	4	1.8	0.01	0	0	0	6
E- Africa	583	38	2.6	0.28	3	0	0	358
S-Africa	676	3	2.2	0.03	0	0	0	1
W -Europe	372	47	4.3	0.58	4	1	2	2
E-Europe	116	6	3.1	0.22	0	0	0	1
F. USSR	2183	206	3.4	0.47	16	2	7	13
Middle East	592	47	3.1	0.33	2	0	0	6
South Asia	509	15	2.3	0.12	1	0	0	2
East Asia	1108	25	2.4	0.10	2	0	0	1
S East Asia	442	0	2.0	0.01	0	0	0	0
Oceania	838	199	3.6	0.91	14	1	6	69
Japan	37	1	3.3	0.08	0	0	0	0
Global	13063	1123	3.0	0.37	96	21	53	7

[a] We use the IEA data of 1996 on the present electricity consumption at a regional level.

6. The cost of wind electricity: the economic potential using regional cost supply curves

6.1 Approach

The economic potential is defined as the amount of wind electricity that can be generated at costs that are competitive with other electricity sources. In this study we construct the supply cost curves for wind electricity, which is a ranking of the technical potential in the grid cells according to the wind electricity costs in the grid cells. To this purpose we calculate the electricity production costs for all grid cells. We annuitize[31] the total investment costs *I* and the annual O&M costs in a grid cell and divide it by its annual output:

$$Coe,i = \frac{\gamma \cdot (1+\varepsilon) \cdot I \cdot D}{Ei} \quad (8)$$

where $Coe_{,i}$ is the production cost of electricity in grid cell i (\$ kWh^{-1}); γ is the annuity factor (-); and ε is the cost of operation and maintenance, defined as fraction of investment cost, but included in annuity.

The annual O&M cost are taken to be constant and scale-independent, at a fixed fraction of the capital costs ($\varepsilon = 0.03$). We neglect that the O&M costs tend to increase over time (Lemming et al., 1999).

The investment cost *I* is determined by the specific turbine investment costs (I_t) and other costs like foundation and grid connection costs. Several studies show that the turbine costs are about 80% of the total investment costs, (Morthorst, 1998; Rehfeldt et al., 1997; Laali et al., 1996; Lemming et al., 1999). Hence, the total specific investment costs are expressed as:

$$I = \frac{I_t}{\zeta} \quad (9)$$

with ζ the fraction of turbine costs in the total.

The specific turbine investment costs are assumed to be a function of the scale of the turbine using a defined reference turbine as basis:

$$\frac{I_t}{I_{t0}} = \left(\frac{P_r}{P_{r0}}\right)^{\beta} \quad (10)$$

---

[31] Annuitizing is done in the usual way: $\gamma = \frac{r}{1-(1+r)^{-L}}$ with r is the interest rate, set at 10%; and L is the economic lifetime set at 20 year.

I_t is the specific investment cost of the turbine (\$ kW^{-1}); It_0 is the specific investment cost of a defined reference turbine (\$ kW^{-1}); Pr_0 is the capacity of the defined reference turbine (kW) and β is the scaling factor (-) ($\beta < 0$).

The reference turbine has a power of 800 kW (Pr_0) specific investment cost of 1000 \$ kW^{-1} (I_{t0}). The parameter β is derived from a set of historical data from German industry (Bundesverband Windenergie, 2001). For 1995 - 1998 it varies between –0.29 and –0.32 (though with a large spread: $0.58 < R^2 < 0.77$). We use $\beta = -0.3$. This relation is used in the sensitivity analysis to investigate the impact of larger turbine sizes.

6.2 Results

For each cell we have calculated the generation costs, using reference turbine data and grid-cell technical potential (Equation 8). The cells in which wind electricity can be generated at costs below 0.06, 0.10, 0.15 and 0.25 \$ kWh^{-1} are shown in Figure 7.

The lowest calculated cost of wind electricity in a grid cell is 0.05 \$ kWh^{-1} (see Figure 9). found at wind speed values of around 8 m s^{-1}. We consider our results consistent with values found in the literature, as literature on the current costs of electricity mentions only slightly higher values around 0.04 – 0.05 \$ kWh^{-1} (Turkenburg, 2000; Morthorst, 1998).

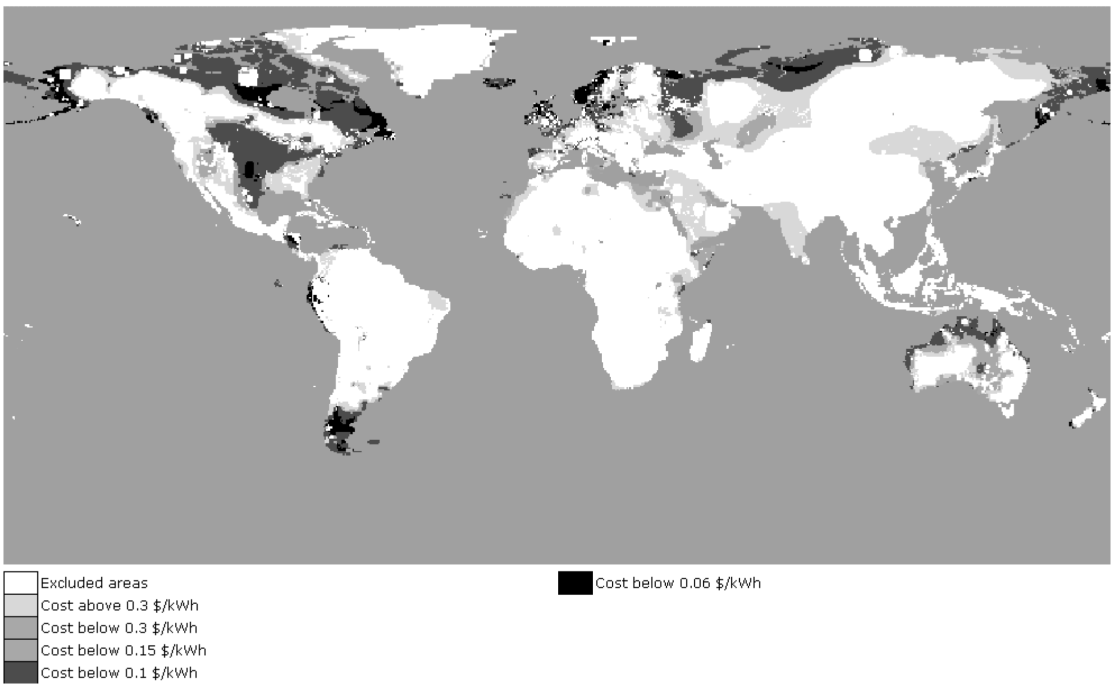


Figure 7: The areas where wind electricity can be generated at various cost classes (costs below 0.20, 0.15, 0.10 and 0.05 \$ kWh^{-1}).

To provide insight into the amount of electricity that can be generated using wind power at certain costs, we combine the cost information with estimates of the technical potential. This is illustrated for the USA in Figure 8a and 8b. USA is taken as an example as it has the highest regional technical onshore wind electricity potential. There is a clear correspondence between high grid-cell potential (Figure 8b) and low production cost (Figure 8b). A large amount (13 PWh y^{-1}) of wind energy can be generated at costs below 0.10 \$ kWh^{-1}. This amount corresponds almost with present global (2001) electricity consumption (BP, 2002). Largest share is found in the Great Plains, consistent with resource assessments at national scale (Elliot and Schwartz, 1993; National Wind Coordinating Committee, 1997; AWEA, 2000). At present the wind energy turbines are installed rapidly in these areas (AWEA, 2000).

Figure 8a: The areas in the USA where wind electricity can be generated at costs below 0.25, 0.15, 0.10 and 0.06 \$ kWh^{-1}

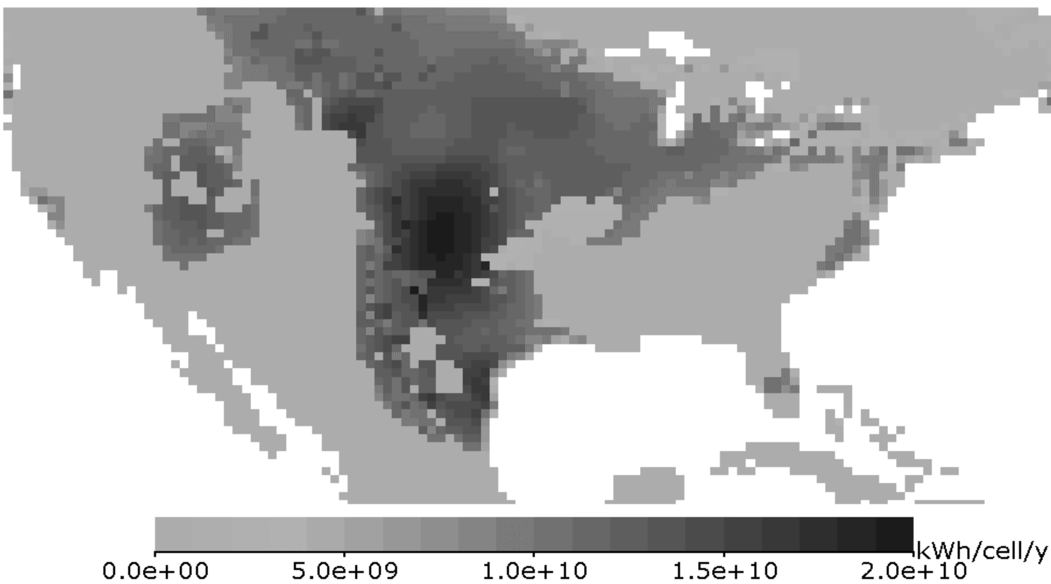


Figure 8b: The technical potential per grid cells for the USA in kWh y^{-1}.

The regional cost-supply curves of the six regions with high technical potential and/or low cost are shown in Figure 9. Also included is the global supply cost curve and the present world electricity production and price range (BP, 2002; Goldemberg, 2000; IEA/OECD, 2002b). At costs below 0.07 \$ kWh^{-1}, an amount of wind electricity can be generated at the level of the present (2001) world electricity production (see Figure 9). This is still high compared to the present average electricity costs around 0.04 \$ kWh^{-1}, although due to variations in the conventional electricity production cost, the wind energy production do fall in the range (IEA/OECD, 2002b; Goldemberg, 2000).

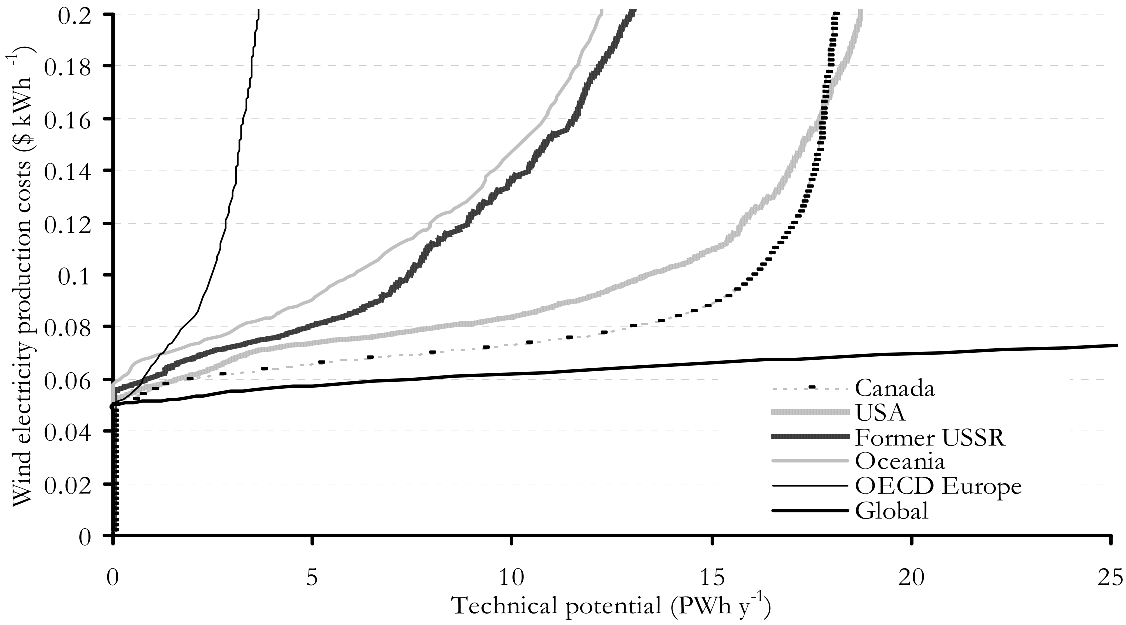


Figure 9: Regional cost supply curve for wind energy (\$ kWh^{-1} versus PWh y^{-1}) for D = 4 MW km^{-2}. For comparison the global cumulative curve is also presented.

7. Discussion of the results

We analyse the results in more detail in two ways: a one-factor sensitivity analysis and a comparison with results from previous studies.

7.1 Sensitivity analysis

A sensitivity analysis aims to give insight into the sensitivity of the output (technical potential and cost-supply curve) to the value of the input parameters. The accuracy of the input parameters used range from high (strong) to low (weak). 'Weak' knowledge (and in here 'weak' parameters) is considered knowledge that is tied to personal and social values and cannot be measured under controlled conditions. 'Strong' knowledge (and so 'strong' parameters) is knowledge that is empirically measurable and controllable, we consider a parameter fair if it is estimated or calculated from measurable values. In this study, we consider the power density and the land-use suitability factor as 'weak' parameters. If wind turbines are installed, the power density can be measured. However, the maximum power density, which is required for the technical potential, is not measurable since it is a function of various social factors. Similar arguments apply for the suitability factors. The share of the agricultural land that can be used for wind turbine installation is among others a function of the value given to wind energy, i.e. does it have a high priority with respect to other land-use options. It is hard to define absolute ranges for these 'weak' parameters. Therefore, we first perform the sensitivity analysis of the 'strong' parameters, before studying the sensitivity of the power density and the suitability factor.

The accuracy of the V_{10} database is subject for discussion. As mentioned before, the variation with empirical values could not be quantified, nor could the range of variation. For the sensitivity analyses, we have multiplied the default V_{10} with 0.75 to 1.25, in line with the earlier observations. The range of η_{ar} and η_a is restricted by the upper limit at 1; at the lower limit a reduction of 25% is assumed, as lower efficiencies are barely mentioned in the literature. The same can be said for the rated power (Pr). Currently installed wind turbines vary from 300 kW to 2 MW (Ackermann and Soeder, 2002). This range is used in the sensitivity analysis although, in the future the rated power might increase even further. A range is found in the literature for the scaling factor β (see Section 6). However, we have taken a broader range of 25% higher and lower since the empirical basis is too weak for us to consider the ranges found as absolute ranges. For the operational and maintenance costs, defined as a fraction of investment costs, the ranges found in the literature are used. The variation in input parameters is summarised in Table IV.

Table IV: The variation of the input parameters used in the sensitivity analysis and variation in the results of the technical potential and the lowest cost.

Parameter	Range relative	Range absolute	Range in global technical potential ($PWh\ y^{-1}$)	Lowest cost (¢ kWh^{-1})
V_{10}	0.75 – 1.25		19 - 210	5.2 – 5.2[a]
P_r	0.33 – 2.0	300 - 2000 kW	87 - 101	4.2 – 7.4
η_{ar}	0.75 – 1.10	0.675 – 0.99	69 - 105	4.6 – 6.8
η_a	0.75 – 1.05	0.71 – 0.99	72 -101	5.0 – 6.8
β	0.75 – 1.25	-0.23 - -0.38		5.0 – 5.2
ε	0.33 – 1.66	0.01 – 0.05 %		4.4 – 5.8

[a] There is no variation in lowest costs as we assumed an upper limit of the full-load hours

The sensitivity analysis with these strong parameters is not complex, as most relationships are linear (see also the complete equation in Appendix A). Figure 10 and Table IV show the sensitivity of the technical potential for η_a, η_{ar}, *Pr* and V_{10}. As expected, the technical potential is highly influenced by the average monthly wind speed (see also Equation 3). The discontinuity shown in Figure 10 is the result from the cut-off wind speed at 4 m s^{-1} at a height of 10 m. A 25% increase in wind speed more than doubles the technical potential. Due to restriction of wind resources at 4.0 m s^{-1} at a height of 10 m, a 25%

reduction of the wind speed is even more significant, the technical potential is reduced to 19%. The technical potential is only slightly sensitive to η_{ar} and η_{a}, and barely to *Pr*. It is understandable that an increase in *Pr* contributes only marginally, to the technical potential since the power density is fixed in this study and so the Pr only influences the hub height (see Equation 4 and 5). Its contribution to the lowest costs is higher due to the assumed cost-reductions with up-scaling.

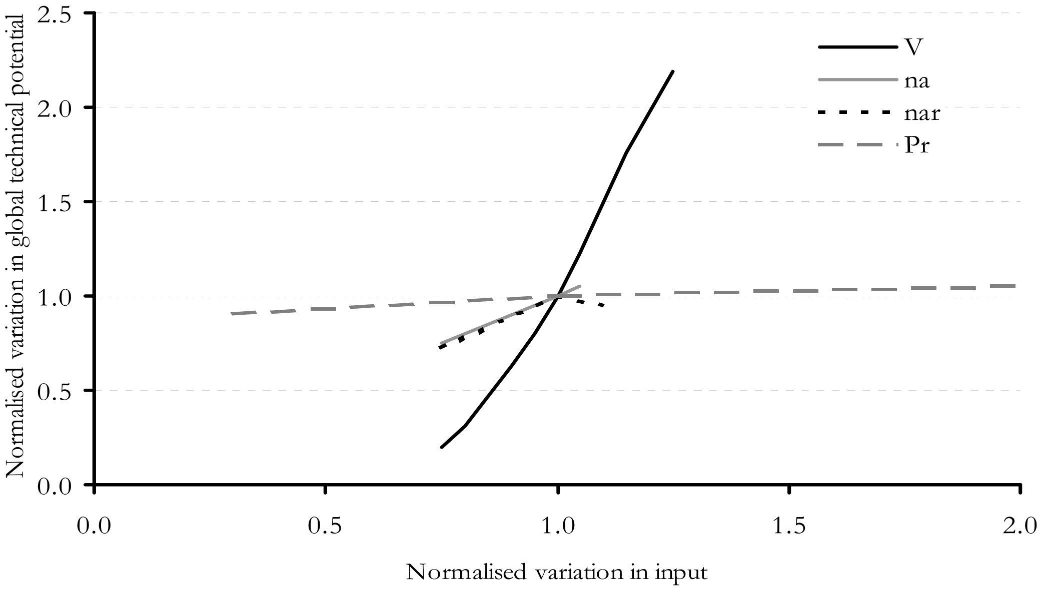


Figure 10: Sensitivity of five input parameters (η_{ar}, η_{a}, *wi*, P_r and V_{10}), to the total technical potential. The variation of the parameters and the output is normalised to the default setting.

The cost- supply curve is also highly sensitive to the annual average wind speed at 10 m (see Figure 11), as well as to the rated power (Pr). The electricity output per turbine increases, due to an increase in nominal power and thus in hub height. Furthermore, as a result of the scaling factor, the specific investment costs are reduced (see Equation 10).

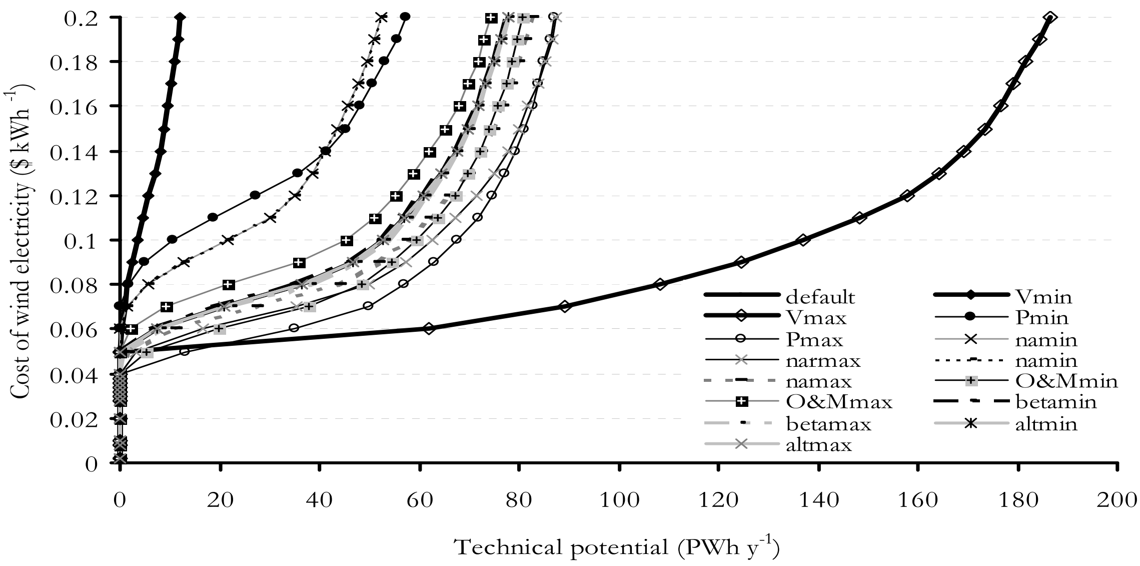


Figure 11: Sensitivity of input parameters (η_{ar}, η_a, w_i, Pr, ε, β and V_{10},) on the global cost-supply curve

The parameters that are considered to be more weakly underpinned, namely the power density and the land-use suitability factors, are studied separately. These parameters have a high impact on the results, as summarised in Figure 12. It shows the four extreme cost supply curves for extreme values of land-use suitability factors (the values presented in Table I are default, low is 25% lower and high is 25% higher). The power density ranges from 0.1 MW km^{-2} in suitable area, similar to those found currently in the Netherlands and Germany (see Table II) to 8 MW km^{-2} in suitable areas, equal to wind farm values. The top right corner of Figure 12 shows the cost supply curve with high power density and high land-use suitability factors. The lowest graph on the left shows the cost supply curve for the low power density and land-use suitability factor. This can be considered as a 'worst case'. Compared to the present electricity consumption, the potentials range from about 10 to 130%.

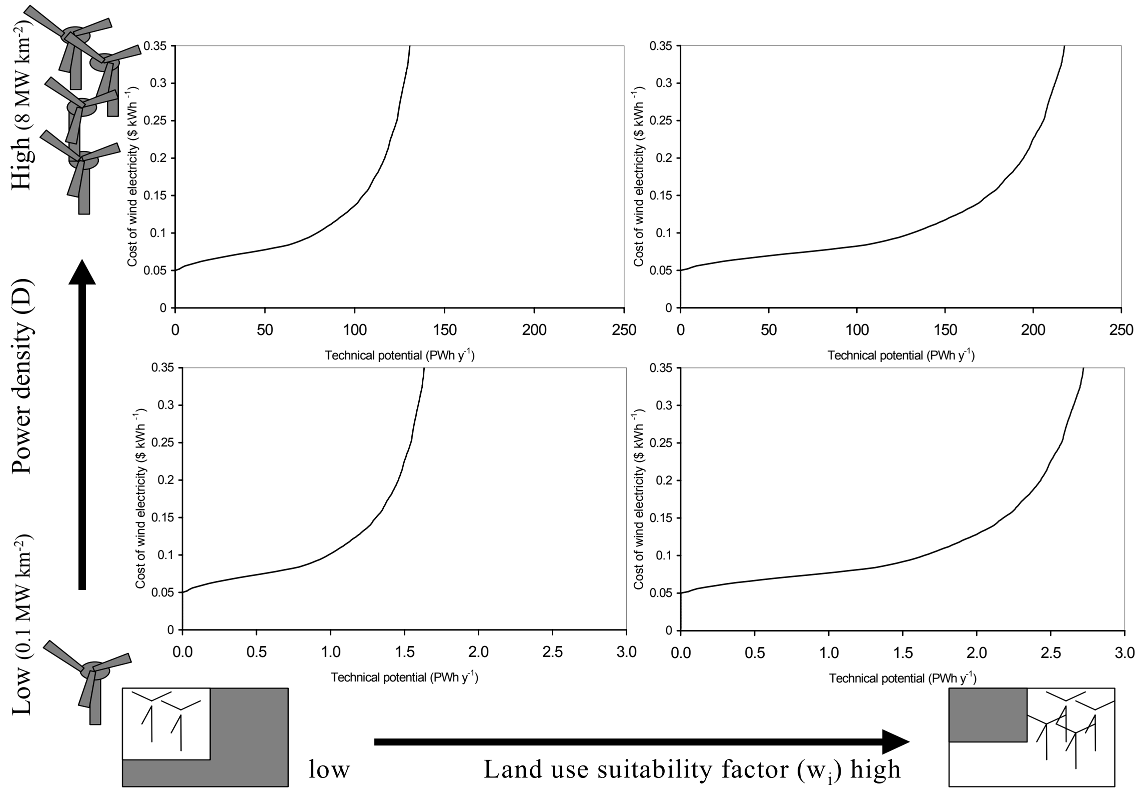


Figure 12: The wind electricity cost supply curve for four extreme situations. The 'weakly' known parameters *D* and w_i are varied over a broad range. Note differences in scale.

7.2 Comparison with previous studies

We have compared the results of the onshore technical potential in detail with three previous studies:

1. the study by Grubb and Meyer (1993);
2. the WEC study (1994) conducted by Utrecht University (World Energy Council, 1994);
3. the IEA/OECD (2000) study conducted by Garrard and Hassan (Fellows, 2000).

All studies assess the global and regional technical potential, including site constraints.

The results of the global onshore technical potential of wind energy vary widely, from 19 PWh y^{-1}, as simulated by the WEC study (1994) to 53 PWh y^{-1} as given by Grubb and Meyer (1993). The IEA/OECD study presents a value of 37 PWh y^{-1} (Figure 13). The estimated wind energy potentials vary widely over the regions. This study finds relatively higher values for all regions except for Central Asia, West Europe and Africa (see Figure 13).

The differences are caused by differences in the input parameters (e.g. wind speed, power density) and main assumptions (cut-off wind speed, land-use constraints). Some of the input parameters are difficult to compare, e.g. wind resource. However, to make a better comparison, we adjusted some input parameters and main assumptions. We assessed the technical potential using assumptions similar to those used in the other studies.

First of all, all studies included only sites where ‘wind resources can be exploited’. Grubb and Meyer define these sites as having wind speeds above 6.0 m s^{-1}, the WEC defined the sites as having wind speeds above 5.1 m s^{-1} at 10 m. We used an exclusion wind speed of 4.0 m s^{-1} at 10 m. When the restriction of 5.1 instead of 4.0 m s^{-1} at 10 m is used, our estimate of the global potential falls by 60%, with large decreases (to even nil) in South Asia (see Figure 13). The reason given for excluding these sites was the decision to include ‘exploitable’ sites only. We have included all sites where technically speaking large-scale wind turbines could be installed. Non-exploitable sites end up in the upper part of the cost supply curve. The IEA/OECD study includes only sites where wind electricity can be generated at costs below 0.20 \$ kWh^{-1}. If we apply this restriction to our data, our figures reduce only marginally (see Figure 13).

Secondly, the WEC excluded areas at a distance of more than 50 km from the existing grid. Due to lack of data on the electricity grid used in the WEC study, the effect of this assumption could not be studied quantitatively. Including this constraint may reduce our results.

Thirdly, the overall power density is an important factor. The WEC study assumed a global average power density of 0.33 MW km^{-2}. This number is based on empirical studies concerning the optimal power density at national level and includes site constraints. IEA/OECD limits the power density to 0.15 MW km^{-2} based on empirical values in Denmark. We use a maximum power density of 4 MW km^{-2} in the suitable area. The calculated power density in the total area varies between 0.01 MW km^{-2} in Western Africa and 1.1 MW km^{-2} in Canada. As a global average, we calculate a slightly higher figure: 0.37 MW km^{-2}. This makes our results only slightly higher than WEC but higher than IEA/OECD by a factor of about 2. Grubb and Meyer do not use a fixed or upper limit for the power density (see Figure 13).

Fourthly, in this study the electricity output is calculated in a similar way as the WEC study and the study by Grubb and Meyer, i.e., on the basis of the full-load hours. However, in the two previous studies the amount of full-load hours per turbine was fixed at 2000 h and 2277 h respectively. If a fixed amount of full-load hours at 2000 h is assumed, our results decrease 14% to a global technical potential of 83 PWh y^{-1}.

Finally, differences between the studies are caused by differences in the input parameter V_{10}, We could not re-assess our calculations with the wind speed data of the previous studies. Hence we were unable to compare the influence of the input parameter V_{10} on the results. Fellows (2000) have been able to compare his data with other digital data for the USA. It was concluded that their database underestimated the wind speed and corrections were made for the overall results. This could not be done in this study.

From the comparison with previous studies it can be seen that our study yields in a higher technical potential. However, as we include the regional cost-supply curves, part of the technical potential neglected by previous studies end up in the upper part of our cost-supply curves. Other important parameters that explain the differences are the assumed power density at grid cell level and the method used to assess the technical output of a wind turbine.

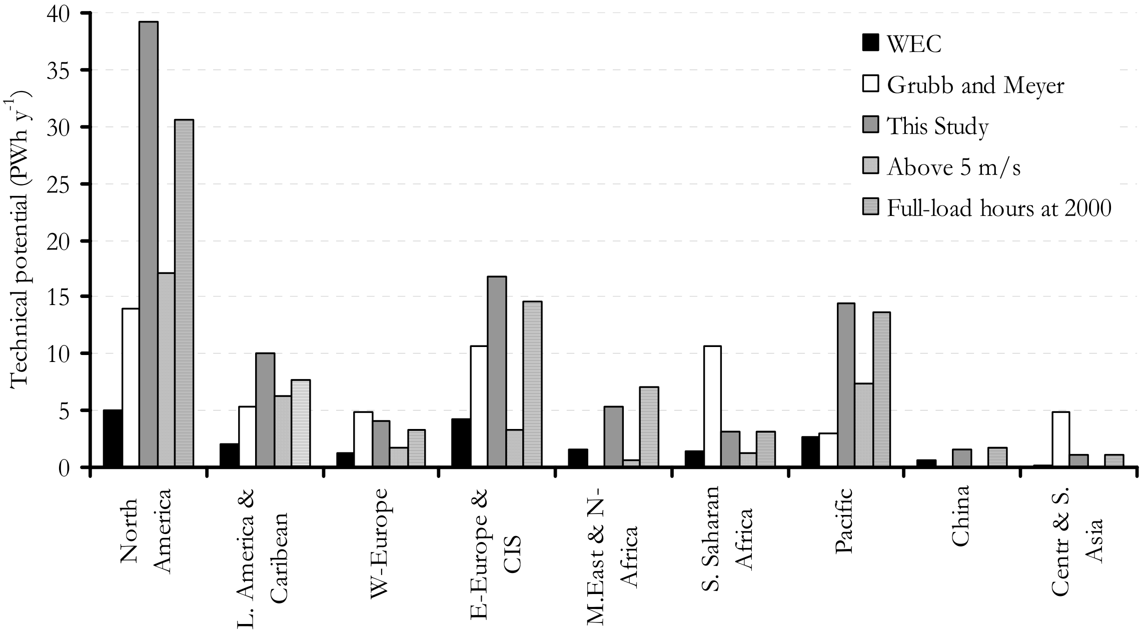


Figure 13: The technical potential assessed in this study compared to three other technical potential assessments and the results if three different assumptions used.

7.3 Discussion of main assumptions

We discuss three aspects of the assessment of the geographical and technical potential and the cost of wind electricity: The method used, the input data used in the assessment and the implication of this method and these input parameters for the results and conclusions.

Approach

First of all, it should be realised that when the technical potential is restricted to the onshore sites, only part of the total wind energy technical potential is included. The technical offshore potential mentioned for Europe is 8.5 PWh y^{-1} at sites where the water is up to 50 m deep. At a global level, values are mentioned of 37 PWh y^{-1} (Leutz et al., 2001). Hence, the overall wind electricity potential (onshore + offshore) is significantly larger (about a factor of 1.4) compared to the onshore figures only.

Furthermore, it is stressed that the potential and cost as assessed in this study do not include grid integration, transmission and distribution of the electricity and the storage capacity that might be required due to the intermittent character of wind. As mentioned earlier, the wind regime can be represented by a Weibull distribution function over the year or month. However, even over a shorter time period, the wind resource fluctuates. This complicates the integration of wind electricity in the grid and accounts for additional costs, see Chapter 7.

Input data

The discussion of the input data is structured in Table V. It shows the accuracy and sensitivity of the data. The sensitivity is discussed in Section 7.1. Input is considered to be strongly accurate if its value is measured, or otherwise empirically supported by (several) literature sources. The parameters that are derived from measurable values are considered fair. Parameters that are not validated in the literature or are closely connected to personal values are considered to be weakly accurate. The sensitivity is derived from the ratio between the range of the input parameter and the range of the results as well as on the range of the calculated lowest wind energy production cost.

Table V: The accuracy and sensitivity of the technical potential to the input parameters

	Accuracy	Sensitivity
Geographical potential		
w_i	Weak	Strong
Technical potential		
V_{10}	Fair	strong
η_{ar}	Strong	Low
η_a	Strong	Low
Pr	Strong	Low
D	Weak	strong
Cost of wind electricity		
O&M	Strong	Low
β	Fair	Low

Parameters that are highly sensitive and fairly or weakly accurate are: *D*, V_{10} and w_i. In particular the values of *D* and w_i are open to discussion. Furthermore, the database containing the average wind speeds is subject to discussion. The values are probably conservative, resulting for instance in a vanishing geographical and technical potential in South and South East Asia. Furthermore, the observation data coverage for Oceania is limited. On the basis of this analysis, in combination with a comparison of the data with the data in the European and USA, Indian and South East Asian wind atlas, we believe that our estimate of the technical potential is on the low side, due to the underestimation of the annual mean wind speed in at least India and South East Asia. Results should therefore be treated with care, particularly for South and South East Asia and Oceania.

8. Conclusions

The aim of our study is to assess the theoretical, geographical, technical and economic potential of onshore wind energy, by constructing regional supply cost curves for wind energy. The onshore global technical potential is estimated to be 96 PWh y^{-1}, or about 6 time the present (2001) world electricity consumption at costs below 1 \$ kWh^{-1}. Assuming an average wind turbine output of 2000 full-load hours, this potential is about 2000 times the annually produced wind energy at present (2001). To supply this technical potential, an area of 1.1 Gha is required assuming a power density of 4 MW km^{-2}. This is similar to the total global grassland area or the size of about China. The regionally highest technical potential is found in the USA (21 PWh y^{-1}). Lowest figures are found in African regions, Eastern Europe and South East Asia.

In most regions the technical potential exceeds the present-day electricity consumption. The highest surplus is found in East Africa where the technical potential exceeds the present consumption level more than 300 times. In OECD Europe, the technical potential of wind electricity is about 2 times the present electricity consumption. In Eastern Europe the technical potential does not exceed the present consumption level.

Globally, roughly an amount equal to the present (2001) global electricity consumption is available at costs less than 0.07 \$ kWh^{-1}, spread over most regions. At a cost of 0.06 \$ kWh^{-1} or below, about 7 PWh y^{-1} wind electricity may be generated, half of the present electricity consumption of 15.7 PWh y^{-1}. This potential is found mainly in Canada, USA, South America, Former USSR and OECD Europe (See Table III). The actual estimate of the technical potential of onshore wind energy (for given cut-off costs) depends critically on assumptions about acceptable power density and land-use constraints.

Since the database for the mean annual wind speed is rather conservative compared to wind speeds in the literature, we can expect our results to represent an underestimate of the technical potential. The results for South and South East Asia and Oceania should be considered with care for this reason.

Appendix A:

Overall equation: $E = \sum_{i=1}^{n} f_i \cdot A_{ai} \cdot \cdot \eta_a \cdot \eta_{ar} \cdot \left(N_{t,i} \cdot \mathrm{Pr}\right) \cdot \alpha_1 \cdot \mathrm{V}_{10,\mathrm{i}} \cdot \left(\frac{\ln\left(\left[\mathrm{C} \cdot \mathrm{Pr}^{\mathrm{w}}\right] / z_{0,i}\right)}{\ln\left(10 / z_{0,i}\right)} \right) \alpha_2$

List of variables:

P	the power per m² swept area	(W m^{-2})
ρ	the air density	(kg m^{-3})
v	the wind speed	(m s^{-1})
Gp_i	the geographical potential in cell i,	(km^2)
Tp_i,	the theoretical potential in cell i,	(kWh)
o_i	the fraction of onshore area in cell i,	(-)
f_i	the suitability factor for socio-geographical constraints in cell i,	(-)
A_i	the total area in cell i	(km^2)
u_i,	the urban area in cell i	(-)
a_i	the binary weighting factor for altitude	(-)
b_i	the suitability factor for bioreserves	(-)
w_i	the suitability factor for land-use and land-cover function of cell i	(-)
r_i	the suitability factor for wind regime restrictions	(-)
H	the height	(m)
v_H	the wind speed at height H	(m s^{-1})
z_o	the roughness length of the surface	(m)
V	the annual average wind speed	(m s^{-1})
C	constant used for the determination of hub height	
w	constant used for the determination of hub height	
P_r	the rated power of wind turbine	(kW)
Cf	the capacity factor	(-)
vi	the cut in wind speed	(m s^{-1})
k	the Weibull shape factor	
a	the Weibull scaling factor	
v_r	the rated wind speed	(m s^{-1})
v_o	the cut-out wind speed	(m s^{-1})
h_f	the full-load hours per year	(h y^{-1})
α_1	constant for the determination of full-load hours	($hy^{-1}m^{-1}s^{-1}$)
α_2	constant for the determination of full-load hours	(h y^{-1})
D_i	the installed power density in grid cell I in the suitable area	(kW km^{-2})
Nti	the number of turbines per km² in grid cell i,	(-)
η_a	the average availability of the turbines	(-)
η_{ar}	the wind farm array efficiency	(-)
E_i	the annual energy output of a grid cell	(kWh y^{-1})
It	the specific investment costs	(\$ kW^{-1})
It_0	the specific investment costs for a reference turbine	(\$ kW^{-1})
Pr_0	the capacity of the reference turbine	(kW)
β	the scaling factor	(-)
I	the total investment costs	(\$ kW^{-1})
ζ	the turbine costs as a fraction of the total investment costs	(-)
$Coe_{,i}$	the production cost of electricity in grid cell i	(\$ kWh^{-1})
γ	/he annuity factor	(-)
ε	the cost of operation and maintenance, as a fraction of I	(-)
r	the interest rate	(-)
L	the economic lifetime	(y)

Part 3

Solar energy

CHAPTER SIX

ASSESSMENT OF THE GLOBAL AND REGIONAL TECHNICAL AND ECONOMIC POTENTIAL OF PHOTOVOLTAIC ENERGY[#]

Abstract

We have assessed the global and regional geographical, technical and economic potential of electricity production by solar PV using a grid cell approach. The present global technical potential of grid-connected PV is assessed at about 370 PWh y^{-1} at levelised production costs below \$ 2 kWh^{-1}, equal to about 23 times the present world electricity consumption. Potentially high contributions, exceeding the present regional electricity consumption almost 1000-4000 times, are in North, East and West Africa and Australia. In Japan, OECD Europe and Eastern Europe the relative potential is less, about 0.6 to 2 times the present regional electricity consumption. In principle, the present world electricity consumption can be generated by PV at a cost ranging from 0.44 to 0.46 \$ kWh-1. It is estimated that on the long term, it will be possible to generate the present world electricity consumption at costs around 0.06 \$ kWh-1. However, this would imply that regions like Northern Africa and Australia export large amounts of electricity, requiring additional investments in transmission and storage of PV electricity, thereby reducing the competitiveness of PV.

[#] Submitted to Energy economics, co-authors are: Bert de Vries, Jobert Winkel and Wim Turkenburg. We are grateful to Wilfried van Sark, Erik Alsema (Utrecht University) and Detlef van Vuuren (RIVM) for valuable contributions to the approach and for comments on earlier drafts and to Bas Eickhout (RIVM) for supplying the required data from the IMAGE 2.2 model.

1. Introduction

Solar radiation can be directly converted into electrical energy by means of solar cells, which usually consist of single junction diodes manufactured from semiconducting materials. Their performance is based on the photovoltaic (PV) effect, which is defined as the emergence of a voltage between two electrodes in or attached to a liquid or solid system in response to light irradiation. Present applications of the PV effect consist of semiconductor material structures in which a p-n junction is fabricated that lead to the creation of an electron-hole pair across which a photovoltage is developed. Upon absorption of a photon in, or close to the p-n junction they will be separated by the built-in electric field of the junction. A current can then be extracted over an external load. Fifty years after Becquerel's discovery of the PV effect in 1839, Fritts made the first actual solar cells, using selenium. Much later, starting in the 1950's, solar cells were used for autonomous power generation in space satellites, creating a solar cell industry in the USA (Butti and Perlin, 1980). As costs fell, terrestrial applications also entered the market (Kelly, 1993). Off-grid applications have been representing the main PV market, with a market share of about 90% in the period 1990-1994 (Maycock, 2003; Turkenburg, 2000; IEA/OECD, 2000a). In the period 1995-1998, the market share of grid-connected PV applications increased to 23% (Turkenburg, 2000; IEA/OECD, 2000a). Nowadays this figure is about 50% (EPIA and Greenpeace, 2002). Most stand-alone applications need storage capacity, e.g. a battery. Although electricity generation costs increase due to this requirement, off-grid applications are competitive in a number of cases: they may be an alternative to extension of the grid or compete with options like small-scale diesel generators. Grid-connected systems on the other hand do not require a separate storage capacity if the grid (in fact, the conventional power system) can handle the variations in electricity production (see also Figure 1). However, due to the present high price of PV compared to other energy supply options, the grid-connected market for PV electricity is very small, although increasing, mainly due to policy measures like subsidy programs and high feed in tariffs (Maycock, 2003). It is estimated that the grid-connected sector grew from 120 MW in 2000 to 275 MW in 2002. According to Maycock, the global production of PV cells/modules increased by about 28% on an annual basis in 1994-2002, with the largest increase of 38% found in Japan. In 2002, the world cumulative production of grid-connected and stand-alone PV modules has been about 2300 MWp (Maycock, 2003). Its share in the total global electricity production was about 0.5 TWh y^{-1} in 1998 (Turkenburg, 2000) and about 1 TWh y^{-1} in 2001.

R&D in combination with the experience gained in the manufacturing of materials, cells and modules, has resulted in an improvement of the conversion efficiency of commercially available modules over time; in the case of crystalline silicon modules, from a few percent in the early 1970's to 12-16 % today and demonstrated efficiencies above 20% (Oliver and Jackson, 2000; Turkenburg, 2000; Green et al., 2003; Yamaguchi, 2001). Together with an increased efficiency of material use and an improvement of manufacturing process, this had an effect on the energy payback time of PV systems. Recent studies show an energy payback time of 2 to 6 years, with a potential reduction in the future to about 1.5 years for systems using multi-crystalline silicon modules and 1 year for systems using thin film modules (Alsema and Nieuwlaar, 2000). With a lifetime of 10-25 year, this makes the PV module a net energy producer. Furthermore a drop in the module-selling price has occurred. In 1979 the price was about 55 $\$_{2002}$ Wp^{-1} (Harmon, 2000), whereas at present (2002) world average PV module prices have reduced to around 6 \$ Wp^{-1} (solarbuzz, 2002), with a lowest figure of about 3 \$ Wp^{-1}. It is expected that the module price will be significantly reduced in the medium and long-term future (after the year 2015) to values of 1 \$ Wp^{-1} or even 0.5 \$ Wp^{-1} (Turkenburg, 2000). From the price development as a function of cumulative installed capacity a so-called experience or learning curve can be constructed. This analysis yields a progress ratio of about 0.8, i.e., the price of PV modules is reduced by about 20% when the cumulative generating capacity is doubled. Market developments and demonstration projects in combination with R&D efforts are envisaged to bring cost-effective PV within close reach, especially in sunny regions.

Solar energy is available at any location on the earth's surface. The time-averaged irradiance - expressed in units of energy (kWh) per unit of time (year) per unit of area (m^2) - varies by a factor of 4 over the earth's surface. The actual irradiance strongly depends on the season and the time of day. The theoretical potential of PV energy supply is enormous. However, the potential future contribution of PV to our energy supply depends rather on its competitiveness, than on the availability of solar energy. Thus, to simulate the potential contribution of PV to the electricity demand energy models need detailed knowledge of the characteristics *and* cost of PV electricity in relation to its technical potential.

Many studies of the potential of PV have been conducted, mainly focusing on specific applications, e.g. integrated in buildings (Haspel et al., 1993; IEA/OECD, 2001a) or in large centralised systems (Kurokawa et al., 1997; Kurokawa, 2003). They usually have geographical boundaries at country or regional scale (Alsema and Brummelen, 1993). Few studies have been performed estimating the potential of PV electricity at a global scale (Sørensen, 1999; Hofman et al., 2002). However, Sørensen (1999) does not include costs and so the economic potential cannot be calculated based on his data. Hofman et al. (2002) do include costs, but only for the year 2020 and focused on PV using concentrating cell technologies as well as electricity production using solar thermal systems. Moreover, the study does not cover the whole globe. Furthermore, for the centralised concentrator modules, only areas with irradiance above 120 W m^{-2} were included. Therefore, a new study on the regional potential of PV electricity at certain cost levels may deliver new insights in the possible contribution of PV in the electricity supply.

In this study we aim to assess the theoretical, geographical, technical and economic potential of PV electricity on a global and regional level in a structured and transparent way for the present situation and the long-term future. The set-up of the study is similar to the approach that has been applied for wind energy (Chapter 5). The spatial distribution of the PV potential is investigated using a grid cell approach. We use a geographical grid of the terrestrial area at a level of 0.5° x 0.5°, which is about 55 km x 55 km at the equator. In Chapter 7 the results of this analysis will be used to explore the impacts of penetration of solar electricity in the energy system using the energy-economy model IMAGE/TIMER 1.0 (de Vries et al., 2002; IMAGEteam, 2001). This model makes a distinction between 17 regions[32] in the world and uses cost-supply curves of energy technologies as main input. The results presented here are therefore expressed as cost-supply curves of PV electricity assessed for these 17 regions and the whole world.

The study is structured as follows: In Section 2 we start with a description of the general approach, the system boundaries and definitions. The methodology we have followed in our assessment of the four types of potential (theoretical, geographical, technical and economic potential) is described in Section 3, 4 5 and 6, respectively. In these sections, the methodology is also applied for the present situation. In Section 7, the methodology is applied for projected future developments. A sensitivity analysis and discussion is presented in Section 8 and 9. The final section summarises the main findings and conclusions of the study.

2. Approach

2.1 System definitions and boundaries

2.1.1 The technology

A photovoltaic system consists of modules that are connected in an array. In case of grid-connected applications, the array is connected to the grid via an inverter. The modules are mounted onto a surface. The surface can be either land (in centralised systems) or an elevated surface like a roof-top (in building-integrated PV). The term 'Balance of System' (BOS) is used to refer to the whole of components of a PV-system apart from the modules (see Figure 1). If a PV system is not connected to the grid, normally storage capacity is added.

Each PV module consists of a multitude of solar cells. Currently, the most widely used material is crystalline silicon (about 85%). Amorphous silicon cells contribute to a much lesser extent to the total PV market (about 9%) (Maycock, 2002). New developments such as the organic solar cell or thin film solar cells made of CdS, CdTe or $CuInSe_2$ may

[32] The 17 regions are: Canada, USA, Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, OECD Europe, Eastern Europe, Former USSR, Middle East, South Asia, East Asia, South East Asia, Oceania and Japan.

be gaining ground in the coming years. However, at present it is too early to identify the most promising technology for the future (Turkenburg, 2000).

2.1.2. Restriction of the applications

We restrict this study to onshore applications. A pre-feasibility study conducted by Hoog Antink (2000), suggests that because of its high costs, PV plants offshore may become a feasible concept in a few rather exceptional cases only, e.g. if there is a specific need for an unmanned large supply of electricity on offshore locations that are less feasible for wind turbines.

Furthermore, stand-alone off-grid systems are not included in our analysis as a separate category. Off-grid applications can be used for a number of applications, like telecommunication and domestic electricity generation. It is estimated that nowadays about 1.6 billion people worldwide do not have access to electricity (IEA/OECD, 2002a). For them, the supply of electricity using stand-alone PV systems (e.g. Solar Home Systems) would be highly valuable. However, this supply would influence the present world energy consumption only marginally. Nevertheless, the stand-alone option is implicitly taken into account in the overall global technical potential, as we do not consider in our analysis the availability of an electricity grid.

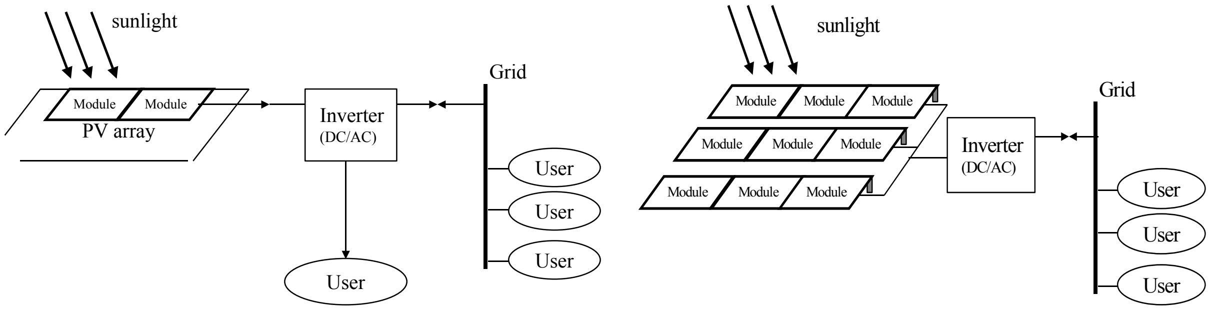
This study focuses on two types of onshore applications, illustrated in Figure 1: centralised and decentralised grid-connected applications. They are defined in a way complementary to one another, which means that there is no overlap between their potentials.

1) Centralised grid-connected PV systems: semi- to large-scale systems (10 kWp to many MWp[33]), installed at the ground in areas with little competing land use options, as large areas are required. Examples are the 1 MWp Toledo PV Plant in Spain[34] and the 3.3 MWp test plant in Southern Italy[35].
2) Decentralised grid-connected PV systems: small- to medium-scale systems (100 Wp to 10 kWp) for domestic electricity supply, installed at or close to houses, utilities or industries. Examples are plenty and include the 100,000 roof photovoltaic program in Germany (Decker and Jahn, 1997).

[33] The unit Watt-peak (Wp) refers to the produced power under standard test condition (STC), i.e., a module is illuminated with light characterized by an AM1.5 spectrum at a total intensity of 1000 W/m^2 while held at a temperature of 25 ºC

[34] see www.toledopv.com

[35] see www.pvresources.com



Decentralised grid-connected PV system (< 10 kWp) Centralised grid-connected PV system (> 10 kWp)

Figure 1: The photovoltaic system consists of modules - clustered in arrays - and the Balance Of System (BOS). The latter is a general term for the power conditioning (e.g. an inverter), power cables and the construction for mounting the modules at a surface (e.g. a roof-top).

2.2 Definition of potential

We define four categories of potential in line with the definitions used in the potential assessment study in previous chapters:

- Theoretical potential: the yearly solar energy irradiated to the surface of the earth (kWh y^{-1}).
- Geographical potential: the yearly irradiance integrated over the terrestrial surface suitable for the installation of PV systems based on geographical constraints (kWh y^{-1}).
- Technical potential: the geographical potential reduced by losses associated with the conversion from solar to electrical power (kWh y^{-1}).
- Economic potential: the technical potential restricted to electricity that can be generated in a commercially viable way, compared to the available alternatives (kWhy^{-1}).

We realise that the borders between the separate categories are rather loose and may be interpreted differently.

For completeness we mention that an additional category can be introduced, viz.:

- Implementation potential: the maximum amount of economic potential that can be implemented within a certain timeframe, taking constraints and incentives into account (kWh y^{-1}). Regarding the constraints, one may think of barriers like aesthetic concerns, the capacity and infrastructure needed to install the PV system and the available capital for investments.

In this study we will not fully explore the economic potential, but focus on a particular aspect of it, viz. the cost-supply curve. This study also excludes the integration of PV systems into the grid, which would result in additional concerns due to the intermittent character of the source (see also Section 3). High penetration levels of solar PV require additional storage capacity in order to secure the power supply and may add at least 0.01 \$ kWh^{-1} to the generation costs (Turkenburg, 2000).

Our approach is schematically illustrated in Figure 2, and will be discussed in detail in the subsequent sections.

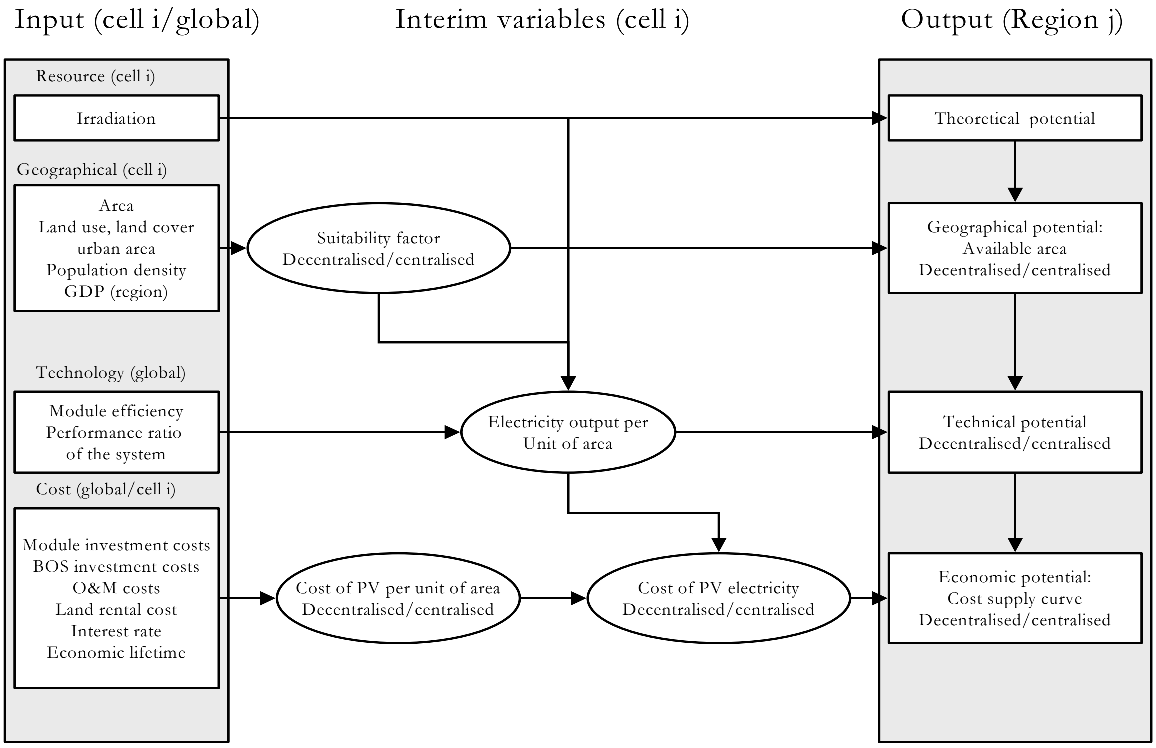


Figure 2: Overview of the approach used in this study to assess the global and regional potential of PV and the cost-supply curves, of PV. The approach is similar for centralised and decentralised grid-connected applications.

3. Theoretical potential: the solar radiation

The theoretical potential is defined as the solar energy (light) irradiated to the surface of the earth on a yearly basis ($kWh\ y^{-1}$). The radiative flux incident at a specific location depends on the time of day and year due to the earth's rotation and on the geographical position on earth (longitude and latitude). The radiative flux is reduced upon traversing the earth's atmosphere towards the surface due to reflection, scattering and absorption of radiation in the atmosphere. The fraction of incoming radiation that is reflected back into space is called the albedo of the earth-atmosphere system. Its yearly global average is around 0.35 (Sørensen, 1999). The radiation flux or irradiance (I_0) ($W\ m^{-2}$) reaching the surface of the earth is given by the following relation (Duffie and Beckman, 1991; Sørensen, 2000):

$$I_0(n,\varphi,\lambda) = \tfrac{1}{24} S \cdot (1-a_0) \cdot \int \cos\theta(n,t,\varphi,\lambda)dt \qquad (1)$$

where n is the day of the year, t is the time of the day (h), S is the solar constant (1353 W m^{-2}), and a_0 is the albedo of the earth-atmosphere system (-). The so-called zenith angle θ between the direction of incident solar radiation and the local normal on earth, at geographical latitude φ and hour angle ω can be expressed as:

$$\cos(\theta) = \sin(\varphi)\cdot\sin(\delta) + \cos(\omega)\cdot\cos(\varphi)\cdot\cos(\delta) \tag{2}$$

where the solar declination δ (degree) (the angle between the direction of solar radiation and the equatorial plane) is given by Duffie and Beckman (1991) based on Cooper (1969):

$$\delta = 23.45\sin\left(360\frac{(284+n)}{365}\right) \tag{3}$$

where the hour angle ω (degree) is written as

$$\omega = 360\cdot(12 - t_{zone})/24 - (\lambda - \lambda_{zone}) \tag{4}$$

Here t_{zone} is the local time (hours) and λ_{zone} is the longitude of the meridian defining the local time zone. In this approximation the 'equation of time', which accounts for the variations in solar time caused by changes in the rotational and orbital motion of the earth (Sørensen, 2000), is neglected.

Using these relations, taking an average value for the albedo (0.35) and assuming that all the not reflected radiation reaches the surface of the earth (neglecting absorption), the surface radiative intensity at different latitudes follows the cycles presented in Figure 3. The maximum irradiance of sunlight on Earth is about 1000 Watts per m^2, irrespective of location.

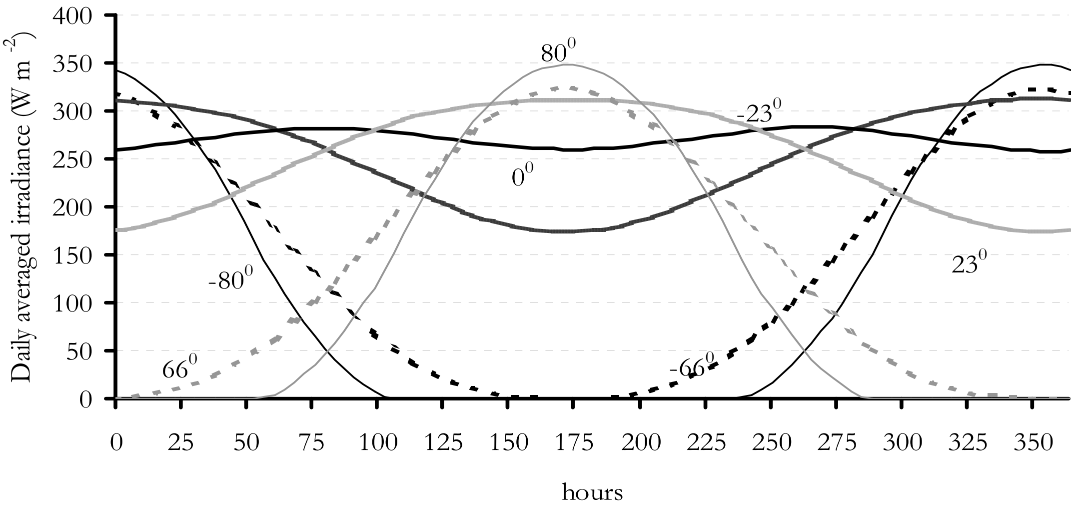


Figure 3: Averaged irradiance excluding cloudiness ($W\ m^{-2}$) over the year for various latitudes (in degrees) from an approximate calculation. (The latitude is positive on the Northern Hemisphere and negative on the Southern Hemisphere.)

In fact, the local theoretical potential is not determined by the global albedo, but depends on local parameters, such as cloudiness. Therefore, we estimate the theoretical potential by summing up the actual values of the yearly-averaged irradiance I_i ($W\ m^{-2}$), available on a surface grid (0.5° x 0.5°) as presented by the Climate Research Unit (New et al., 1997)[36]. This database is constructed from measurements at 4040 stations covering the world in the period 1961-1990. An example is presented in Figure 4.

The data represent the irradiance at a horizontal plane and include both direct and diffuse irradiance. Values in between the stations are determined using an interpolation method as a function of longitude, latitude and elevation. At the highest latitudes yearly average values as low as approximately 60 $W\ m^{-2}$ are measured. The highest values of around 250 $W\ m^{-2}$ are found in some desert areas in Western and Northern Africa and Australia. Since the absorption of radiation in the atmosphere is included in the CRU data, the results differ from the theoretical figures presented in Figure 3. The difference is indicated in Figure 4. The total global theoretical potential is the integral over all longitudes. On the basis of the CRU data, this results in a total theoretical potential of $176 \cdot 10^3$ PWh y^{-1}, or $633 \cdot 10^3$ EJ y^{-1}, which is about 1500 times the present world primary energy use. Values for the regional theoretical potential and the averaged irradiances are given in Table V (Section 10).

[36] The co-ordinates of the CRU irradiance data do not completely match with the definition of grid cells in IMAGE 2.2, especially with regard to the definition of land versus sea. Thus for 4200 (border) grid cells the data have been converted using a linear interpolation approach. Following the definition in the IMAGE model, cells that border the shore are included in this study if more than 10% of their area is land. In these cells only the onshore area fraction is taken into account.

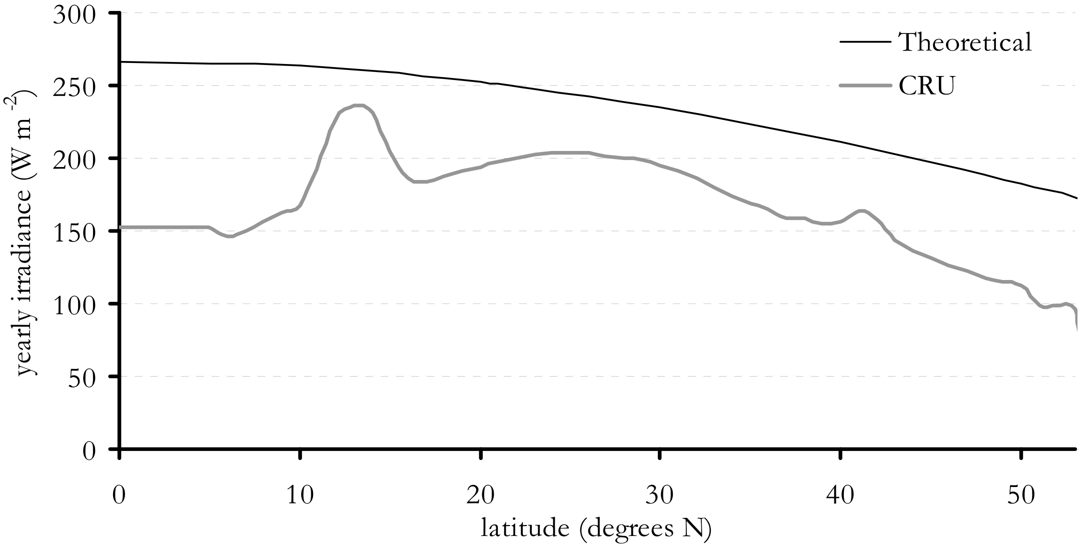


Figure 4: The average irradiance (W m^{-2}) in the period 1960 – 1990 as a function of latitude for longitude $\lambda = 0°$ (Greenwich). This figure compares the result of the theoretical model (see text) with the empirically derived database from the Climate Research Unit (CRU). The latter takes into account solar irradiance absorption of clouds. The data are restricted to terrestrial areas. Therefore, no figures are presented for latitudes above 54° N at $\lambda = 0°$.

4. The geographical potential

From the theoretical potential we deduce the geographical potential, defined as the theoretical potential restricted to the solar radiation at areas suitable for solar PV electricity production. Thus the geographical potential G_i (kWh y^{-1}) of cell *i* equals

$$G_i = 10^3 \cdot I_i \cdot h \cdot A_{a,i} \tag{5}$$

where I_i (W m^{-2}) is the time-averaged irradiance in cell i; h=8760 (h y^{-1}) is the number of hours in a year; $A_{a,i}$ is the available or suitable area for PV (km^2) in cell i.

In our analysis, we use the irradiance data (I_i) from the Climate Research Unit as described in the previous section.

4.1 Suitable area

First we consider the suitable area as function of location, based on the IMAGE 2.2 data in grid cells of 0.5° x 0.5 °. To quantify the geographical constraints we introduce a suitability factor (f_i). It represents the fraction of the onshore area of cell i (A_i) available for the installation of PV modules. The available area (km^2) in cell i ($A_{a,i}$) is expressed as

$$A_{a,i} = f_i \cdot A_i \tag{6}$$

Since the available area is subject to different constraints for centralised and decentralised grid-connected systems, f_i is estimated independently for the two application types. Centralised systems are assumed to be installed on land surface. The available area depends therefore on competing land use options, such as urban area, agriculture, nature or farming. Decentralised systems are assumed to be installed at roof-tops, façades or in any case near settlements and utilities. Hence, when estimating the available area, different approaches are required.

4.1.1 Suitability factor for centralised grid-connected applications

The geographical potential is a function of the competition among various land use categories. The various options for land use, such as human settlements, land for food production or nature conservation, result in a dynamic competition, determined among others by the amount of population, and by economic development. As there is little experience with centralised PV systems, it is difficult to quantify the geographical constraints that are encountered. A dynamic system approach is not explored in this study, as data on most competing options are not available at the level of detail required for such an assessment. Moreover, it would involve a complex evaluation of social (institutional) factors. Instead, we introduce suitability factors for different land use types, shown in Table 1. Figures about land-use types are taken from the IMAGE 2.2 database (IMAGEteam, 2001). In IMAGE 2.2 values for the urban area were derived from the DIScover database, which supplies detailed data for 1 km x 1 km cells (Belward and Loveland, 1995; Loveland and Belward, 1997). This database, in which urban area is defined as land covered by buildings and other man-made structures, has been converted to 0.5° x 0.5° grid cells to construct a database giving the fraction of urban area in each grid cell.

The idea behind introducing suitability factors is that only part of the area is physically available for PV applications as it may block other land use options, e.g. large-scale PV systems on cropland would reduce agricultural production. Available area at cropland is therefore restricted to small parts next to infrastructure or fallow area. Extensive grassland is given a higher suitability factor than agricultural areas, as these areas are used more extensively and PV applications would block to a lesser extent the original function of the land. Furthermore, there are land use functions like the conservation of bioreserves or landscape of natural beauty, which do not allow any installation of centralised PV systems. Consequently, protected areas and forest areas are fully excluded. Also urban areas are excluded as it is assumed that in these areas decentralised PV systems are preferred above centralised PV applications.

Quantification of the suitability factors is arbitrary in some respects, as empirical data are not available. For centralised applications, we use the quantification of Sørensen (Sørensen, 1999). Sørensen distinguishes three values: 0%, 1% and 5%. The average of these values at a global is higher than the 1% of arid, non-productive land proposed to be a reasonable estimate by Weingart (1978). Sørensen does not discuss the underlying arguments in detail, however, these values do give an order of magnitude that seems reasonable to assume for the installation of centralised PV systems. For example, they can be compared with data on the urban area and paved road area in a very densely populated country like the Netherlands, which seems reasonable as fulfilling energy requirements is a basic human need like sheltering and mobility. The urban area of the Netherlands is about 6.6% and the paved roads cover 3% of the total land surface of the country (Centraal Bureau voor de Statistiek, 2002).

Table I: The assumed suitability factors taken from values proposed by Sørensen (1999), the area of various land-use types and the total suitable area as well as the suitable area as fraction of the total terrestrial area.

Land use type	Land-use suitability factor f_i (-)	Area per land-use type (Million km^2)	Land-use area as percentage of total terrestrial area	Suitable area for centralised PV (Million km^2)	Suitable area for centralised PV as percentage of total land area
Urban area	0	0.2	0.2%	0.00	0.00%
Bioreserve	0	8.3	6%	0.00	0.00%
Forest	0	37.0	27%	0.00	0.00%
Agriculture	0.01	32.3	24%	0.32	0.24%
Shrubland	0.01	8.1	6%	0.08	0.06%
Savannah	0.01	5.6	4%	0.06	0.04%
Tundra	0.01	8.3	6%	0.08	0.06%
Grassland	0.01	17.1	13%	0.86	0.63%
Extensive grassland	0.05	16.9	12%	0.85	0.62%
Desert	0.05	2.3	2%	0.02	0.02%
Total		136.1	100%	2.27	1.67%

The orientation of the installed PV modules and arrays towards the sun is of high importance for the output. The optimal tilt angle and orientation of an array is a function of latitude and the fraction of diffuse radiation at that location. At optimal tilt, the amount of solar irradiation on the surface of the arrays is maximised. However, when the arrays are not placed horizontally, the electricity output per unit area may suffer from shadowing effects of neighbouring arrays, unless they are installed at a proper distance from each other. Thus, when calculating the geographical potential of centralised PV, we assume that the modules are placed horizontally.

4.1.2 Suitability factors for decentralised grid-connected applications

The total available area for decentralised grid-connected systems is related to the available area at and around settlements, here referred to as 'roof-top area', consisting in principle of roof-tops, façades and small surfaces around the house when available. It is related to the size of the houses, the number of houses per building, the number of other buildings (e.g. offices, industrial plants) and the area close to the buildings. To assess the total suitable area per grid cell, we assume an average suitable area per person.

Two studies have assessed the roof-top area per capita for the use of PV applications (Alsema and Brummelen, 1993; IEA/OECD, 2001a)[37]. Both give estimates of the solar building roof-top surface (km^2), based on roof-top surfaces at houses, offices and industrial buildings at country level for the European OECD countries, and the IEA study also for Australia, Canada and Japan. Average roof-top areas per capita available for decentralised PV applications at country level ranges from 11 m^2 $capita^{-1}$ to 52 m^2 $capita^{-1}$ in (IEA/OECD, 2001a) and from about 2 m^2 $person^{-1}$ to 16 m^2 $person^{-1}$ in (Alsema and Brummelen, 1993).

The IEA study focuses on roof-tops and façades, using various case studies (e.g. in Australia, Switzerland, the Netherlands, Sweden, U.K. and the USA) that have been conducted to assess the roof-top area based on ground-floor data per capita. These case-studies were used to construct a set of rules-of-thumbs to derive the suitable roof-top and façade area from ground floor area per capita required for buildings. These rules-of-thumbs include orientation (also sub-optimal orientations are included) and morphological aspects concerning the architecture of the buildings. The total area suitable for PV is limited by architectural reasons (shading elements and historical elements) as well as by solar-architectural reasons (orientation of the roof). The combination of these two suitability factors relative to the ground floor determines the so-called utilization factor; on average 0.40 for roof-tops and 0.15 for façades. From these utilization factors and the ground floor area per capita derived from various sources, the suitable roof-top area was derived.

Alsema and Brummelen (1993) use a bottom-up approach to estimate the suitable surface for decentralised PV at country level. Different categories of built environment have been analysed (utilities, industries, cottages and dwellings). Flats are included by means of specific indicators such as the average number of floors in a flat and the average number of persons living in a flat. Furthermore, assumptions are made regarding the share of farms and the average roof orientation. The study results in an overall average area per capita.

The differences between the results of these studies are large and difficult to explain. The variations in the results are partly due to differences in the amount and types of roof-tops included. The IEA study includes more buildings, such as agricultural buildings and an extra category 'other buildings'. Moreover the study includes façades of buildings, which

[37] Sørensen (1999) has also made an assumption regarding the available area for decentralised PV application, using a different approach. Sørensen assumed that 1% of the urban horizontal land, plus 0.01% of the cropland area is available for decentralised PV applications (see also the sensitivity analysis in Section 8).

are not taken into account by Alsema and van Brummelen. The studies use similar reduction categories for solar and architectural suitability, however, Alsema and van Brummelen are more stringent as they only include optimal orientations. Other variations in the estimation of the available roof-top area are caused by differences in the followed approach, as the IEA study estimates the roof area from the ground floor area per capita of buildings, whereas Alsema and van Brummelen use statistics on average roof-top area directly.

Both studies are limited in the number of countries considered (i.e. only OECD). Thus, in our study we have to extrapolate their results to the whole world. We propose that the available area is related to income (e.g. GDP per capita (Worldbank, 2000)), as an increase in economic welfare results in an increase in settlements, size of settlements and utilities. In Figure 5 we show the results of both studies on the available area per capita versus the GDP per capita. From Figure 5 it can be seen that there is no correlation between the estimated available roof-top area for PV applications and the GDP per capita. However, we remain with the problem of the lack of data in the regions that not have been studied, the less developed regions. We state that these regions have lower roof-top areas. This is quantified by including an extra data point, representing an imaginary country with extremely low GDP per capita and low roof-top area (100 \$ y^{-1} cap^{-1} and 1 m^2 cap^{-1} available roof-top area). We have fitted both the IEA and the data from Alsema using a power-law function and this imaginary point. This results in a low correlation with the GDP and the existing data points that has the shape of a power law (Figure 5). For estimating the regional average roof-top area we use this power law fit applied to the data of the IEA. These data are taken as they are more recent and include more types of buildings. Furthermore, the correlation found was higher. However, we acknowledge that as well we could have used one value for the developed regions because the correlation is low. This has been included in the sensitivity analysis. The roof-top area per capita ($R_{c,i}$) (m^2 cap^{-1}) in grid cell i as a function of the GDP per capita is expressed as follows:

$$R_{c,i} = 0.06 \cdot GDP_i^{0.6} \tag{7}$$

Using this approach we are aware that an overestimation is made for Japan. Japan has a high GDP, resulting in a high roof-top area per capita using our approach (about 37 m^2 cap^{-1}, see Figure 5). However according to the IEA, this region has a lower average roof-top area (11 m^2 cap^{-1}). This results in an overestimation of the technical potential of decentralised of 3.4 times compared to the IEA study.

The available area for decentralised PV systems per grid cell is expressed as the product of available roof-top area per capita times the population in a cell. The population density and the GDP data used in this calculation are also based on the IMAGE 2.2 model (IMAGEteam, 2001).

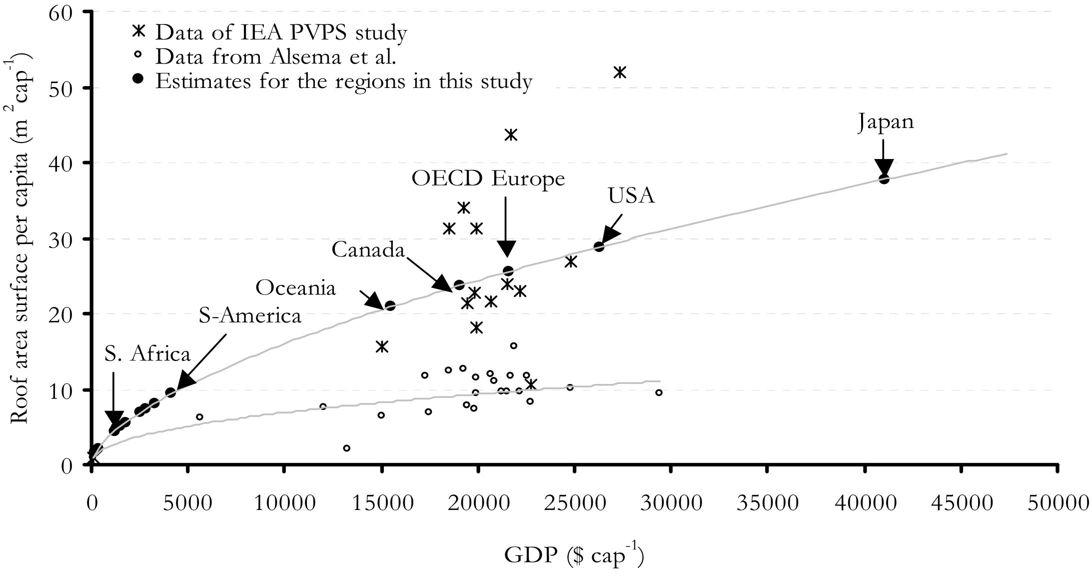


Figure 5: Roof-top area per capita suitable for decentralised PV systems as estimated in (Alsema and Brummelen, 1993) and (IEA/OECD, 2001a) plotted against the GDP per capita for the year 1995 taken from the Worldbank (Worldbank, 2000). Furthermore, we have plotted power law fits to these data and the regional GDP per capita, as obtained from the IMAGE 2.2 database for the year 1995.

4.2 Results on the geographical potential

Figure 6 shows the suitable area for centralised PV systems for the different categories of land use. Here the irradiance is plotted as function of the cumulative area suitable for centralised PV systems by selecting the cells in decreasing order of irradiance[38]. It can be seen that a variation of the suitability factor has more impact on the global geographical potential in the case of desert area than in the case of tundra area because of the higher irradiance.

[38] It should be noted that for illustrative reasons we have plotted the selected cells in decreasing order of irradiance as a functional relationship with the available area, whereas this is not correct. A more correct representation would have been a histogram.

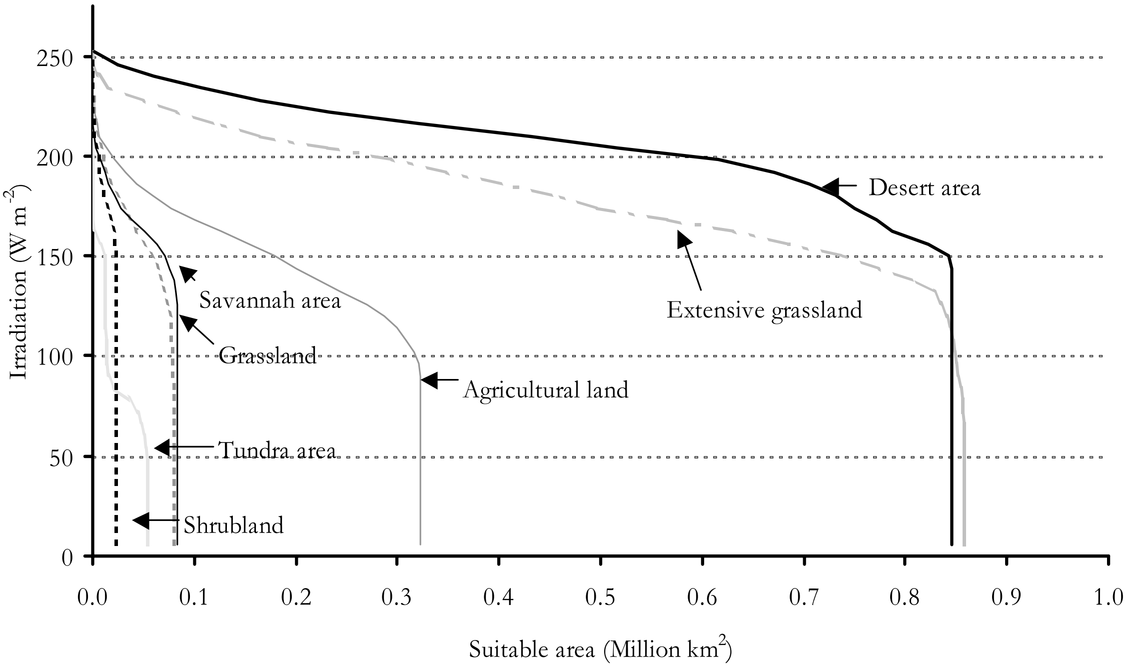


Figure 6: The irradiance versus the suitable area for centralised PV electricity production on a global level, shown for the different categories of land use

Based on the assumptions made, the potential area for centralised PV systems is calculated at about 1.7% of the total terrestrial area. This is about 2.3 million km^2, equal to the size of a country like Sudan (Table I). The highest figure (0.26 million km^2) is found for Oceania, the lowest one (900 km^2) for Japan. The total irradiance on this surface is calculated at 3.5 $\cdot 10^3$ PWh y^{-1}. Regional details are given in Table V.

The potential area for decentralised systems is calculated at 0.11% of the global terrestrial area, which equals about 0.15 million km^2. Regional values range from 250 km^2 in East Africa to 9500 km^2 in OECD Europe. The total irradiance on this surface is 0.6 $\cdot 10^2$ PWh y^{-1}. The global figures for centralised and decentralised systems are about a factor of 32 and 0.5, respectively, of the world primary energy consumption of about 400 EJ y^{-1} in 1998 (Goldemberg, 2000).

5. The technical potential

5.1 How to estimate the technical potential

The technical potential (E_i) of annual PV electricity production in grid cell *i* is defined as the geographical potential G_i (kWh y^{-1}) of the cell corrected for the losses due to the conversion to electricity and can be written as

$$E_i = G_i \cdot \eta_m \cdot pr \qquad (8)$$

where η_m is the conversion efficiency of the PV modules (-) and *pr* is the performance ratio of the PV system (-). Note that we assume that the suitable area is completely covered by PV modules.

The module efficiency η_m depends on the type of PV cells, but also on e.g. the module temperature. The efficiency of commercially available crystalline silicon modules has increased in the last decades, from a few percentages in the early 1970's to 12-16% today (Oliver and Jackson, 2000; Turkenburg, 2000), whereas efficiencies above 20% have been demonstrated for pilots (Green et al., 2003; Yamaguchi, 2001). In this study we assume an average worldwide module efficiency of 14% for both centralised and decentralised systems.

The module efficiency decreases if the module temperature increases. This can be significant in tropical countries, where daily outdoor (and so module) temperature can be high and efficiencies may decrease relatively by about 5%[39]. However, on a yearly basis, the resulting efficiency variations are found to be much less. Furthermore, there are many local circumstances that influence the module temperature, e.g. the availability of wind to cool the system. Therefore, it is decided to neglect this dependency in this study.

The performance of a PV system suffers from losses occurring within the rest of the PV system, e.g. inverter losses, mismatch losses, shading and cable losses, etc. These are taken into account in the performance ratio *pr*, which is expressed as the ratio between the actual performance of the system and the performance of the module under standard test conditions. The best systems currently have performance ratios between 0.66 and 0.85 (Turkenburg, 2000; Baltus et al., 1997; Bucher, 1997; IEA/OECD, 2000a; Betcke et al., 2003). In this study we assume a value of 0.75, corresponding to an overall efficiency of 10.5% for both centralised and decentralised systems.

5.2 Results of the technical potential assessment

The technical potential equals the geographical potential multiplied by the system efficiency of 10.5%. Thus we find a global technical potential of 366 PWh y^{-1} (about $1.3 \cdot 10^3$ EJ y^{-1}) for centralised applications and of 6 PWh y^{-1} (about 22 EJ y^{-1}) for decentralised applications. These values are a factor 23 and 0.4, respectively, of the current (2001) global electricity consumption of 15.7 PWh y^{-1} (BP, 2002). Compared to regional electricity consumption levels, it should be noted that especially in regions with a low electricity demand, there is a high technical potential of PV electricity, e.g. North Africa, Oceania, and the Middle East (see Table V).

[39] This estimate is based on the assumption that the efficiency decreases by 0.4% K for wafer modules (crystalline) and by 1%/K for thin film modules (amorphous silicon) (Green, 1982; Bucher, 1997). This yields, next to the given decreases, also to a maximum increase in efficiency of 10-20% in very cold regions. However, these barely contribute to the technical potential, due to low irradiances in these regions.

6. The economic potential of PV electricity

In the previous sections we have elaborated on the theoretical, geographical, and technical potential of PV electricity. These types of potential can be considered individually, i.e. not influenced by other energy options. This is different for the economic potential determined in this section. The economic potential cannot be analysed outside the context of competing energy options, which is beyond the scope of this article. Therefore, our study of the economic potential is limited to a construction of the cost supply curve of PV electricity for state of the art technology. This curve can then be compared with present electricity generation cost, using conventional energy technologies.

6.1 The cost of PV electricity

The levelised electricity production cost of PV systems is based on turnkey investment costs as well as the Operation and Maintenance (O&M) costs. Here we assume that the investment costs are the sum of the module costs and Balance of System (BOS) costs. The latter are relatively low for decentralised systems as the systems can often be integrated in roof-tops, avoiding land acquisition, fencing access roads and major support structures for the modules (Oliver and Jackson, 2001; Alsema, 2003). For centralised options, on the other hand, land costs and cost for support structure have to be included. The land costs are subject to the demand for land for other applications and to e.g. the quality of land for agricultural purposes. In this study this competition is not taken into account, as this would require a dynamic economic land-use model. Instead, we have studied the land rental costs given in the literature. The FAO presents land rental cost for cropland paid by farmers varying from 25 $ ha^{-1} y^{-1} to 570 $ ha^{-1} y^{-1} for non-irrigated land (FAO, 1997), while various other studies mention land rental costs at levels between 0 $ ha^{-1} y^{-1} and 840 $ ha $^{-1}$ y^{-1} for non-irrigated land (e.g. (Kunte et al., 1998; Turhollow, 1994; Turhollow, 2000; Strauss et al., 1988a; Strauss et al., 1988b; Williams and Larson, 1993; Perlack and Wrights, 1995; de Jager et al., 1998; Faundez, 2003; Walsh, 1998; van den Broek, 2000)). Evidently, the range of the land rental costs is large. As most of these studies do not supply the type and quality of the land, we are unable to deduce a relationship between land rental cost and e.g. soil quality. Furthermore, no relationship was found between GDP or population density and land rental costs. Therefore, the global average land rental cost of 100 $ ha^{-1} y^{-1} is used in our analyses as a general figure.

The production cost of PV electricity ($ kWh^{-1}) in grid cell *i* can be expressed as follows:

$$C_i = \frac{a \cdot (M + B) + C_{O\,\&\,M}(M + B) + L}{e_i} \tag{9}$$

where *a* (y^{-1}) is the annuity factor[40], *L* is the annual land rental price ($ m^{-2} y^{-1}), M is the investment cost of the PV modules ($ m^{-2}), B the BOS cost ($ m^{-2}) and $C_{O\&M}$ is the annual O&M cost as percentage of the total investment costs ($ m^{-2} y^{-1}). Finally, e_i is the specific annual electricity output (kWh m^{-2} y^{-1}) of cell *i,* defined as the technical potential of the cell per unit available area (m^2).

The module costs (M) have decreased in time (see Section 1). The present (2002) weighted global average price provided by SolarBuzz is around 6 $\$_{2002}$ Wp^{-1} (solarbuzz, 2002). However, solarbuzz mentions also prices below 4.5 $\$_{2002}$ Wp^{-1}. The price decreases with size. Large-scale purchases can reduce the price even further due to economies of scale (Ahmed, 1994). Lowest values of 3.3 – 3.7 $\$_{2002}$ Wp^{-1} are mentioned in Turkenburg(2000) and Harmon (2000). In this study we assume lower module prices for centralised systems than for decentralised modules. In concreto, we assume for centralised systems an average price per module of 4 $ Wp^{-1} and for decentralised systems of 5 $ Wp^{-1}.

The BOS costs (B) are more difficult to determine since it is the product of various cost components. However, from literature it can be concluded that for decentralised systems lowest BOS costs were found of 1.6 $\$_{2000}$ Wp^{-1} in 1997 (Lesourd, 2001). For the year 1998, values in the range 2 – 6 $\$_{2000}$ Wp^{-1} are mentioned by Turkenburg (2000). For decentralised systems in Germany values for BOS costs including the labour costs for the installation of the systems range from 3.1 to 4.3 $\$_{2000}$ Wp^{-1} for the year 1999 and first estimates for the year 2002 value lead to about 2 $\$_{2000}$ Wp^{-1} (Laukamp, 2002). In this study we assume a value of 3 $ Wp^{-1} for the centralised systems and 2 $ Wp^{-1} for the decentralised PV systems. It should be noted that part of the BOS cost is power related, part is area related. The BOS costs do not include grid connection, but do include installation costs. Hence, for both centralised and decentralised PV systems the combined module and BOS costs are 7 $ Wp^{-1}.

The O&M costs ($C_{O\&M}$) expressed as a fixed fraction of the total investment costs. We use a value of 3% in this study, which is in the middle of the range of 2 – 4% mentioned in the literature (Chabot, 1999; Zweibel, 1999).

6.2 The cost of PV electricity and the PV cost-supply curve

The present electricity generation costs using PV is calculated to range from 0.44 $ kWh^{-1} to some values above 2 $ kWh^{-1} in the Northern regions. The range depends on the location as shown in Figure 7. These values do not include the cost of grid connection, transmission and distribution. Also storage costs (if applicable) are not included. The

40 The annuity factor is given by $a = \frac{r}{1-(1+r)^{-LT}}$, where *r* is the interest rate, set at 10%, and *LT* the economic lifetime of the product, set at 20 years, hence *a* = 0.117.

results merely show the levelised production cost of PV electricity. Costs below 0.50 $ kWh^{-1} are found only in Africa, the Middle East and Oceania.

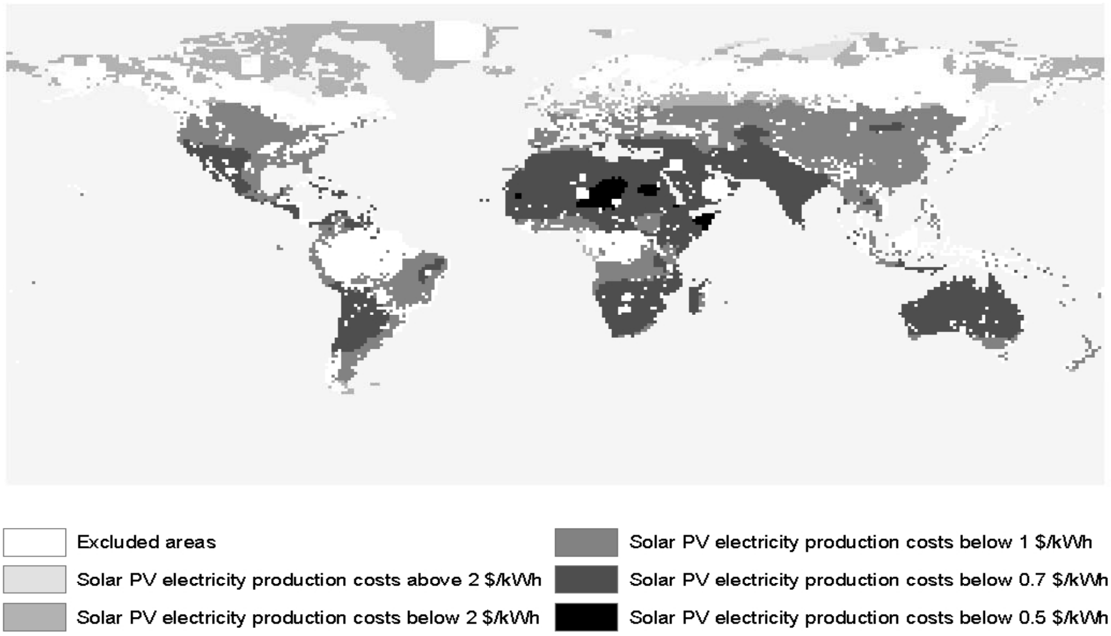


Figure 7: The spatial distribution at grid cell level of the centralised PV electricity production costs over the world at different cut-off values of the production cost (present situation).

Combining the results on costs with the figures on technical potentials gives the cost-supply curves per type of application, regionally and globally. Figure 8 presents the cost-supply curves for centralised PV systems. Figure 8 is limited to 9 regions that have either low cost or a high technical potential; OECD Europe is included for comparison. For decentralised systems, the cost-supply curve is similar, however the supply lies a factor of about 60 lower.

The most interesting regions regarding the technical and economic potential of PV electricity are Northern, Western and Eastern Africa and Oceania. In Northern and Western Africa an amount of electricity equal to the present world electricity consumption can be generated at costs below 0.50 $ kWh^{-1}. This is also the case for the Middle East. The present world electricity consumption and its costs range, taken from Goldemberg (2000) is also shown in Figure 8. From our cost-supply curve we derive that at a cost cut-off of 0.46 $ kWh^{-1}, an amount of PV electricity can be generated that equals the present global electricity consumption. It illustrates that, although the potential of PV electricity is large, the production costs of grid-connected PV systems are at present far above competing levels.

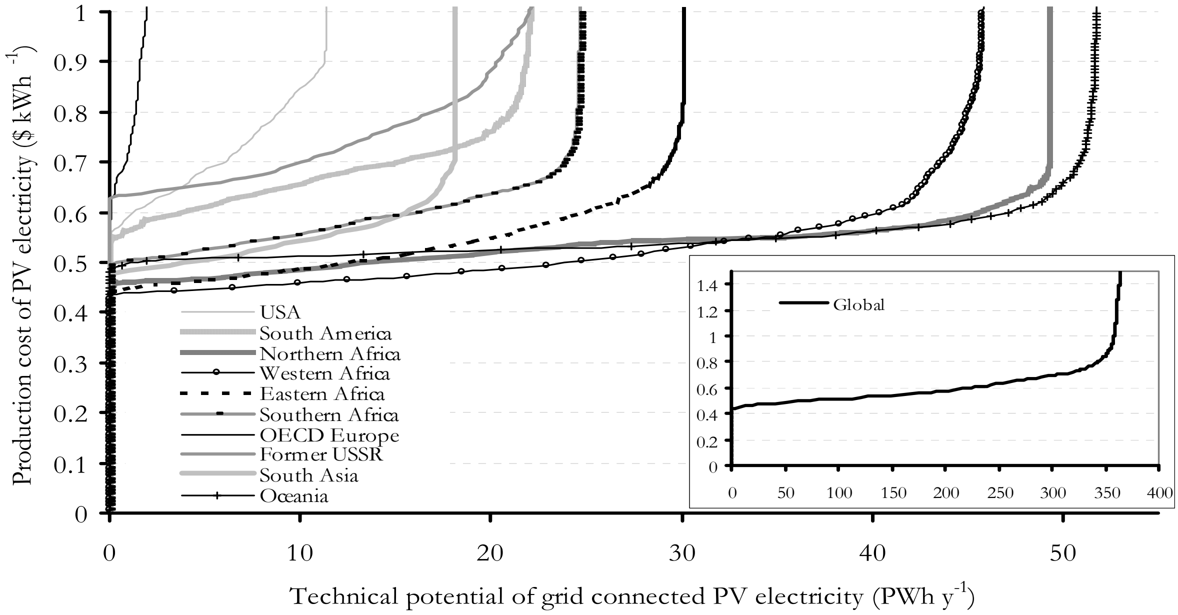


Figure 8: Cost-supply curve for grid-connected centralised PV applications, globally, and for ten regions (present situation). The black square in the 'global' curve indicates the present electricity consumption and range of production costs of electricity (Goldemberg, 2000).

The regional technical potential of centralised PV at cut-off costs of 0.6, 0.8, 1.0 and 1.2 $ kWh^{-1} are shown in Figure 9. At cut-off costs of 0.82 $ kWh^{-1}, PV electricity can be generated in every region, although only marginally in some regions (Canada and Japan).

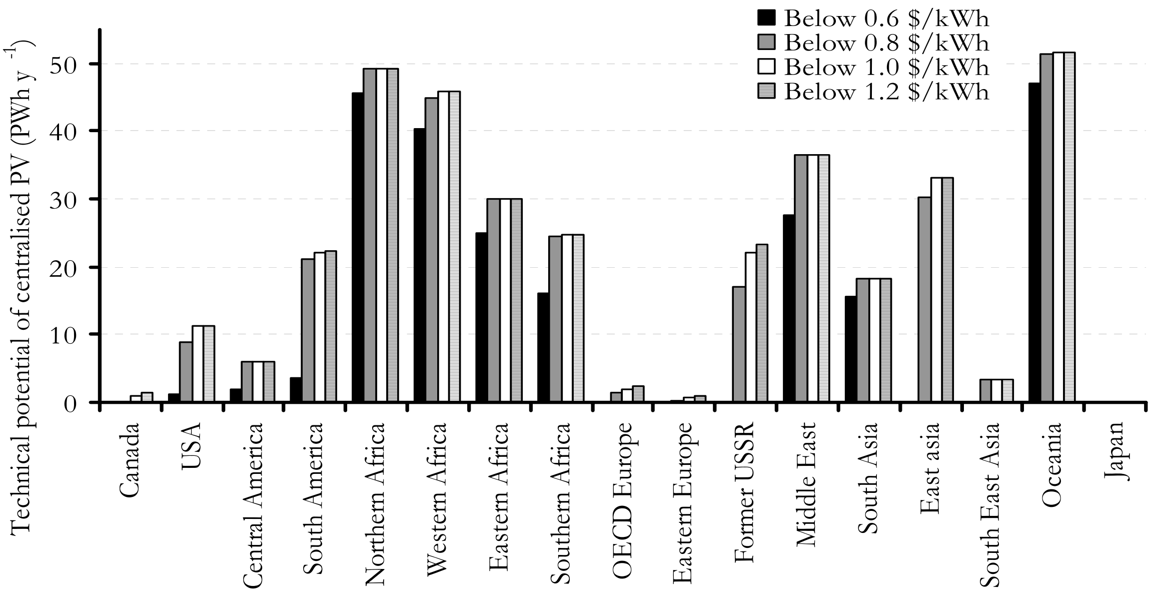


Figure 9: The economic potential of centralised PV electricity production in the 17 regions of the world for different cost cut-off values (present situation).

7. Future perspective of PV electricity

As is seen from the results presented above, the present cost of PV electricity is high compared to the electricity costs of conventional power plants, i.e. 0.02 - 0.03 \$ kWh^{-1} off-peak and 0.15 - 0.25 \$ kWh^{-1} peak (Goldemberg, 2000), which raises a major barrier against large-scale implementation of PV. However, the technical potential is large. It is therefore most interesting to analyse the possible future development of the technical potential as well as the production cost of PV electricity.

To reduce the kWh-costs of PV, an important element is the improvement of the cell and module conversion efficiency. In theory, the thermodynamic limit on the conversion efficiency of sunlight into electricity is 93% (Green, 2000). However, in practice this upper limit will never be achieved. Values such as 30-40% may be attainable, requiring (new) improved concepts in solar cell technology that make much better use of the solar spectrum, following e.g. a multigap-cell approach tandem-cell approach). This concept is based on stacking two or more solar cells with different band gaps on top of each other (Green, 2000). Another approach to improve the conversion efficiency would be the use of concentrator cells in sunny regions. As a result module efficiencies may rise to 15 – 20% on the medium term (2010-2020) (Hoffman, 2001; Alsema and Nieuwlaar, 2000) and even exceed 30% in later times (Turkenburg, 2000). The system efficiency can also be improved. The performance ratio of PV-systems could increase to 0.90 on the long term (Turkenburg, 2000; Betcke et al., 2003).

To reduce the production costs of solar cells and modules, amongst others, the amount of material used to manufacture the cells should be reduced. It is generally accepted that thin-film cells deposited directly onto a substrate (glass, plastic, and stainless steel) offer the best long-term perspective for very low production costs (Turkenburg, 2000). Various studies state that the costs of PV modules are expected to be reduced in the future (Turkenburg, 2000; Oliver and Jackson, 2000; Mackay and Probert, 1998). This can be expected from technology foresight studies and from the expected future development of the experience curve of PV technology. Various authors have analysed the (global) historical development of the lowest PV module price as a function of the cumulative production. Snik (2002) has made an overview of various experience curves for photovoltaic technologies, indicating an average figure for the progress ratio of about 0.8. This value is low (implying high technological growth) compared to the values for wind energy technology (Junginger, 2000) and gas turbines (McDonald and Schrattenholzer, 2001). In the World Energy Assessment a simple analysis has been done using these progress ratios and the grow rates of the past years to assess the system costs in the future (Turkenburg, 2000). If up to the year 2020 the PV system production increases with 15% - 25% and the progress ratio ranges from 0.8 to 0.9, the estimated range of PV system costs is 1 – 4.8 \$ Wp^{-1}.

Several foresight studies have analysed the origin of such a reduction of costs. One of the main factors is the economy of scale (Oliver and Jackson, 2000; Payne et al., 2001; Bruton et al., 1996). Another factor is technological breakthroughs. The MUSIC FM study (Bruton et al., 1996) has shown for a module manufacturing plant of 500 MWp that a cost reduction to 0.9 \$ Wp^{-1} may be obtained for crystalline silicon. Ultimately, for thin-film solar cells modules the manufacturing cost is expected to be reduced to 0.5 \$ Wp^{-1} and for the PV system to 1 \$ Wp^{-1} (Turkenburg, 2000). BOS costs decrease faster than module prices and can be reduced further (Schaeffer, 2003). Thus the costs of PV technology might fall significantly in the future.

How would these costs reductions alter the cost-supply curve of centralised PV? To answer this question, we simulated the cost-supply curve using the long-term data as presented in Table II. All other data are kept equivalent to the present situation.

Table II: Values assumed for the assessment of the future perspective.

	Default	Long term
Module efficiency (%)	14	25
Performance ratio (%)	75	90
Module costs (\$ Wp^{-1})	4 – 5 (centralised – decentralised)	0.5
BOS costs (\$ Wp^{-1})	2 – 3 (decentralised – centralised)	0.5

The potential long-term cost-supply curve is shown in Figure 10. The technical potential of centralised PV would increase with a factor of 2.1 as a result of enhanced module and system efficiency. For decentralised systems, a larger increase can be expected due to an increase in the GDP (see sensitivity analysis in next section). For centralised systems there is a technical potential exceeding the present electricity consumption that could be generated at a cost around 0.06 \$ kWh^{-1}. Moreover, at a cost below 0.10 \$ kWh^{-1}, 5 times the present electricity consumption may be produced. However, it is stressed that the costs in Figure 10 do not include grid connection, transmission, distribution and storage.

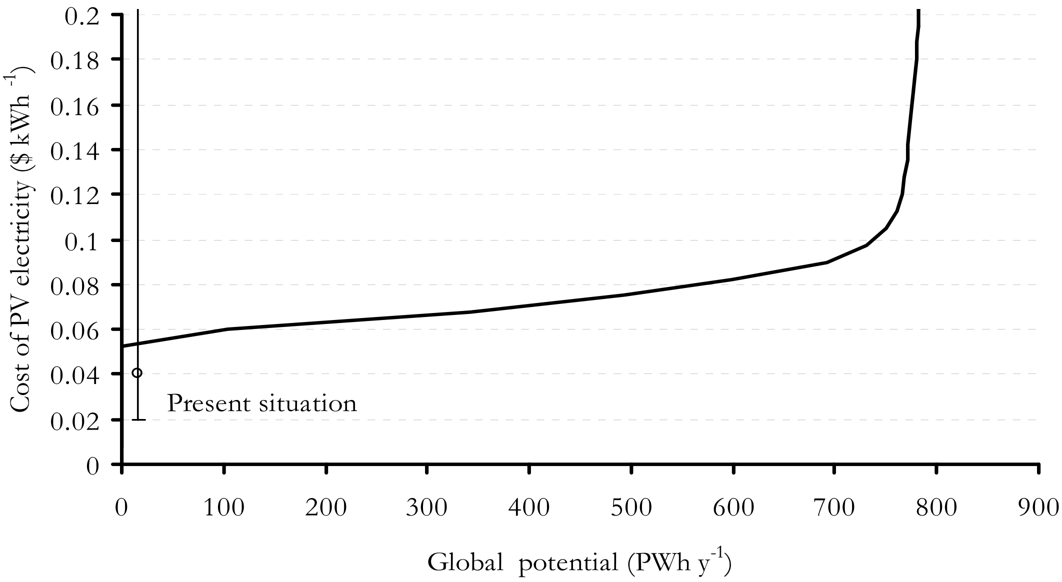


Figure 10: PV electricity production costs as a function of the potential supply of electricity by centralised PV systems (long term situation). The data point on the left indicates the present (2001) electricity consumption and production costs of conventional systems taken from Goldemberg (2000).

8. Sensitivity analysis

To assess the impact of the value of the input parameters, we use a one-factor sensitivity analysis of the technical potential and the cost-supply curve for the centralised applications in the present situation. The sensitivity of the results for the decentralised cost-supply curve is similar, except for the suitability factor due to an increase in GDP. Therefore, this factor is also included in this analysis, ranging the GDP from 70% to 130%. Furthermore, for decentralised systems we have evaluated the approach by calculating the technical potential using 3 other methodologies discussed later in this paragraph. In the whole study we have taken one average figure in all grid cells for the conversion efficiency, the losses and the costs. These figures are well chosen as averages however, within regions variations exists. Therefore we use ranges found in the literature for all input parameters to evaluate the sensitivity of the parameters.

The yearly-averaged irradiance is based on empirical values interpolated over the grid cells (see Section 3). The values could not be compared with other sources, because at this level of detail, other numerical data are not available. It should be noted that the amount and distribution of irradiance on earth can change if the cloud coverage changes due to e.g. global changes in the climate system. Therefore, we have multiplied the irradiance data with a factor varying between 0.9 and 1.1 in the sensitivity analysis.

The suitability factors for the use of land to install centralised PV systems and the per capita suitable area to install decentralised systems are not measurable. How much land is considered as suitable for solar panels will strongly depend on the outcomes of assessments of the advantages to install solar systems compared to other land use functions. However, such studies suffer from a certain degree of arbitrariness. It is therefore difficult to assign a definite range to this parameter. The averaged land use suitability factor is varied in the sensitivity analysis from 50% to 150% of default values used.

As discussed in the previous section, the efficiency of crystalline silicon solar modules varies from 12 – 16% at present, to 15 - 20% in the medium term and up to 30% (or more) in the long term. On the other hand, the effect of temperature on the conversion efficiency may reduce the conversion efficiency somewhat. Therefore we vary the module efficiency from 10 to 30% in our sensitivity analysis.

The performance ratio is a function of many local factors, such as defects, shading effects, as well as losses in inverter and grid connection. The IEA PV Power System Program has evaluated the performance of 170 grid-connected systems (mainly decentralised PV applications). The performance ratio is found to vary from 0.2 to 0.9 (IEA/OECD, 2000a). The same range is considered here.

The prices of modules are verifiable and therefore known to reasonably high accuracy. However, significant variations are found in the literature. The production costs are a function of costs of capital, labour and feedstock, i.e., regionally specific factors. The production costs also depend on the size of the module, the size of the production plant, and the scale of the purchases, due to the effect of economies of scale in production and transport. The prices are a function of costs and further increase with the profit margin. Present estimates of modules prices vary from about 3 - 6 \$ Wp^{-1} (Turkenburg, 2000; solarbuzz, 2002). On the long term, the lowest modules costs may come down to 0.5 \$ Wp^{-1}. In this sensitivity analysis we use a range in module cost of 0.5 - 6 \$ Wp^{-1}.

The BOS costs depend among others on the type of inverter and mounting construction that is used, the size of the system, and the labour costs involved. Literature values for present systems vary from around 1.5 – 10 \$ Wp^{-1}. On the long term, the lowest BOS costs may come down to 0.5 \$ Wp^{-1}. Therefore we vary the BOS cost in the sensitivity analysis from 0.5 \$ Wp^{-1} to 10 \$ Wp^{-1}.

The price of land depends heavily on the type, function and quality of the land, the competing land use options in the region and the possibilities of multi-functional use of the land. In this study, the land rental price was included as a fixed value as detailed information on (the background of) regional variations was not available. It is noticed that the accuracy of this parameter is rather low. For the sensitivity analysis we use a range of 0 – 1000 \$ ha^{-1} y^{-1}, corresponding to the range found in literature.

The interest rate is hard to quantify, because it depends on local socio-economic parameters. Its value depends on questions like: Who is the main investor, e.g. private companies or the government? What is the availability of capital? What are the risks of investment? What is the interest rate on the market? What is the required return of investment period? In the sensitivity analysis we use a broad range of 5 to 25%.

The economic lifetime of PV systems is difficult to estimate as little experience has been gained so far. The physical lifetime can be long. However, module performance can be limited due to reduced efficiencies caused by e.g. high variations in the temperature degeneration of materials or impact to pollution. For the sensitivity analysis a range from 10 to 25 years seems reasonable (Turkenburg, 2000).

The approach to assess the roof-top area per capita is rather weakly underpinned. It has already been mentioned that the geographical potential and the technical potential of decentralised PV in Japan is overestimated using the relationship between the roof-top area per capita and the GPD per capita. We have therefore also estimated the technical potential of decentralised PV applications using the OECD average roof-top areas according to the study for the IEA (IEA/OECD, 2001a) (27 m^2 cap^{-1}) and from Alsema (Alsema and van Brummelen, 1993) (10 m^2 cap^{-1}) as a global average. Furthermore, we have applied the approach proposed by Sørensen (Sørensen, 1999): 1% of the urban horizontal land, plus 0.01% of the cropland area is available for decentralised PV applications, which we had to interpret as 1% of the total urban area and 0.01 % of the agricultural land, using the IMAGE 2.2 database.

The results of the different approaches to assess the decentralized technical potential and the results for different input parameters on the centralized technical potential are significantly different to the default values, indicating the variability of the results (see Table III). An overview of the ranges of the input parameters used in the sensitivity analysis, as well as the range found for the technical potential of centralised PV electricity, is shown in Table III.

Table III: Potential variation of input parameters used in the sensitivity analysis for centralised PV electricity production, the default value for the input parameter, the calculated range of the technical potential and the calculated lowest production cost of centralised PV electricity.

	Name	Relative range of input parameter	Absolute range of input parameter	Default value of input parameter	Unit	Range of technical potential (PWh y^{-1})	Range of lowest production cost (\$ kWh^{-1})
Centralised PV							
I	Irradiance	0.9 – 1.1			-	329 – 402	0.40 – 0.49
pr	Perf. ratio	0.3 – 1.2	0.2 – 0.9	0.75	-	98 – 439	0.37 - >2
η_m	Module eff.	0.7 – 2.1	10 – 30	14	%	261 – 784	0.44– 0.44
fi	Suitability fact.	0.5 – 1.5			-	183 – 549	0.44 – 0.44
M	Module costs	0.1– 1.3	0.5 – 6	4	\$ Wp^{-1}	-	0.22 – 0.56
B	BOS costs	0.2 – 3.3	0.5 -10	3	\$ Wp^{-1}	-	0.29 – 0.87
L	Land rental costs	0.1 – 10	10 – 1000	100	\$ ha^{-1} y^{-1}	-	0.44 – 0.44
r	Interest rate	0.5 – 2.5	5 – 25	10	%	-	0.33 – 0.84
LT	Eco. Lifetime	0.5 – 1.25	10 - 25	20	y	-	0.42 – 0.57
Decentralised PV							
GDP	GDP per cap.	0.7 – 1.3			\$ cap^{-1}	5.1 - 7.0[a]	
	Abs.roof-top area per cap.		27 m^2		m^2 cap^{-1}	22.1[a]	
	Abs. roof-top area per cap.		10 m^2		m^2 cap^{-1}	8.2[a]	
	Approach Sørensen					0.8[a]	

[a] Compare to the value of 6 PWh y^{-1} found using default setting .

The sensitivity of the technical potential for variation of the parameter values is linear as can be seen from the equations; thus the technical potential is equally sensitive for all input parameters. However, the ranges found for the technical potential vary along the ranges found in the input parameters. This is different for the cost-supply curve of PV electricity. Figure 11 shows the global cost-supply curves of centralised PV for the various input ranges. The values for the lowest cost are shown in Table III, note that the default value is 0.44 \$ kWh^{-1}.

The PV electricity costs are not lowered with an increase of the conversion efficiency. This is not completely correct as the BOS costs are partly area related, and the area depends on the conversion efficiency. Finally, it should be noted that to reduce the electricity costs of PV significantly, a combination of the effects presented in Figure 11 is required, e.g. as discussed in Section 7.

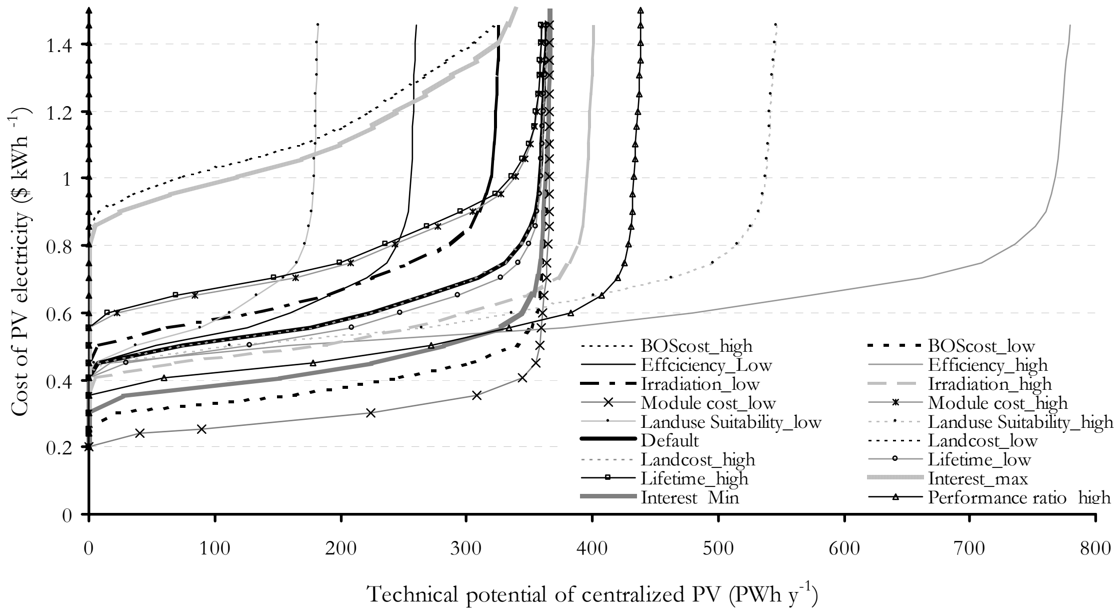


Figure 11: The cost-supply curve for centralised PV systems using the ranges of input parameters given in Table III.

9. Discussion

In this study we have assessed the global geographical, technical and economic potential of grid-connected PV. The exact value of the input parameter and the empirical basis of the input parameters are highly variable. To indicate the variability of the quality of the input parameters, we use the qualification 'weak', 'fair' and 'strong'. Input is considered to be highly accurate (strong) if its value is measured, or otherwise empirically supported by (several) literature sources. The parameters that are derived from measurable values or have broad ranges in the literature are considered fair. Parameters that are not validated in the literature or are closely connected to personal values are considered to be weakly accurate. The accuracy of the input parameters, described using this terminology and the sensitivity to the default value of the parameters are summarised in Table IV. A typical weak parameter is the suitability factor describing the availability of area for PV module installations (see Table I). The conversion efficiency is considered strong as it is measurable and data in the literature are not highly variable. All input parameters are linearly sensitive to the geographical and technical potential of PV electricity. The costs of PV electricity are highly dependent on the interest rate of the investments, causing wide ranges of production costs (e.g. see the spread in the lowest cost, given in Table III). The value of the interest rate is rather weak as it depends on local social and economic factors. The other parameters like module and BOS costs are fairly accurate, the range given in the literature is broad but the exact value is measurable. The land costs vary widely, but have only marginal impact on the PV electricity production costs. In conclusion, on the basis of these results, the land use suitability factors and the interest rate should be considered in more detail in order to improve the assessment of the PV potential presented here.

Table IV: The accuracy and sensitivity of the input and output parameters on the various (intermediary) results.

	Accuracy of input parameter	Sensitivity to direct output parameter
Geographical potential		
Land Use suitability factor	Weak	High
Roof area per capita	Weak	High
Technical potential		
Irradiance	Fair	High
Module conversion efficiency	Strong	High
Performance Ratio	Fair	High
Cost of PV electricity		
O&M	Strong	Low
Module cost	Fair	High
BOS cost	Fair	High
Interest rate	Weak	High
Land cost	Fair	Low

Before drawing conclusions based on the results, some remarks on the limitations of the study and a comparison with previous studies are made. In our analysis, the availability of the electricity grid was taken for granted. At locations without electricity grid, additional costs due to the transmission of electricity need to be taken into account. Sørensen (1999) estimates these costs as one-third of the future (2050) generation costs. Furthermore, it should be noticed that high penetration levels of the intermittent PV source are not possible without the installation of additional storage capacity. This will add to the total electricity costs. Moreover, it is stressed that the results of the geographical potential and so the technical and economic potential depend linearly on the suitability factor representing the available area for PV systems. This suitability factor is subject to normative assumptions regarding the available of land at various different land-use types for centralised PV system and at roof-top areas for decentralised systems.

As mentioned in Section 1, two previous studies have estimated the technical potential of PV electricity at a similar level (Hofman et al., 2002 and Sørensen, 1999). In these studies, the technical potential of centralised PV is estimated at respectively 365 PWh y^{-1} and 457 PWh y^{-1} and for decentralised systems respectively 8 PWh y^{-1} and 6 PWh y^{-1}. These figures are similar to the results obtained in this study: about $3.7 \cdot 10^2$ PWh y^{-1} for centralised PV systems and about 6 PWh y^{-1} for decentralised systems. This can partly be explained by the fact that both studies use a similar approach. However, there is a difference in input data. Hofman et al. (2002) use the same solar radiation data, but different land-use data. The solar and land-use data used by Sørensen (1999) differ from the data used in this study. For centralised PV, the suitability factors in our study are based on the figures introduced by Sørensen (1999), so these are similar, although applied at different land-use data. Hofman et al. use 5% of all the land after excluding mountainous areas (with a slope of 5% or more), all nature areas, agricultural areas and built environment. We differentiate more among land-use types. In our study only extensive grassland and dessert areas are assumed to be suitable for 5%. As Hoffman et al. (2002) also exclude all areas with radiance below 120 W m^{-2}, we exceed their suitability factors for the agricultural areas, whereas for tundra, grassland, etc., we are more stringent. Regarding the conversion efficiency we assume for the state of the art technology similar values as Sørensen (1999) for the year 2050. In our analysis of the future situation, higher conversion efficiencies are used. Hofman et al. (2002) assume concentrating cells with a conversion efficiency of 30%. However, as they take shadowing effects of 50% into account, the overall results are remarkably similar. For decentralised PV, we have slightly higher figures than Hoffman et al. (2002) mainly due to a slightly higher estimate of the roof-top area originating from the same data by (IEA/OECD, 2001a). A comparison with Sørensen (1999) was included in Section 8.

As observed, the present electricity production costs of PV vary from 0.44 \$ kWh^{-1} to over 2.0 \$ kWh^{-1}. This is relatively high compared to the range given by the World Energy Assessment of 0.31 – 1.22 \$ kWh^{-1} (Turkenburg, 2000). Lesourd presents an even more optimistic range of 0.19 – 0.34 \$ kWh^{-1} (Lesourd, 2001). Most of the higher cost estimates in this study can be explained by a difference in assumptions about the PV system costs, as the World Energy Assessment assumes lowest PV system costs around 5 \$ Wp^{-1}, whereas in this study 7 \$ Wp^{-1} is taken. The lowest value given in the World Energy Assessment is furthermore based on 5% interest, compared to 10% in this study. Moreover, the World Energy Assessment uses an economic lifetime of PV systems ranging from 10 to 25 years, whereas in this study a default lifetime is used of 20 years. The assumed solar irradiance may also contribute to the differences, although this is expected to result in lower PV production cost in our study, as the highest absolute value of solar irradiance found in our database is higher than the upper limit taken in Turkenburg (2000). Finally, in this study we have assumed that all modules are installed horizontally. Under optimal orientation, however, the output per module may increase with a tilt factor, resulting in lower cost. A typical value for the tilt factor in the Netherlands is 1.14 (Betcke et al., 1998).

10. Summary and conclusions

In this study we have assessed the theoretical, geographical, technical and economic potential of PV electricity at a regional level. The global technical potential of grid-connected (centralised and decentralised) PV is assessed at a value of about $3.7 \cdot 10^2$ PWh y^{-1}, or about 23 times the present world electricity consumption. For more than 98% it consists of centralised PV applications. At cut-off costs of 1 \$ kWh^{-1}, the technical potential at present is about $3.6 \cdot 10^2$ PWh y^{-1}. At cut-off costs below 0.5 \$ kWh^{-1}, this figure is reduced to 70 PWh y^{-1}. The present global electricity consumption can be generated at costs between 0.44 and 0.46 \$ kWh^{-1}. It should be noted that this figure does not include grid-connection, transmission, distribution and storage costs. The regional figures for the technical potential are shown in Table V. Potentially high contributions, exceeding the present regional electricity consumption almost 1000-4000 times, in North, East and West Africa and Australia. In Japan, OECD Europe and Eastern Europe the relative potential is less, about 0.6 to 2 times the present regional electricity consumption. The potential highly depends on the available area for PV modules, which at a regional level can be less than 1% of the total area, as well as the conversion efficiency of PV modules and performance ratio of PV systems. The assumptions regarding the suitability of land for PV system made in this study results in an available area for centralised PV systems of 1.7% of the terrestrial area on earth (2.3 million km^2, i.e. about the size of Sudan[41]) and 0.11% for decentralised PV applications (0.15 million km^2). Depending on future achievements in technology development, like an increase of the conversion efficiency of PV modules or an improvement of the performance ratio of PV systems, the technical potential of centralised PV applications may increase with about a factor 2. The technical potential of the decentralised systems might even increase more due to increased roof-top areas. It is also estimated on the basis of potential future cost reduction that it may become possible to generate the present consumption at a cost below 0.06 \$ kWh^{-1}. This would imply that regions like Northern Africa and Australia would export large amounts of electricity. This would require high transmission costs. To estimate the real economic potential of PV electricity, these costs need to be included in the cost-supply curve of PV electricity.

[41] This equals 0.23 Gha

Table V: Summary of the regional values of time-averaged irradiance, suitability factors of area for PV, technical potential and average kWh-cost for centralised and decentralised grid-connected PV systems, ratio between technical potential and current electricity consumption, and technical potential at a cost cut-off of 0.5, 0.7 and 1.0 $ kWh^{-1}.

Region	Avg irradiance ($W\ m^{-1}$)	Area (km^2)	Theoretical potential ($EWh\ y^{-1}$)	suitability factor	Suitability factor	technical potential ($PWh\ y^{-1}$)	technical potential ($PWh\ y^{-1}$)	lowest cost of PV elect ($ kWh^{-1})	Lowest cost of PV elect ($ kWh^{-1})	Ratio techn. Pot. and electr. Cons (-)[a]	techn. pot at cut-off at 0.5 $ kWh^{-1} ($PWh\ y^{-1}$)	techn. pot at cut-off at 0.7 $ kWh^{-1} ($PWh\ y^{-1}$)	techn. pot at cut-off at 1.0 $ kWh^{-1} ($PWh\ y^{-1}$)
				Central	Decentral	Central	Decentral	Central	Decentral	Total	Total	Total	Total
Canada	93.6	9.5	8	0.50%	0.01%	4	0.1	0.82	0.94	7	0.0	0.0	1.0
USA	127.4	9.2	11	0.92%	0.08%	12	1.0	0.56	0.63	4	0.0	6.2	12.4
Central-America	175.9	2.7	4	1.38%	0.04%	6	0.2	0.52	0.59	29	0.0	5.9	6.2
South-America	152.4	17.6	24	0.84%	0.02%	22	0.4	0.55	0.62	38	0.0	15.5	22.6
North-Africa	203.1	5.7	10	4.50%	0.01%	49	0.1	0.46	0.52	413	14.1	49.3	49.3
West- Africa	184.1	11.3	18	2.10%	0.00%	46	0.1	0.44	0.5	1252	24.8	43.8	45.9
East- Africa	195.3	5.8	10	2.71%	0.00%	30	0.0	0.44	0.51	3961	13.3	29.4	30.2
South- Africa	180.2	6.8	11	2.10%	0.01%	25	0.1	0.5	0.57	111	0.9	23.9	24.8
OECD Europe	108.8	3.7	4	0.69%	0.26%	3	1.1	0.57	0.63	2	0.0	0.9	2.5
East- Europe	124.4	1.2	1	0.63%	0.08%	1	0.1	0.69	0.79	2	0.0	0.0	0.9
Former. USSR	95.8	21.8	20	0.92%	0.01%	25	0.2	0.62	0.71	20	0.0	10.4	22.7
Middle East	198.1	5.9	10	3.32%	0.03%	37	0.3	0.47	0.54	83	14.8	36.6	36.9
South Asia	193.0	5.1	9	1.92%	0.05%	18	0.5	0.47	0.54	37	4.6	18.5	18.6
East Asia	149.4	11.1	15	2.14%	0.06%	33	0.9	0.64	0.73	23	0.0	15.6	34.2
South. East Asia	158.6	4.4	6	0.51%	0.05%	3	0.3	0.51	0.59	13	0.0	2.8	3.7
Oceania	188.5	8.4	14	3.32%	0.01%	52	0.1	0.49	0.56	243	1.9	51.0	51.8
Japan	126.4	0.4	0	0.23%	1.21%	0.1	0.5	0.77	0.82	0.6	0.0	0.0	0.6
World	156.2	130.6	175	1.69%	0.11%	366	6.0	0.44	0.51	27	74.5	309.9	364.3

[a] We have taken the electricity consumption from TIMER, based on IEA figures for the year 1996 (IMAGEteam, 2001)

List of variables:

I	direct radiation flux or irradiance	($W\ m^{-2}$)
n	day of the year	(-)
t	time of day	(h)
S	solar constant	($W\ m^{-2}$)
a_0	albedo of the earth-atmosphere system	(-)
θ	solar zenith angle	(degrees)
φ	geographical latitude	(degrees)
λ	geographical longitude	(degrees)
δ	solar declination	(degrees)
ω	hour angle	(degrees)
t_{zone}	local time	(h)
λ_{zone}	longitude of the meridian defining the local time zone	(degrees)
h	hours per year	($h\ y^{-1}$)
I_i	yearly-averaged irradiance in cell i	($W\ m^{-2}$)
G_i	geographical potential of solar energy in grid cell i	($kWh\ y^{-1}$)
A_i	onshore area of cell i	(km^2)
$A_{a,i}$	suitable area of land-use for PV in grid cell i	(km^2)
f_i	suitability factor for PV in grid cell i	(-)
E_i	technical potential of annual PV electricity production in grid cell i	($kWh\ y^{-1}$)
e_i	annual electricity production of PV systems in grid cell i per unit of area	($kWh\ m^{-2}\ y^{-1}$)
η_m	conversion efficiency of the module	(-)
pr	performance ratio	(-)
C_i	cost of electricity in a grid cell	($\$\ kWh^{-1}$)
a	annuity factor	(-)
r	interest rate	(%)
L	land rental price	($\$\ ha^{-1}\ y^{-1}$)
M	module cost	($\$\ Wp^{-1}$)
B	BOS costs	($\$\ Wp^{-1}$)
$C_{O\&M}$	percentage of O&M cost of the total investment costs per m^2 of suitable area	(%)
LT	economic life time of the PV system	(y)

PART 4

ELECTRICITY SYSTEM

CHAPTER SEVEN

EXPLORING THE IMPACT ON COST AND ELECTRICITY PRODUCTION OF HIGH PENETRATION LEVELS OF INTERMITTENT ELECTRICITY IN OECD EUROPE AND THE USA[#]

Abstract

In this study we explore for the USA and OECD Europe dynamic changes in electricity production, cost and CO_2 emissions when intermittent electricity sources are used with increasing penetration levels. The focus is on penetration of wind electricity in the electricity system simulated by a new long-term electricity model called EPG using a constrained experiment. With increasing penetration levels the cost reduction of wind electricity caused by technological learning is counteracted by the cost increase due to (1) the need for additional back-up capacity, (2) generation of wind electricity at less favourable sites, and (3) discarded wind electricity because of supply-demand mismatch. This occurs after about 20% wind electricity penetration. At this level about 500 (OECD Europe) to 750 (USA) TWh y^{-1} wind electricity is absorbed wind in the system. , Wind electricity is found to be discarded when the production is about 55 (USA) to 10 times (OECD Europe) the present electricity produced from wind power. At 30% penetration the discarded wind electricity is the most significant factor for cost increase. This excludes storage, which could reduce the increase significantly. In both regions the use of wind electricity would mainly avoid use of natural gas. However, the CO_2 emissions abatement costs differ in both regions due to a more rapid overall wind electricity cost increase in OECD Europe. Lowest levels of potential CO_2 abatement costs are found at about 14 (OECD Europe) to 33 (USA) $ per ton CO_2. At about 40% wind electricity penetration, about 560 (OECD Europe) to 750 (USA) Mton CO_2 emissions can be reduced.

[#] Co-authors are Detlef van Vuuren, Bert de Vries and Wim Turkenburg. We are grateful to the technical support of Rineke Oostenrijk (RIVM) with the estimation of the transmission distance and to Peter Vaessen (KEMA) for the information on transmission costs.

1. Introduction

The geographical and technical potential to generate electricity from intermittent renewable energy sources using wind turbines and solar PV systems are much larger than current total electricity consumption, even excluding offshore locations (see Chapter 5 and 6). For wind energy it is found that currently a significant part of the technical potential may be produced at cost levels that are almost competitive with present conventional electricity production. Further R&D and development of the installed wind turbine capacity may reduce these costs. For grid connected solar PV in the long term, electricity production costs could come down to competitive levels for sites with significant solar irradiance, depending on the costs of conventional power production.

These conclusions are drawn from regional and global static cost-supply curves for wind and solar PV electricity[42]. However, when considering competitiveness with other electricity sources at longer timeframes, integrated in an electricity system, constructing static on-site cost-supply curves is not a sufficient approach. First, because increased use of wind and solar PV leads to reductions of the electricity generation costs, due to technological learning and developments. Second, because not only electricity production costs determine investment strategies of energy companies; also suitability with existing power and transmission systems and the reliability of supply are considered. Clearly, a key factor here is that the time and duration of electricity supply from wind and solar sources are outside the control of the system operator.

At present the solar PV capacity connected to grids world-wide is small, maybe 0.5 or 1 GW in total. For wind turbines, this figure is over 30 GW. Wind electricity has already significant shares in the electricity supply in some countries, e.g. about 17% in Denmark (Danish Wind Industry Association, 2002), or in parts of countries, e.g. 25% in Schleswig-Holstein (Bundesverband Wind Energie, 2003). Such high penetrations require technical adaptations such as additional transmission capacity (Anonymous, 2002a) or back-up capacity. If wind and solar PV would penetrate at the levels simulated in some future energy scenarios, such as RIGES (Johansson et al., 1993), FFES (Lazarus, 1993) and SRES (Nakicenovic, 2000), significant adaptations to the planning and operational strategy of the electricity system will be needed. The most important ones include the need for back up capacity (especially load-following or storage capacity), spinning reserve capacity, and transmission capacity. These issues influence the overall production costs of electricity from intermittent sources. They are also important for the cost of CO_2 abatement that can be achieved with wind and solar PV technologies.

[42] These on-site production costs are here referred to 'wind turbine electricity production costs', or 'solar PV module electricity production costs', compared to the 'overall electricity production costs', which includes the additional costs when integrating in the electricity system.

The objective of this study is to explore on a regional scale, i.e. the USA and OECD Europe, the dynamic changes in electricity production and CO_2 abatement costs as function of the penetration of intermittent electricity sources. In our study, especially the following questions are of interest: What factors determine the overall electricity production costs of wind and solar PV electricity with increasing penetrations? What is the effect of the depletion of wind and solar PV resources (i.e. the generation of wind and solar PV at less favourable sites) with increasing penetrations? From which penetration onwards must wind and/or solar PV electricity partly be discarded? What are the overall electricity production costs of wind power with increasing penetrations? Which fuels are saved by the introduction of wind in the electricity system? How much CO_2 emissions can be reduced and what are the CO_2 abatement costs?

This type of analyses has been done before for strictly defined electricity systems and/or at a national level, e.g. Grubb (1988); van Wijk (1990) and Giebel (2000a). However, the number of studies dealing with this issue for long-time scales and large regions is small e.g. Fellows (2000). In our study we focus on the regional level to make the results applicable for world energy scenarios. The analysis is done using data on electric power production of the regional energy model TIMER 1.0 of the RIVM, the Netherlands (de Vries et al., 2002). Also we use a new, Load Duration Curve based electricity model called EPG (Electric Power Generation) that has been developed recently as part of the TIMER 2.0 model (van Vuuren et al., 2004). The model uses regional cost-supply curves of wind and solar PV electricity from earlier studies, (see Chapter 5 and 6). We are interested in what factors influence the amount of intermittent electricity absorbed and the overall costs of wind electricity production. Therefore, we do not analyse full scenarios for regional electricity demand and supply developments, but instead we present a simulation experiment with constrained parameter settings:

- Electricity demand is kept constant as a function over time. This implies that new capacity is installed only when old capacity has to be replaced.
- Fuel costs of coal, oil, gas and biomass and specific investment costs of related power plants are kept constant over time.
- Wind (and solar PV) capacity is given a desired fraction of the total capacity, up to 50% penetration (in terms of capacity) using two penetration paths.

In this study we focus on wind electricity production mainly. To assess fuel and CO_2 savings we have run the electricity model over 50 years (2000-2050) with no additional wind capacity and have compared the results with a run where wind capacity is added.

In our study we distinguish two penetration paths. In the first one (Experiment A) the intermittent capacity is assumed to penetrate to 50% share in 2050 with 1% growth each year, starting with 1% capacity share in 2001. The second one (Experiment B) is based on present installed capacities in the USA and OECD Europe and the targets for wind capacity installed in the year 2010 and/or 2020 formulated by the American and European Wind Energy Association, i.e. 30 GW in 2010 for the USA (AWEA, 1998) and 75 GW in 2010 to 180 GW in 2020 for OECD Europe (EWEA, 2003). For the remaining years, we assumed an exponential growth of 8% for 2010 - 2050 in the USA and 3% for the period 2020 – 2050 for OECD Europe. The desired capacity is only installed if a demand for replacement capacity exceeds these exogenous pathways.

The regions USA and OECD Europe have been chosen as they have a significant technical potential of wind electricity and relatively good data availability.

This study is structured as follows. First, the static cost-supply curves of wind and solar PV are given and extended with transmission costs. Also monthly fluctuation characteristics are presented (Section 2). Next, Section 3 focuses on the technical aspects and cost implications of high penetrations of intermittent sources. In Section 4 we describe the model used to investigate technical, environmental and economic aspects of the penetration of wind and solar PV power into regional electricity systems, while Section 5 presents the results of the model experiments. The sensitivity for key parameters is investigated in Section 6, followed by a discussion in Section 7 and a summary and conclusions in Section 8.

2. Regional static cost-supply curves of wind and solar PV

As a starting point we use the regional cost-supply curves of onshore centralised wind and solar PV electricity presented in Chapter 5 and Chapter 6[43]. The yearly average technical potentials presented by these curves[44] are recalculated at a monthly level using the variation of the wind and solar resources as presented by (New et al., 1997; New et al., 1999). The electricity demand as simulated by the TIMER 1.0 model (see Section 4) for the year 2000. The technical potential of wind electricity and solar PV electricity (independent of costs) is given in Table I. It shows that the demand density is lower in the USA compared to OECD Europe. As the supply density is higher in the USA, it can be expected that in this region the impact of the depletion with increasing penetration is less severe than in OECD Europe.

[43] Note that we included centralised PV systems only, as these systems are more comparable in terms of investment strategy to conventional plants than decentralised systems. In Chapter 6, the estimated cost-supply curve of solar PV electricity consists mainly of centralised systems, so this restriction does not influence the results in the experiments conducted here. Furthermore, we excluded offshore wind electricity.

[44] The technical potential has been calculated at grid cell level, at 0.5° x 0.5° accounting for the spatial distribution of the climate and land-use changes.

Table I: The total electricity demand as simulated by the TIMER 1.0 model for the year 2000 and the technical potential of wind electricity and solar PV electricity.

	Electricity demand (kWh y^{-1} km^{-2})	Wind electricity potential (kWh y^{-1} km^{-2})	Solar PV electricity potential (kWh y^{-1} km^{-2})
USA	$4.3 \cdot 10^5$	$2.2 \cdot 10^6$	$1.3 \cdot 10^6$
OECD Europe	$7.5 \cdot 10^5$	$1.1 \cdot 10^6$	$7.6 \cdot 10^5$

The resulting average value of the technical potential at 2 \$ kWh^{-1} cut-off on-site generation costs and the monthly variation for the two regions are given in Figure 1. The figure shows that there are considerable variations in supply. For wind the difference between the highest and lowest month can be a factor 3, and for solar PV more than a factor 5. For wind, the technical potential of electricity supply is 21 PWh y^{-1} for the USA and 4 PWh y^{-1} for OECD Europe. For solar PV it is 15 PWh y^{-1} for the USA and 4 PWh y^{-1} for OECD Europe. It should be noted that the electricity consumption in the year 2000[45] in the USA was about 4.0 PWh y^{-1} and in OECD Europe 2.8 PWh y^{-1}.

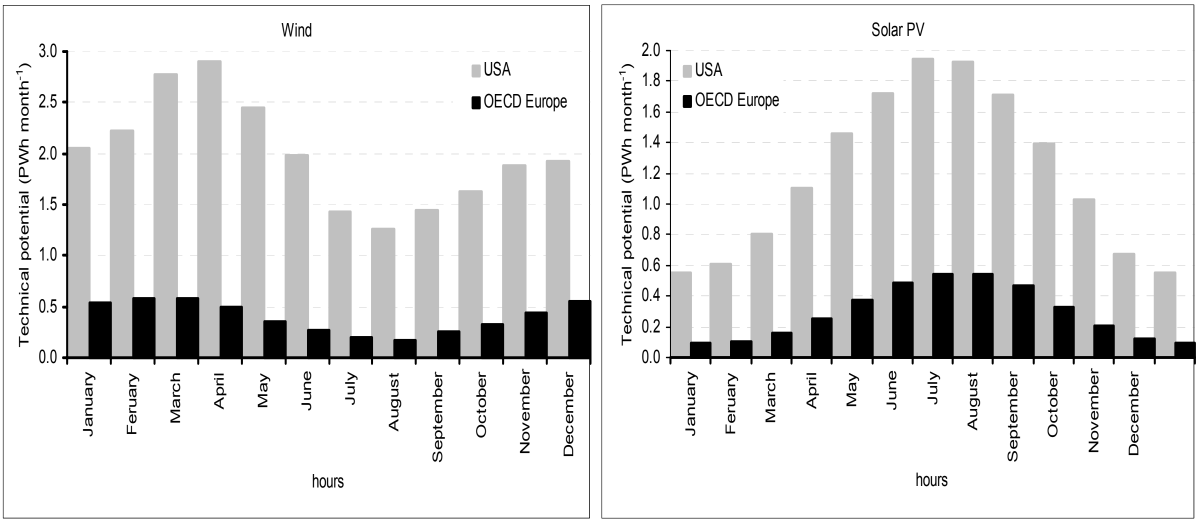


Figure 1: Monthly variation in an average year of the technical potential of wind and solar PV electricity at cut off on site costs of 2 \$ kWh^{-1}, for USA and OECD Europe as constructed from Chapter 5 and 6 and used in the simulation experiments.

For both wind and solar PV[46] Figure 2a and 2b show the spatial cost distribution of on site electricity production for the two regions. In this figure also the areas that are excluded for wind or solar PV electricity production are indicated, as discussed in Chapter 5 and 6. In the USA, there is one large area (Great Plains) where wind power may be produced at relatively low cost. In OECD Europe, the low cost sites are more spread. For

[45] See BP statistics, available at *www.BP.com*

[46] The costs of wind power are based on an average turbine size of 1 MW, total specific investment costs of about 1170 \$ kW^{-1} and a load factor that depends on the wind speed. For a wind speed of 7 m s^{-1} at hub height, a load factor of about 0.25 is assumed Chapter 5 For solar PV systems the conversion efficiency was assumed to be 10% and the total specific investment cost at 7 \$ Wp^{-1}. In the two regions the solar irradiance ranges between 60 to 250 W m^{-2} see Chapter 6.

solar PV electricity, significantly higher generation costs are found and also the geographically distribution is different.

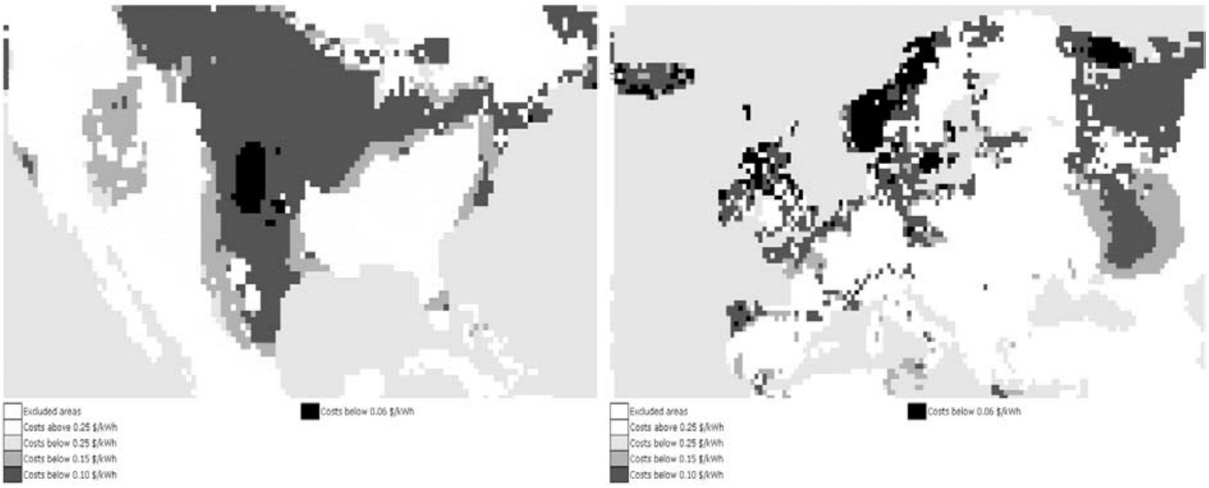


Figure 2a: Spatial distribution of wind turbine electricity costs (on-site). Source: Chapter 5.

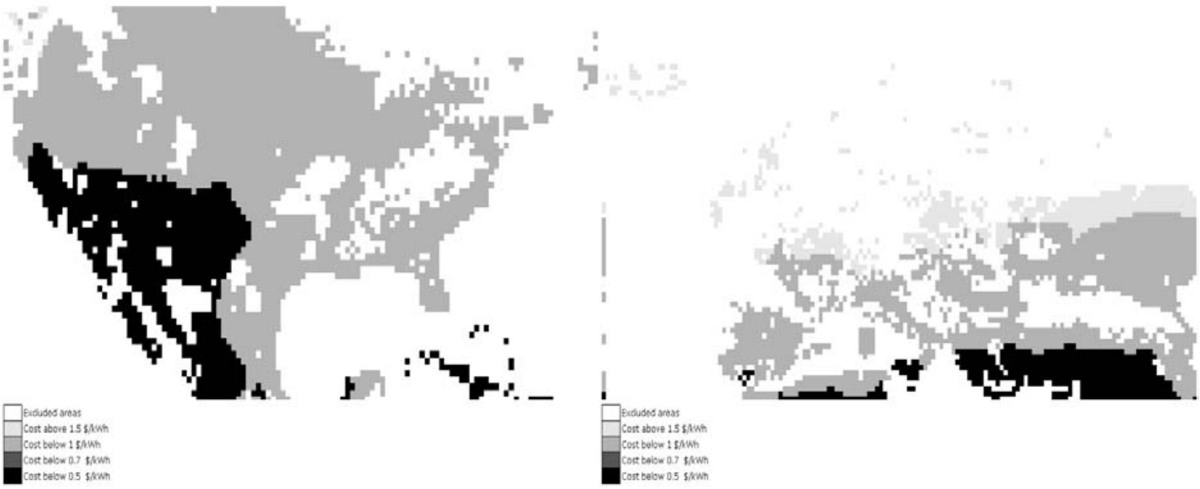


Figure 2b: Spatial distribution of module electricity production costs of solar PV (on site). Source: Chapter 6.

The cost-supply curves of on-site electricity produced by wind turbines and solar PV systems are shown in Figure 4. A difficult problem is to estimate the additional costs for connection to electric power networks, as we have no detailed information on grid characteristics or load centres – let alone their changes over time. Therefore, we have chosen a simplified approach to estimate transmission costs. First, we estimate the electric load demand in the 0.5° x 0.5° grid cells, by allocating the regional electricity use from the TIMER 1.0-model proportional to the population density in the year 2000 from the IMAGE 2.2 model (IMAGEteam, 2001). The second step is to postulate a critical value of the load at which a grid cell can be considered to have an electricity grid; in this case the cell is designated a load centre. The transmission distance to a load centre is assumed to be equal to the radius from a grid cell to its neighbouring cells for which the sum of the electricity demand in these cells equals or exceeds the critical value. This critical value is chosen equal to the supply of electricity that can be expected from a power plant of 50 MW with a load factor of 0.8[47]. An estimated distance of e.g. 40 km means that within a radius of 40 km from that grid cell, a power demand is found equal to the critical value of 50 MW. The distance to the load centres is used to estimate the additional transmission costs of wind and solar PV electricity. The calculated distances are given in Figure 3, shows that for the major share of the region, distances below 100 km are calculated.

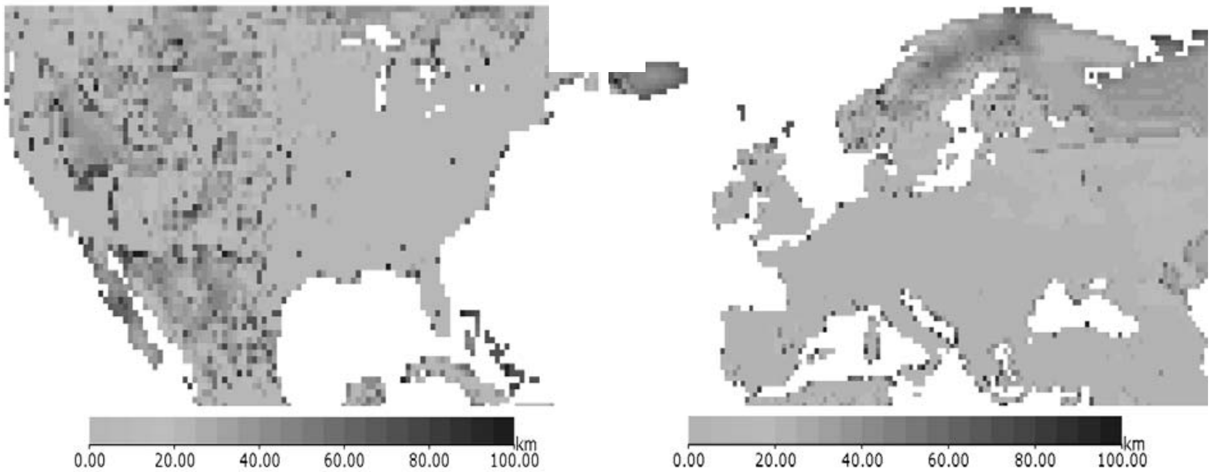


Figure 3: Spatial distribution of the estimated transmission distances at grid cell level in USA and OECD Europe. A distance of e.g. 40 km means that within a radius of 40 km from that grid cell, an average power demand is found equal to 50 MW.

Typical costs for the construction of a 400 kV overhead line are in the range of $100 \cdot 10^3$ – $160 \cdot 10^3$ \$ km^{-1} (Kurokawa, 2003, Brower and Tennis, 1995), or in the range of 0.05 to 0.3 eurocent kWh^{-1} 100 km^{-1}, from 100 to 4000 MW transported (Vaessen, 2003). However, in practice, these costs can vary considerably depending on specific circumstances like river crossing and mountains. In our cost calculations we assume investment costs of $160 \cdot 10^3$ \$ km^{-1}, energy losses at 0.05% km^{-1}, a lifetime of transmission lines of 60 years (Betcke, 1995) and an interest rate of 10%. These assumptions are comparable with about 0.2 eurocent kWh^{-1} 100 km^{-1}, which would be the costs for the transmission of 250 MW (Vaessen, 2003). Note that in our study we include additional transmission costs only and neglect transmission reinforcements. The cost of the latter may be relatively small (Fellows, 2000).

The sum of the production and transmission cost is re-arranged in ascending order of costs; the resulting curves are shown in Figure 4. These costs do not include overheads like insurance and administrative costs, distribution and grid connection costs nor costs

[47] With this amount of electricity produced, a small to medium sized city can be supplied

due to forced outages[48]. It is seen that the resulting curve differs marginally from the curve without transmission costs for the two regions considered especially in the case of solar PV electricity. This would be different if wind and solar PV electricity had to be transmitted at large distances (Kurokawa, 2003).

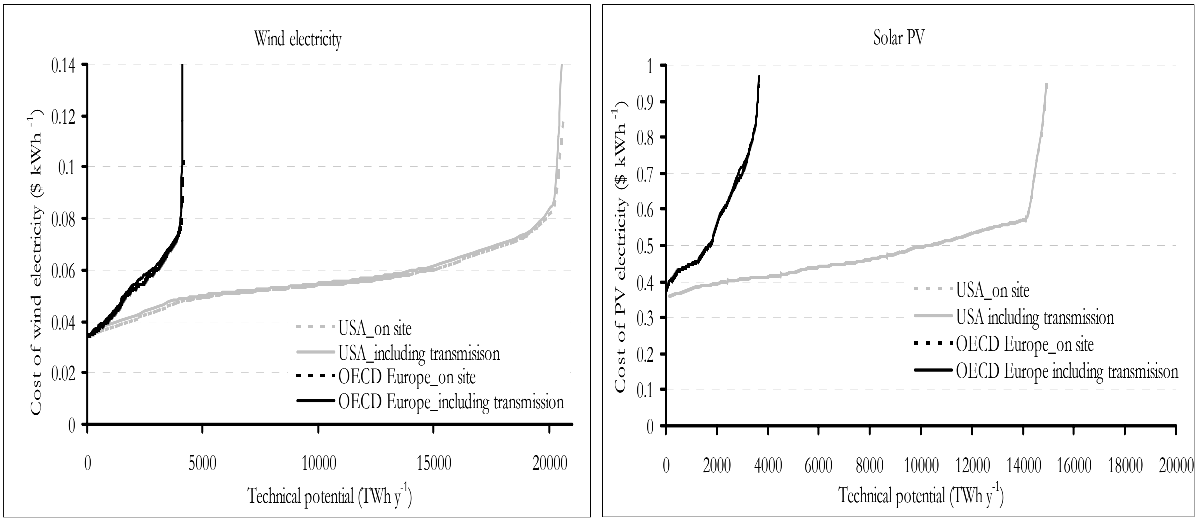


Figure 4: The cost supply curve of wind and solar PV electricity in the year 2000 for USA and OECD Europe with and without inclusion of transmission costs.

Finally, in the case of wind power, we have corrected the electricity production costs for grid connection and overhead costs (insurance, administration costs, distribution costs, etc.)[49]. For that purpose, we used a recent estimation of the delivered cost of wind electricity in the Netherlands (van Sambeek et al., 2003) and multiplied the cost values of the supply curves in Figure 4 with the ratio between the estimates and the cost values. This ratio is 1.5 and results in a higher cost-supply curve with a lowest value of the production costs in the year 2000 of about 8 ¢ kWh^{-1} for wind electricity. Similar factors are also used in TIMER-EPG for other technologies.

3. Factors determining the overall production cost of wind and solar PV in the electricity system

Using intermittent sources such as wind and solar energy to produce electricity differs from generating electricity by conventional power plants because availability and quality are largely outside control of the system operator. This has technical consequences for the power system at different time scales, varying from seconds and minutes to days and longer (Pantaleo et al., 2003; Wan and Parsons, 1993). The focus of this study is mainly on the time-scale of days and longer, approximating more short-term aspects in aggregated system parameters (see Section 4).

[48] Costs for forced outages have been included in Chapter 5 and 6, but are excluded in this figure as the EPG model includes these costs and we present in Figure 4 what we use as input.
[49] As we focus our cost analysis on wind, this correction has only been applied for wind electricity

The main objective of a power system is to satisfy the demand for electricity power effectively, efficiently and reliably within certain technical, environmental and economic constraints. This requires day-to-day operation of installed generation capacity in a way that follows the fluctuating demand at the lowest overall costs, provided that environmental constraints are met. The basic rule-of-thumb here is the merit order strategy: power plants are operated in order of variable costs. Capital-intensive plants with low operational costs, such as nuclear but also wind and solar power, will therefore in principle be operated as many hours as possible, i.e. in the base-load. They may be run the whole year except when taken out for repair and maintenance or due to failure (forced outage). Consequently, they are filling the bottom part of the Load Duration Curve (LDC) of a power system. Intermediate plants are designed to serve the shoulder load, which is not constant during the day. These intermediate plants are typical partly loaded conventional plants that use a variety of fuels such as coal, oil or natural gas. Often the demand for power exceeds this base-load and shoulder-load and the system operator has to run plants with excellent load-following capabilities (fast start-up). During short periods of the year demand may be extremely high. Such peak-loads are fulfilled by units with low specific capital costs, quick-start capability and high variable costs due to their low conversion efficiency and/or expensive fuel, e.g. gas turbines or diesel engines, but also hydropower or pumped storage plants can be used during these periods.

3.1 Additional cost factors with increasing penetration levels

Various studies have focused on the cost and value of wind and solar PV in the electricity system e.g. (Grubb, 1988; Fellows, 2000; Milligan, 2002; Giebel, 2000a; van Wijk, 1990). Based on these studies, we distinguish four mutually related factors, which tend to cause additional costs as wind and solar PV power penetrate deeper into the local or regional system:

1. Declining quality of the resource in terms of power density and location, i.e. depletion of the wind resources.
2. The need for large investments in back-up capacity due to a low and decreasing capacity credit of wind and solar PV power.
3. Additional operational requirements, such as an increase of spinning reserve due to the fluctuating nature of wind and solar PV power.
4. The necessity to discard part of the available solar and wind electricity at higher penetrations unless this energy can be stored.

1. Declining quality of resource: With increasing installed capacity, on site wind turbine or solar PV module power generation costs will tend to increase as less favourable sites with lower wind speed or lower irradiance, lower load factors and/or higher additional transmission costs come into operation. This ‘depletion effect’ is covered by the cost-supply curve.

2. Need for back-up capacity: To ensure system reliability[50], the system operator has to reckon with the non-availability of wind-solar power during parts of the day or the week and possibly during hours of maximum demand. As a consequence, for each additional MW or wind-solar capacity that is installed, only a small part can be considered to be available capacity from a system operating point-of-view. This has been extensively analysed in the literature. The fraction of the installed wind or solar PV capacity by which the conventional capacity of the electricity system can be reduced without affecting the reliability of the total system is called capacity credit see e.g. Giebel (2000a); van Wijk (1990) and Alsema et al. (1983). Several utilities are reluctant to assign any capacity credit to wind power plants (Milligan, 2002; Gardner et al., 2003). Present experiences and detailed studies on the capacity credit suggest that this is too pessimistic (Giebel, 2000a). The capacity credit depends in the first place on the time characteristics of the source (wind/solar), secondly on the characteristics of the renewable energy conversion technology, thirdly on the penetration, fourthly on the characteristics of the other power plants in the system and finally on the grid characteristics.

The consequence of a low or zero capacity credit is that the reserve margin, defined as the ratio between simultaneous maximum demand (SMD) and the capacity of plants that should have been installed to guarantee a reliable electricity supply, has to be increased by the installation of back-up capacity with (eventually) good load-following capability (Fellows, 2000). Model experiments on the capacity credit of wind turbines show that at low penetrations the capacity credit equals the load factor. For a system with up to 5 - 10% of its installed capacity in the form of wind turbines, most utilities accept 20 - 30% of the installed wind capacity as guaranteed. The remainder shows up in the form of cost-increasing back-up power that has to be installed (van Wijk, 1990; Giebel, 2000a; Pantaleo et al., 2003; Milligan, 2002). Part of these costs should be allocated to wind electricity production.

3. Additional operation requirements: The fluctuating nature of the wind-solar power generation impairs the load-following characteristics of the system. Additional spinning reserve and possibly a change in operational strategy (more load following operational capacity) have then to account for the possibility of short-term drops of significant amounts of intermittent power, due to e.g. storms in which the wind speed exceeds the cut-out wind speed of the turbine. This requires quick-start capacity, which is normally obtained by the so-called spinning reserve, that is, conventional thermal capacity operated at less than its full rating (Fellows, 2000). High spinning reserve requirements lead to higher fuel use and emissions. A typical level of spinning reserve at system level is 1.5 - 3% of the peak load (Pantaleo et al., 2003), depending amongst others on the size of the largest plant. Estimates of the spinning reserve required at high wind power penetration given in the literature range from about 10% to 85% of the installed wind capacity

[50] A widely used measure of reliability is the loss of load probability (LOLP).

(Milligan, 2002; Grubb, 1988; Fellows, 2000). As shown by Grubb (1988), the highest end of the range is unlikely high. Fellows (2000) assumes in his assessment on the cost of wind electricity no additional need for spinning reserve thanks to the use of wind forecasting, wind curtailment and additional peaking capacity. High values are to be expected when the existing park relies on significant amounts of slow-start capacity, e.g. large nuclear or coal-fired plants and/or if no good forecasting instruments are available.

Another reason for additional costs with rising shares of wind and solar PV power are additional operational losses. Parts of the operated conventional power plants will make more repeated plant starts or be operated more often on part load – both causing additional fuel costs and emissions. According to Grubb (1988), such operational losses might be in the range of maximum 5 - 8% of the fuel use in parts of the operated plants. We have not included this effect in our study, as we do not simulate each plant separately.

4. Discarded electricity: A related cost impact with increasing penetration of intermittent sources is that part of the power may be generated at times when the system cannot use it due to the demand profile, the strategy of power supply used in the system, or limited transmission capability. Without storage options (mechanical or chemical) this electricity is to be discarded. For the European situation the amount of discarded wind power has been studied by Giebel (2000a). He found that at wind power penetration (at electricity basis) of about 35% in the European electricity system, on average up to 25% - 35% may remain unused, depending on the accuracy of the forecasting system for wind power. Much lower levels of discarded wind electricity are mentioned for the Egyptian and UK situation by Fellows (2000). He assumed the global average wind to be discarded as function of the penetration of total annual electricity consumption to be zero at levels up to 25%, rising to 60% at 100% penetration of wind electricity. Evidently, new systems to store electricity or to convert it to a chemical carrier such as hydrogen in combination with fuel cells, can significantly alter these estimations.

3.2 Related aspects for the overall cost development of intermittent electricity

At least four related aspects determine how much the above factors will influence the penetration and costs of intermittent sources: their geographical dispersion, the ability of power forecasting, the load following capabilities of the generation mix and the interconnection with other grids.

Load Supply Curve of intermittent sources; Geographical dispersion.

If wind or solar power supply is geographically uncorrelated, fluctuations in both supply and in severity and frequency are reduced and supply is smoothened. For the Northern European countries it was found that wind power supplies from sites of more than 1500 km apart are nearly uncorrelated (Giebel, 2000b). For the Nordic countries it was found that on a time scale of 12 hours, variation can be up to 30% once a year and production is never completely down. If data of only Denmark are used, production can come down to zero in about a few hours. Similar results for wind supply are found for Germany: fluctuations for a single turbine on a time scale of 12-hours were reported over the total power range (100%), whereas the output of 1496 widely spread turbines showed maximum variations of 60% in the 4-hour gradient (FGW and ISET, 2000). This effect of geographical dispersion reduces the need for back-up and spinning reserve capacity due to a smoothening of output fluctuations and will also reduce the amount of discarded electricity.

Forecasting of power output

The planning of slow-start and quick-start capacity operation is typically done a day ahead. If the load expected from intermittent wind and/or solar PV power can be forecasted within this period, it improves the utilization of these sources and lowers operational costs (Brand and Kok, 2003). In the USA and Europe commercial wind forecasting instruments are available and applied (Milligan, 2002). Typical accuracy reached for forecasting wind power 48 hours ahead are in the order of 10%, see e.g. Anonymous (2003a), but also less accurate forecasts are mentioned (Brand and Kok, 2003).

The load following capacity of the generation mix

The load following capability of the generation mix is an important factor. Large numbers of quick-start plants such as gas turbines and/or hydropower or storage plants with high load-following capability can compensate larger amounts of intermittent supply than typical base-load units such as large nuclear and coal-fired plants (Pantaleo et al., 2003; Giebel, 2000a). If large fluctuations occur, this cannot be dealt with using baseload plants. If the load following capacity is limited, it implies that wind power is discarded (Grubb, 1988).

Interconnection with other grids

Interconnection between electric power systems increases the capability to match supply and demand. The importance of interconnection of national systems in Europe can be illustrated by two extreme cases: Denmark and Spain. The interconnection of the Danish system with the Nordic and the German system is about 30%, in contrast to about 3% interconnection of Spain with France. The main reason for the smooth penetration of large quantities of wind in the Danish system is the well-established interconnection with the Nordic countries having large quantities of hydropower (FGW and ISET, 2000). The fact that the Red Eléctrica Española (REE) in Spain can import very little power to cover drops in voltage is mentioned as one of the main reasons for the grid instabilities due to wind power in Spain, next to the low geographical dispersion of the wind resources and the difficulties with wind forecasting in mountainous areas (Anonymous, 2002c). The degree of interconnection affects the capacity credit as well as the amount of discarded wind electricity.

3.3 Technological learning: declining capital costs

There is one major factor that may cause a decline in production cost with increasing penetration: technological learning reducing the specific investment costs. Wind and solar PV technologies have developed significantly in the past decades. Wind turbines have increased in scale, from about 30 kW in the mid-1970's (rotor diameter about 10 m) to above 1 MW at present (rotor diameter about 80 m). Partly due to this up-scaling, large reductions in wind electricity production costs took place. Technological developments of solar PV modules reduced module costs and increased conversion efficiencies. For the future, further reductions are expected in wind and solar PV electricity production cost. It is empirically observed that costs tend to evolve as a power function of the cumulative production, which can be plotted in a so-called experience curve, see e.g. (Argote and Epple, 1990) and (McDonald and Schrattenholzer, 2002). For wind and solar PV various historical experience curves have been constructed, see (Neij, 1999; IEA/OECD, 2000b; Junginger et al., 2003; Harmon, 2000; Parente et al., 2002; van der Zwaan and Rabl, 2003). This historical evidence suggests that with further penetration, the specific (capital) cost of these technologies can come down; especially, there is room to improve cost-benefit ratios. This effect should be included when studying the cost of intermittent electricity with increasing penetration.

4. Simulation of wind/solar PV penetration: the use of the TIMER-EPG model

The penetration of wind and solar PV in the North American and European electricity systems is simulated using the electricity sub-model of the TIMER 2.0 model (van Vuuren et al., 2004). It is an intermediate-level model based on the use of a Load Duration Curve that focuses on the overall long-term dynamics of regional electricity production. Using a geographical aggregation of 17 regions, it aims to model long-term dynamics of the world energy system.

4.1 General description of TIMER-EPG

The EPG model simulates investments in various technologies of electricity production in response to electricity demand, based on changes in the relative fuel prices and changes in relative generation costs of thermal and non-thermal power plants. It also investigates operational strategies, as well as costs and emissions of power production. For a detailed description of the EPG module we refer to van Vuuren et al. (2004).

The EPG model and its use in this study are represented in Figure 5, with a focus on the use of intermittent sources. Demand for capacity is based on electricity demand (here assumed to be constant) and demand for replacement capacity. The investment strategy is based on operational costs, resulting in market shares of technologies that are loaded in the operational strategy.

The costs of intermittent sources are determined by the cost-supply curves accounting for the depletion effect, by technology-induced cost reductions and by additional costs from discarded electricity, back-up capacity and additional required spinning reserve (see Section 3).

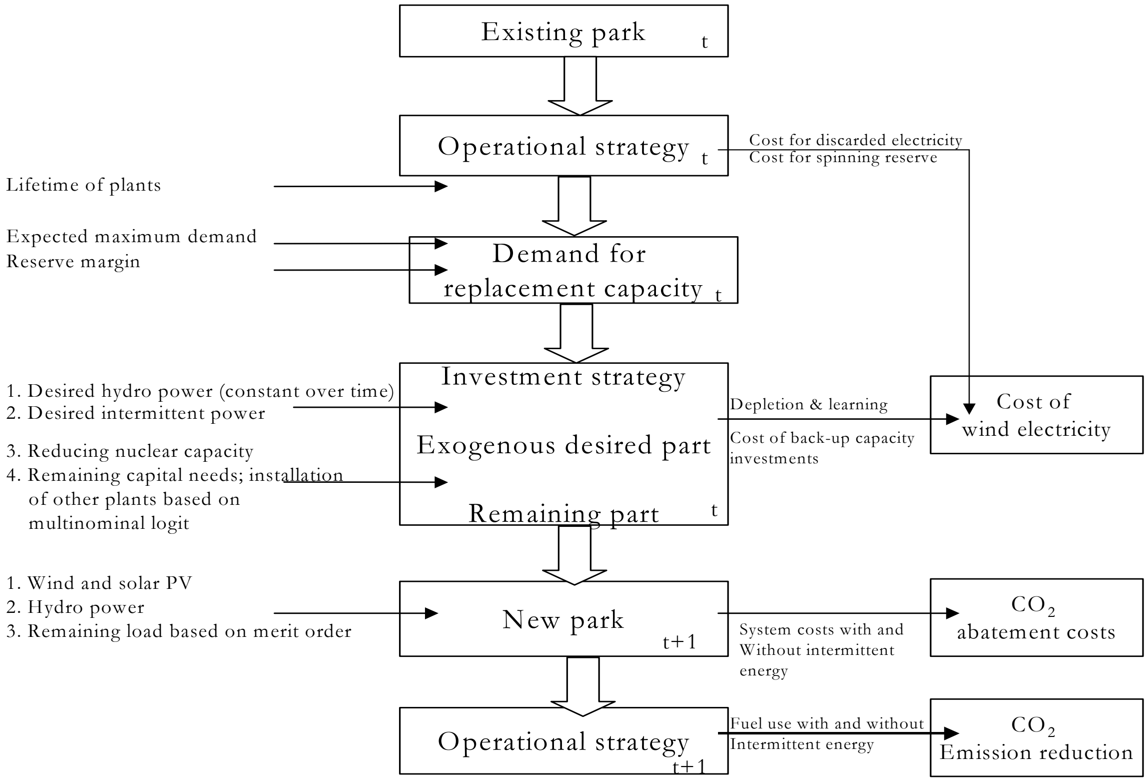


Figure 5: Schematic presentation of the annual use of the TIMER –EPG 2.0 model indicating the simulated steps from year t to year t+1.

4.2 Investment strategy

In the regular version of the TIMER-EPG model, the demand for capacity is determined by e.g. an increase in electricity demand, replacement of existing capacity after its technical lifetime[51] and a demand for new capacity (e.g. wind and back-up capacity) given certain reliability constraints. In our constraint experiment the demand for capacity and the investment strategy are constrained in the model experiment as follows:

- We assume the electricity demand to remain constant from 2000 onwards; only demand for replacement capacity is accounted for.
- We force the construction of intermittent source capacity using two penetration paths (see Section 1), with a maximum of the replacement capacity. Back-up capacity, according to the capacity credit, is assumed to secure reliability.
- Hydro capacity investments are made such that the capacity is constant over time; nuclear capacity is assumed to decline over time.

[51] If the capacity has a technical lifetime of 25 years (see Table II), after 20 years a fraction (10%) of the installed capacity is replaced each year until 5 years after the technical lifetime. This accounts for the fact that some plants have a longer and other plants a shorter technical lifetime than average.

- For the remaining demand for capacity, i.e. the demand for replacement capacity minus the desired capacity for intermittent (plus back-up capacity) and hydro, market shares are given based on the relative generation costs in a multinomial logit formulation. (This formulation assigns a market share to all options based on relative generation costs), for a detailed description see (de Vries et al., 2002).

4.3 Electricity demand

Gross electricity demand is taken from the energy demand module of the TIMER 2.0 model for the period 1971-2000 and assumed to be constant thereafter. It is equal to the sum of the annual net electricity demand, net trade and net transmission losses. The average monthly demand is constructed from this annual demand with an exogenously derived annual Load Demand Curve (LDC)[52] different for each region. The load distribution within a month is based on two parameters that indicate the minimum and the maximum demand (Figure 6). These parameters and the Load Duration Curve are derived from a module that includes the monthly distribution of e.g. mean temperature and daylight hours, and are assumed constant in the future (van Vuuren et al., 2004). In Figure 6 the estimated net electricity demand for the USA and OECD Europe in the year 2000 and the upper and lower limit of demand in the twelve months is shown. The demand for capacity is derived from the maximum demand and a fixed reserve margin of about 10% of the ratio of the desired installed capacity multiplied with the load factor and the maximum demand. This margin is based on a comparison of the Simultaneous Maximum Demand (SMD) in Europe with the European installed capacity. The SMD is estimated as the sum of the load duration curves in seven European countries, covering about two third of the European demand (van Vuuren et al., 2004).

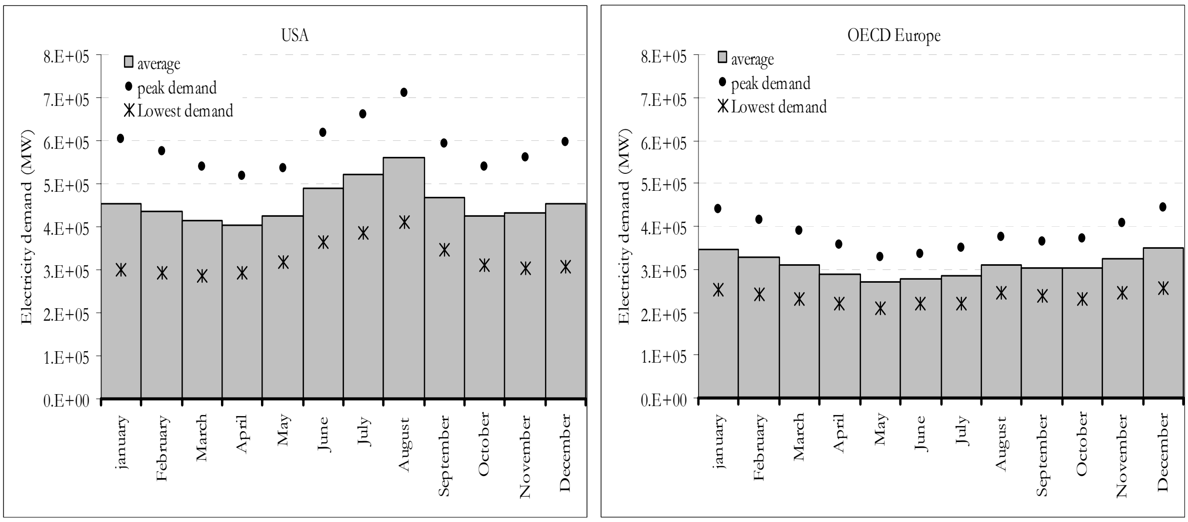


Figure 6: The estimated monthly distribution in the simulated load demand for USA and OECD Europe in the year 2000.

[52] When classifying this monthly demand in 10 equal fractions, an approximation of the load duration curve can be given.

4.4 Spinning reserve and back-up capacity

The required spinning reserve is assumed to be 3.5% of the installed capacity of the conventional park. If wind and solar PV penetrate the market, it is assumed that more spinning reserve is needed equivalent to about 15% of the intermittent capacity. However, this additional spinning reserve will not be allocated until the overall spinning reserve capacity exceeds 2% of the conventional park, as is assumed that part of the required spinning reserve can be covered by the existing one.

Back-up capacity is added to account for the low capacity credit of the intermittent sources. It is assumed to be the product of the rated power and one minus the capacity credit. It is assumed that for the first 5% penetration of the intermittent capacity, the capacity credit equals the load factor of the wind turbines. If the penetration of intermittent sources increases further, the capacity credit is assumed to decrease linearly to a value of 0.1 at 50% penetration (at capacity basis). Thus at 50% penetration (at capacity basis), the back-up capacity is equivalent to 90% of the installed intermittent capacity. To install back-up capacity from the beginning may be conservative as it can also be argued that for the 10% of wind electricity penetration, the existing park can account as back-up capacity, e.g. Fellows (2000). The type of plant with the lowest capital costs is assumed to be used as back-up power, i.e. here mainly gas combined cycle and conventional gas thermal plants.

Only 30 to 50% of the cost for the back-up capacity is allocated to the production costs of the intermittent sources. As the installed back-up capacity can also be used in the operational strategy, complete allocation of the costs would be an overestimation. We assume that for the first 5% wind penetration (at capacity basis), 30% of the capital costs of back-up plants are allocated to the wind costs reducing to 50% of the capital costs if wind capacity reaches 50% penetration level, related to the capacity credit reduction. It is assumed that both gas combined cycle and peaking capacity is used for back-up in the ratio 1 : 2.

The cost for spinning reserve is completely allocated to wind electricity.

4.5 Supply and cost of conventional electricity

The TIMER-EPG model includes 25 different technologies of which a number are used in this study, see Table II. The installed capacity for the year 2000 is derived from model simulations for 1971 – 2000 and calibrated with statistical data (IEA/OECD, 2002b; IEPE, 1998). For each technology used in this study the installed capacity in the year 2000 and 2050 (for Experiment A), the specific investment costs and technical lifetime and the fuel costs of coal, oil, gas and biomass are given in Table II. The data for the year 200 in Table II are the results of the simulations for 1971-2000.

Table II: The main characteristics of the electricity systems and the technologies used in this study for the year 2000 and, using Experiment A for the year 2050 (van Vuuren et al., 2004).

Technologies	Installed capacity GW (year 2000)		Installed capacity GW (year 2050)		Fuel costs ($ GJ^{-1})		Spec.invest. costs (10^3 $ kW^{-1})		Economic lifetime (years)
	USA	OECD Europe	USA	OECD Europe	USA	OECD Europe	USA	OECD Europe	
Solar power	0	0	0	0			7	7	25
Wind power	2	9	669	434			0.9[a]	0.8[a]	25
Hydro power	91	175	99	187			2.9	2.8	50
Other renewable	4	1	4	1			2	2	25
Nuclear	118	134	8	9			3.1	3.1	30
Conventional coal thermal	362	119	223	90	1.5	2.1	1.5	1.5	30
Conventional oil thermal	40	45	35	34	3.0	3.2	1.4	1.4	30
Conventional NG thermal	98	41	36	11	3.2	4.4	0.8	0.8	30
Co-firing waste	13	21	7	9	4.0	4.0	1.6	1.6	30
IGCC	0	0	3	1	1.5	2.1	2.5	2.5	30
OGCC	0	0	3	3	3.0	3.2	2.1	2.1	30
CC NG	116	80	163	18	3.2	4.4	0.8	0.8	30
Biomass CC	0	0	1	1	4.0	4.0	2.5	2.5	30
Additional peaking capacity	0	0	149	95	3.2	4.4	0.4	0.4	30
CHP coal	5	4	3	2	1.5	2.1	1.7	1.7	30
CHP oil	0	6	0	5	3.0	3.2	1.6	1.6	30
CHP gas	7	17	10	17	3.2	4.4	0.9	0.9	30
CHP biomass	3	11	0	4	4.0	4.0	1.8	1.8	30

[a] These costs are for the year 2000, derived from the calibration for 1970-2000. These costs are assumed to decline due to technological learning. The difference between the USA and OECD Europe are due to a difference in the depletion effect, which is included in the specific investment costs.

4.6 Supply of wind and solar PV electricity

To account for the variation of wind power within a month and to estimate the amount of discarded electricity, we simulate the distribution of wind power as a combination of two extreme situations: (1) wind power supply coincides fully with the LDC and (2) it fully anti-coincides (Figure 7). The actual coincidence of wind supply and the LDC is assumed to be a combination of these two based on figures about wind supply distribution in Scandinavia and the rest of Northern Europe (Giebel, 2000b). These two extremes of wind supply coincidence are not completely equivalent to a random around the means, but the uncertainty related to the exact form of the load supply curve of wind power is considered larger than the error when using this approach.

For solar PV, a parabolic shape is used to describe the coincidence with the LDC, such that within a month, the solar PV supply never fully coincides with the peak demand and, during parts of the month at low load demand, the supply is down to zero. Within a region, this may not be a correct representation, e.g. for sunny areas in the USA solar PV supply is found to coincide with the peaking demand, mainly for cooling. However, for a region as a whole, this shape is preferred. Planned outage at a level of 5% of the installed wind and solar PV capacity is assumed to be allocated over the lowest demand months. Forced outage at a level of 5% of the installed capacity is allocated uniformly on the year.

4.7 Discarded wind and solar PV electricity

Wind and/or solar PV electricity is discarded if it exceeds the electricity demand in a month as given by the LDC. Given limited interconnection between the systems in which intermittent sources are installed and also operational constraints (see Section 4.8), electricity is probably discarded earlier than at the minimum load demand of the LDC. To account for that, we introduce the 'mismatch coefficient' (φ). The LDC is multiplied with this factor ($0 < \varphi < 1$) to obtain the level from which wind or solar PV power starts to be discarded. The discarded electricity for wind is 50% of the area *A* and *B* in Figure 7, as it is assumed that this extreme situation occurs for 50% of the time. For solar PV it is the part of the parabola above the dashed line (C).

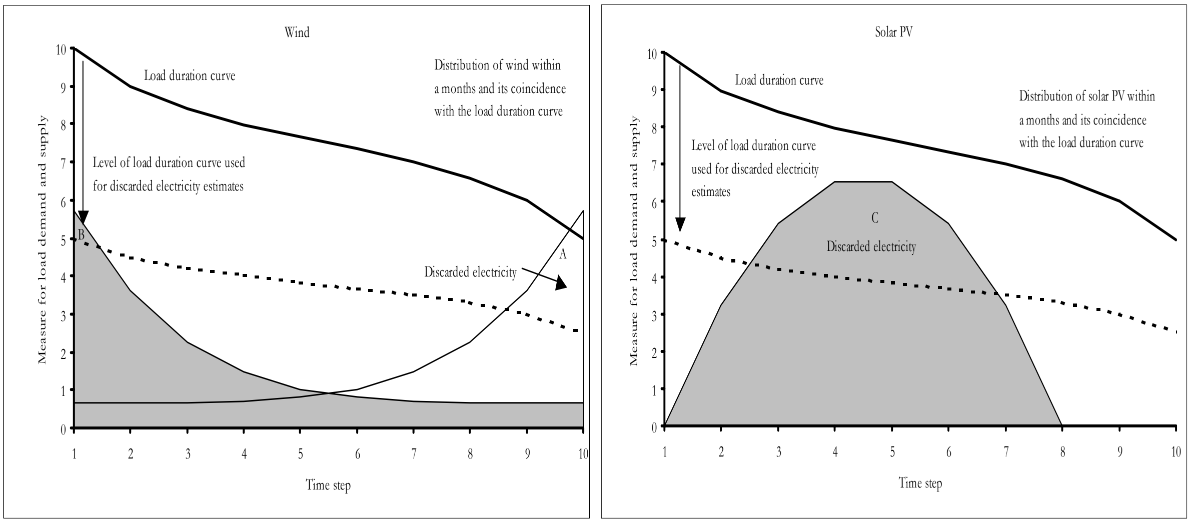


Figure 7: Illustrative representation of the contribution of the wind and solar PV power supply within the 10 time steps of a month: their coincidence with the Load Duration Curve and the method to calculate the amount of discarded wind and solar PV electricity.

4.8 Operational strategy

The operational strategy determines how much of the installed capacity is used and when. It reflects that electric power companies minimise the production costs while maintaining the required system reliability. In theory, the merit order strategy is the most cost-effective strategy and assumed here. Thus, wind and solar PV capacity is loaded first in the simulation because of zero or low operational costs, followed by hydro capacity. In reality, the merit order strategy is more complex; combined with the use of intermittent sources, also conventional power should be operational at partial load. This limits the acceptance of intermittent capacity, increasing the amount of discarded electricity. This effect is incorporated in φ. The resulting monthly LDC is restructured and the remaining generating options are planned according to the merit-order strategy, in which capacity is operated according to variable costs.

4.9 Technological learning: declining capital costs

Technological learning is introduced in the form of an experience curve at a global level, leading to investment costs reductions. For wind power we follow the more conservative figure published by Neij (1999) and use a progress ratio of 0.9 between the year 2000 and 2050. This figure is higher than the estimated historical global progress ratio for wind turbines estimated at 0.81 – 0.85 (Junginger et al., 2003). Also, it should be mentioned that experience gained in other regions is not considered in our constrained experiment.

5. Results

We can now address the questions related to high penetration of wind and/or solar PV in the electricity system as formulated in the introduction. We focus on wind and present results of solar PV only for comparison, as currently wind power is much cheaper than solar PV, has a more significant contribution and by doing so better comparison with previous studies is possible.

5.1 Intermittent electricity production and load factor (Experiment A)

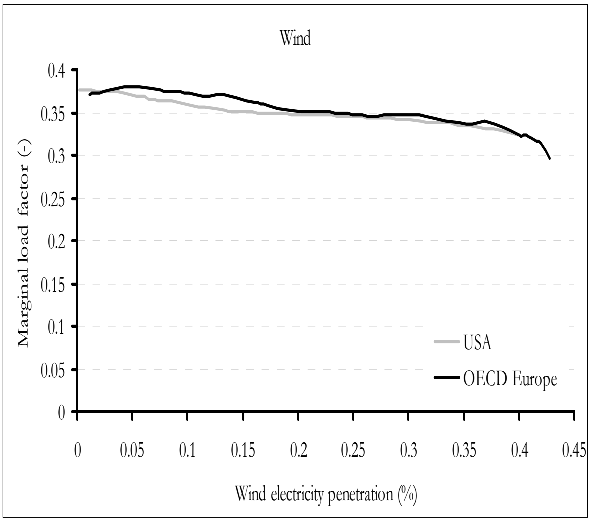
In Experiment A we analyse the amount of wind and solar PV capacity installed, and electricity produced and absorbed in the system if wind and solar PV independently penetrate linearly to a desired level of 50% penetration (at capacity basis) in 2050, are given in Table III.

Table III: The amount of capacity installed, electricity produced and electricity absorbed in the electricity system in the USA and OECD Europe if wind or solar PV capacity penetrated to about 50% (on capacity basis) for two penetration paths (Section 1).

Experiment A (2050)	Unit	USA		OECD Europe	
		Wind	solar PV	Wind	solar PV
Capacity installed	GW	669	678	434	515
Capacity installed as percentage of total installed capacity	%	47	47	47	47
Electricity potentially produced	TWh y^{-1}	1910	1095	1252	830
Electricity potentially produced as percentage of techn. potential	%	9	7	30	23
Electricity absorbed in the electricity system	TWh y^{-1}	1475	881	990	567
Electricity absorbed as percentage of electricity consumed	%	40	24	43	24
Electricity discarded as percentage of intermit. elect. produced	%	23	20	21	32
Experiment B (2050)	Unit	USA		OECD Europe	
		Wind	solar PV	Wind	solar PV
Capacity installed	GW	595		434	
Capacity installed as percentage of total installed capacity	%	44		47	
Electricity potentially produced	TWh y^{-1}	1714		1251	
Electricity potentially produced as percentage of techn. potential	%	8		31	
Electricity absorbed in the electricity system	TWh y^{-1}	1406		990	
Electricity absorbed as percentage of electricity consumed	%	38		43	
Electricity discarded as percentage of intermit. Elect. produced	%	18		21	

Figure 8 shows the marginal[53] load factor[54] of wind and of solar PV capacity in the two regions as function of the electricity penetration of these technologies. It declines from 0.37 to 0.32 (USA) and 0.29 (OECD Europe) at about 40 (USA) - 43% (OECD Europe) electricity penetration. Average values, based on absorbed electricity, are found at around 0.35 at about 43% electricity penetration. This is rather high compared to average load factors reached in OECD Europe in 2000, ranging from 0.21 in Germany to 0.32 in the U.K. (BTM, 2001). However, for single projects, higher load factors are not uncommon, even of 0.51 in New Zealand (Anonymous, 2003b) and 0.41 in the US (Anonymous, 2002b). One explanation is that our figures are based on a turbine size of 1 MW whereas the average turbine size installed in OECD Europe in 2000 ranged from 484 kW in the U.K. to 646 kW in Germany (BTM, 2001). A smaller turbine implies in practice lower hub heights, resulting in lower wind speed and probably load factor.

For comparisons, we include the results of solar PV. For solar PV the load factor is related to solar irradiance. Depending on the penetration, the marginal load factor is reduced from 0.22 to 0.19 in the USA. In OECD Europe, the marginal load factor is reduced from 0.23 to 0.19.



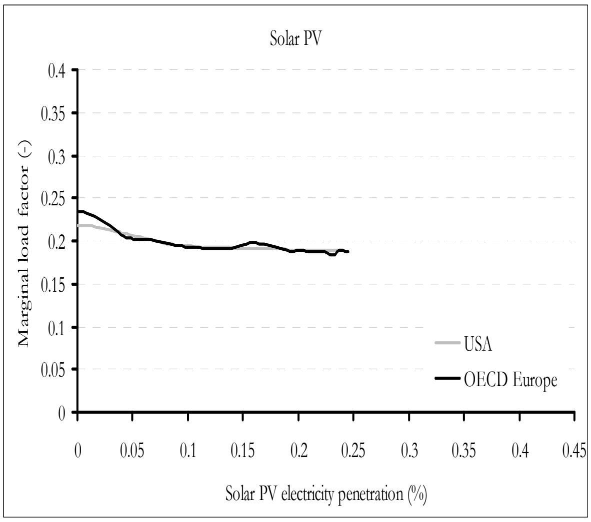


Figure 8: Marginal load factor with increasing electricity[55] penetration of wind and solar PV[56]

[53] We use in this study both marginal and average figures. The latter is referring to the average over the total installed capacity. The former refers to the figure for the latest installed unit.
[54] The load factor for wind and solar PV is the ratio of the full-load hours per year and the total amount of hours in a year.
[55] We use penetration level on electricity basis, as this is most comparable with figures from the literature. Intermittent electricity penetration level is defined as ratio of the absorbed intermittent electricity and the total produced electricity.
[56] Note that we have used the installed capacity for the x-axis, instead of a time-axis. This is correct for most cases, as time does not influence the results. This is different for the cost estimates due to replacement of existing wind turbines (or solar modules), the technological learning factor increases more than only the installed capacity. However, we have neglected this effect.

5.2 Discarded electricity from intermittent sources (Experiment A)

In the case of wind electricity production, assuming Experiment A, Figure 9 shows the amount of discarded wind electricity as function of penetration for three values of φ: 0.3; 0.5 and 1. It is also compared with two previous studies. The set estimated by Giebel (2000a) for OECD Europe is derived from existing, hourly data using two different assumptions regarding the wind forecasting. The figures of Fellows (2000) are based on a literature review of discarded wind electricity as function of the wind electricity absorbed by the system in Egypt and the U.K. (see Section 3).

At ideal conditions (i.e. φ equals 1), in our experiment wind electricity is discarded from about 40% electricity penetration onwards. The discarded amount is about 1% (OECD Europe) - 3% (USA) at 50% (USA) - 53% (OECD Europe) electricity penetration. If we consider φ at 0.5, wind electricity is discarded from an electricity penetration of about 18 - 19% electricity penetration. If wind penetrates to a share of 40% (USA) – 43% (OECD Europe), about 21% (OECD Europe) to 23% (USA) of the wind electricity is estimated to remain unused. In this case the amounts of discarded electricity are higher than the figures assumed by Fellows (2000), but slightly lower than estimated by Giebel (2000a). If φ is 0.3, our results approach estimates of Giebel (2000a).

Figure 9 shows the importance of φ. The choice of φ is difficult to quantify as, on this stage, no empirical evidence could be found for the value of this proxy. For the approach used in this study, we consider the values derived by Giebel too pessimistic. We rather use a φ of 0.5 delivering results in between Fellows (2000) and Giebel (2000a).

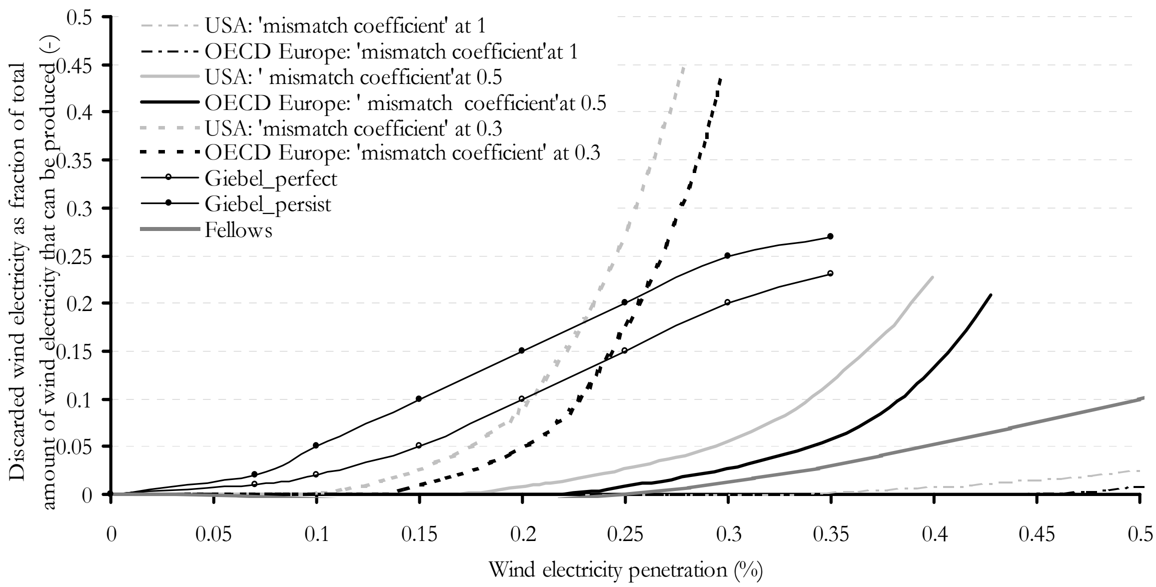


Figure 9: Average value of discarded wind electricity in the USA and OECD Europe indicated as fraction of the potentially produced wind electricity, as function of the penetration (on electricity basis), within Experiment A and for three values of the 'mismatch coefficient' φ.

The marginal value of discarded electricity is significantly higher than the average. The marginal value of discarded electricity for wind and solar PV for φ is 0.5 is given in Figure 10. The bent-like shape is caused by the approach to simulate the Load Supply and Load Demand Curves discontinue, in 10 distinct fractions (see Figure 7): discarded electricity is computed in fractions of 10 time steps.

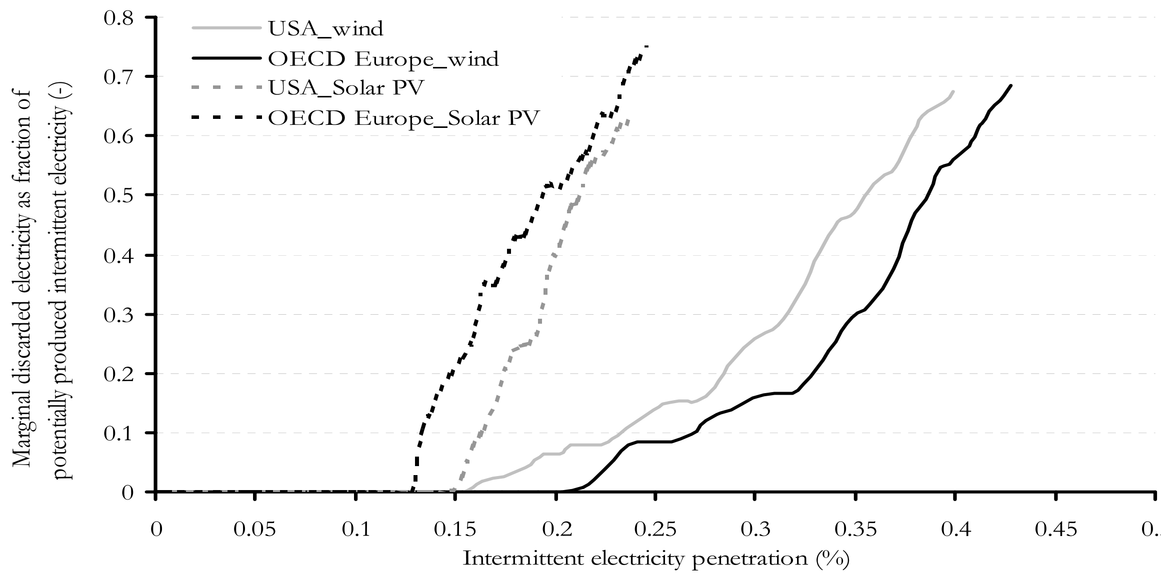


Figure 10: Marginal value of discarded wind or solar PV electricity as function of the penetration of these renewables (on electricity basis) in the USA and OECD Europe indicated as percentage of the absorbed wind or solar PV electricity.

5.3 Costs of wind electricity (Experiment A)

At higher penetrations, the marginal wind electricity costs will decrease with cumulated experience. In our simulation and parameter choice for Experiment A, after about 20% electricity penetration, other effects will increase the marginal costs: depletion of favourable wind turbines sites; increase of the amount of discarded electricity; increasing need to install back-up capacity; higher spinning reserve costs.

With φ of 0.5, the cost increase due to the amount of discarded electricity starts to become the highest cost factor from penetration levels of about 30% onwards (Figure 11a and 11b), assuming no storage capacity. The additional cost of spinning reserve is small; it includes only some additional fuel costs. The cost of back-up capacity is only slowly increasing with the penetration due to a reduced capacity credit and increased allocated capital costs. The installed backup capacity increases from about 65% up to 90% of the installed wind capacity and 30 – 50% capital costs are allocated. We have for illustrative reasons also indicate constant costs and the cost for depletion if no technological learning is included. It shows that the assumed technological learning largely counteracts the depletion effect.

At certain levels of discarded energy, investing in storage capacity e.g. in combination with demand side management, can be a cost-effective option to reduce the cost of wind electricity. Cost for storage of wind electricity may be small: values of 1 ¢ kWh^{-1} for storage of wind electricity are mentioned (Turkenburg, 2000). However, costs depend on the storage-time, the storage technology and the amount of electricity that is stored. At wind electricity penetration below 45%, storage costs below 7 ¢ kWh^{-1} can avoid any discarded electricity.

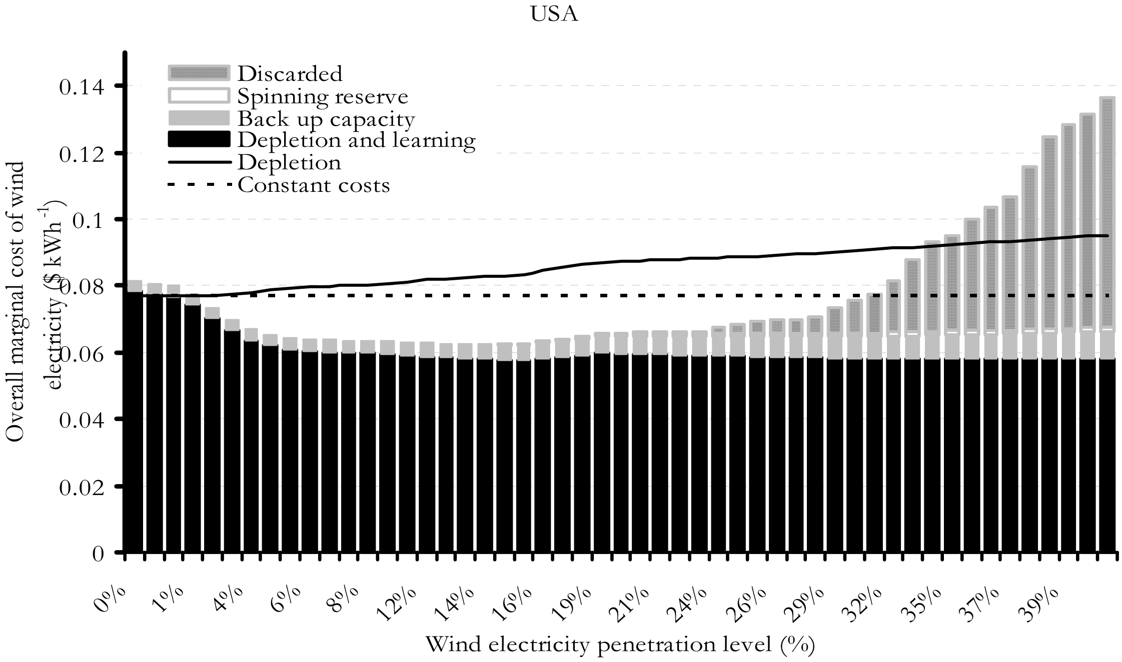


Figure 11a: The marginal cost development of wind electricity in the USA with increasing wind electricity penetration subdivided in different cost components (Experiment A).

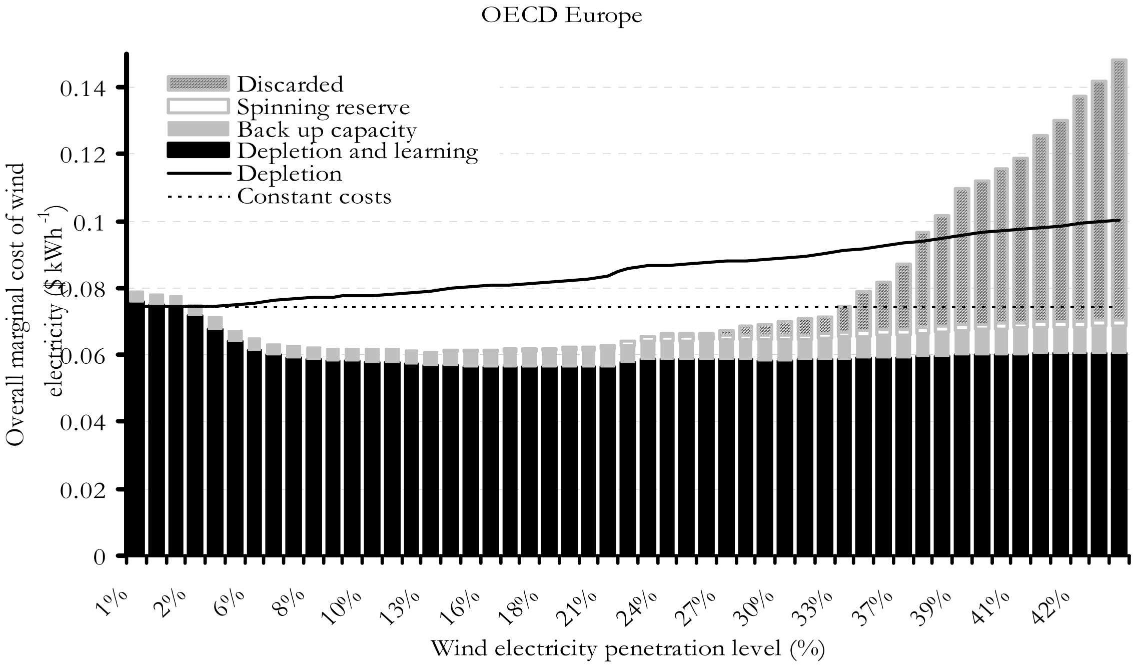


Figure 11b: The marginal cost development of wind electricity in OECD Europe with increasing wind electricity penetration subdivided in different cost components (Experiment A).

We compare our figures for OECD Europe with the average values mentioned by Fellows (2000). His estimates are based on a wind electricity production of 1200 TWh y^{-1}, which is slightly higher than our estimates of 990 TWh y^{-1}, but similar at electricity penetration level. At these production levels, Fellows estimates average additional costs of about 1 ¢ kWh^{-1}, compared to about 1.5 ¢ kWh^{-1} in our study (Table IV). The most important difference stems from is the estimated costs of discarded electricity. The discarded amount of electricity in this study is higher than assumed by Fellows (2000). Furthermore, we assume higher on-site wind generation costs. The different costs for back-up capacity is due to the assumption that we have allocated back-up capacity costs already for the first installed capacity of wind, whereas Fellows assumes no costs until wind electricity exceeds a penetration of 10%.

Table IV: The estimated average additional costs of wind electricity at high penetration in the OECD Europe system according to Fellows (2000) compared to this study.

	This study	Fellows (2000)	Unit
Wind Electricity absorbed	990	1200	TWh y^{-1}
Wind electricity penetration[a]	43	44	%
Discarded electricity	0.9	0.2	¢ kWh^{-1}
Spinning reserve	0.1	0	¢ kWh^{-1}
Additional reserve	0.3	0.6	¢ kWh^{-1}
Additional peaking capacity	0.3	0.2	¢ kWh^{-1}
Total additional costs	1.5[b]	1.0	¢ kWh^{-1}

[a] The penetration level of Fellows (2000) is derived from a curve he gives on the total electricity demand in 2020.

[b] The difference with the sum is due to rounding of the values.

5.4 Fuel savings (Experiment B)

To study the fuel savings with increasing wind electricity penetration, we use Experiment B. The development over time of the capacity and the wind electricity absorbed by the systems is given in Figure 12. In the year 2010 (target year), about 65 TWh y^{-1} wind electricity is absorbed by the electricity system of the USA and about 180 TWh y^{-1} in the OECD European system, which results in a wind electricity penetration of about 2% (USA) to 7% (OECD Europe).

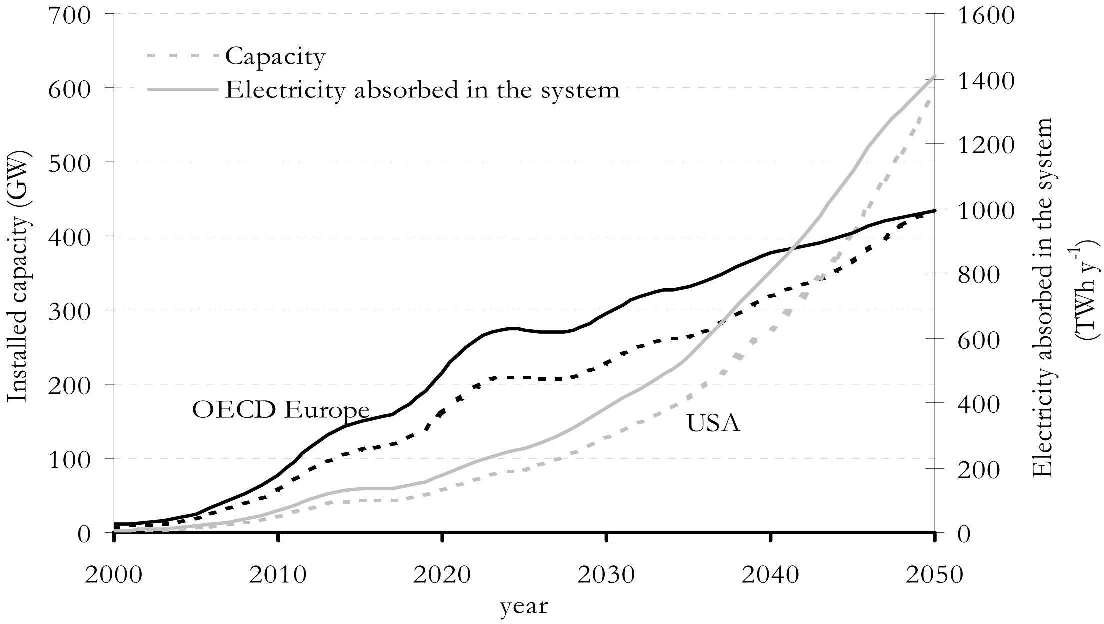


Figure 12: The development over time of the installed wind capacity and amount of wind electricity absorbed by the systems in USA and OECD Europe (Experiment B).

The differences in fuel use with or without wind power penetration over the next 50 years (Figure 12) are the estimated amounts of fuel saved by wind power (Figure 13). Initially, wind power replaces mainly old conventional coal and gas. Soon, however, wind replaces slightly more natural gas.

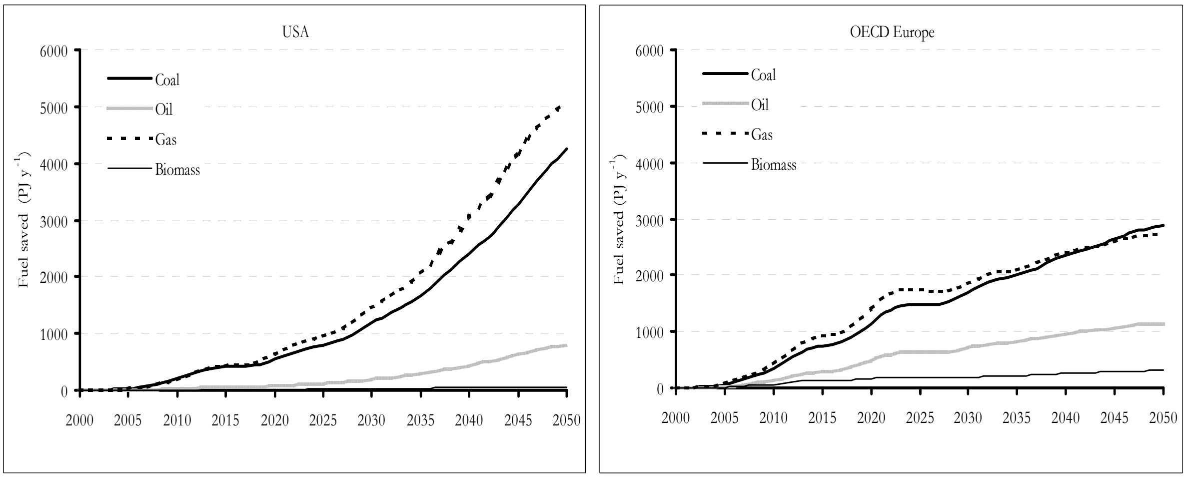


Figure 13: Fuel use avoided due to wind power if wind capacity increases to about 38%(USA) - 43% (OECD Europe) penetration in 2050 in Experiment B.

5.5 Potential CO_2 abatement costs (Experiment B)

We now calculate the overall electricity production costs of the system with and without wind penetration for the timeframe 2000 to 2050. The results can be combined with the avoided CO_2 emissions as a result of the fuels saved (Figure 13) to estimate the potential

CO_2 abatement costs[1]. The result is shown in Figure 14. Note that constant fuel and capital costs of the fossil-fired plants have been assumed. At first, abatement costs decline due to technological learning to about 33 $ per ton CO_2 avoided in the USA and to a level of about 14 $ per ton CO_2 avoided in OECD Europe. In 2010, in OECD Europe - assuming an installed capacity of 75 GW – emission of about 76 Mton CO_2 can be avoided at average costs of about 18 $ ton per CO_2. This is about 26% of the total target of CO_2 abatement according to the Kyoto protocol (den Elzen and Both, 2002). As in the first years the share of wind electricity in OECD Europe increases more significantly compared to the USA (see Figure 12), the CO_2 abatement costs increase more rapidly too. These costs may be reduced significantly if storage of discarded electricity is applied (Figure 11). The lowest costs are higher than values presented by Fellows (2000) (Figure 14). He also estimates that wind electricity mainly replaces gas-fired electricity production. The differences with our results originate mainly from the lower overall wind electricity costs assumed. Negative costs, as indicated by Fellows (2000) for OECD Europe at low penetration, were also concluded by Sims et al. (2003). This can be explained mainly by the lower wind turbine electricity costs assumed, i.e. about a factor 2 lower compared to our values for the USA.

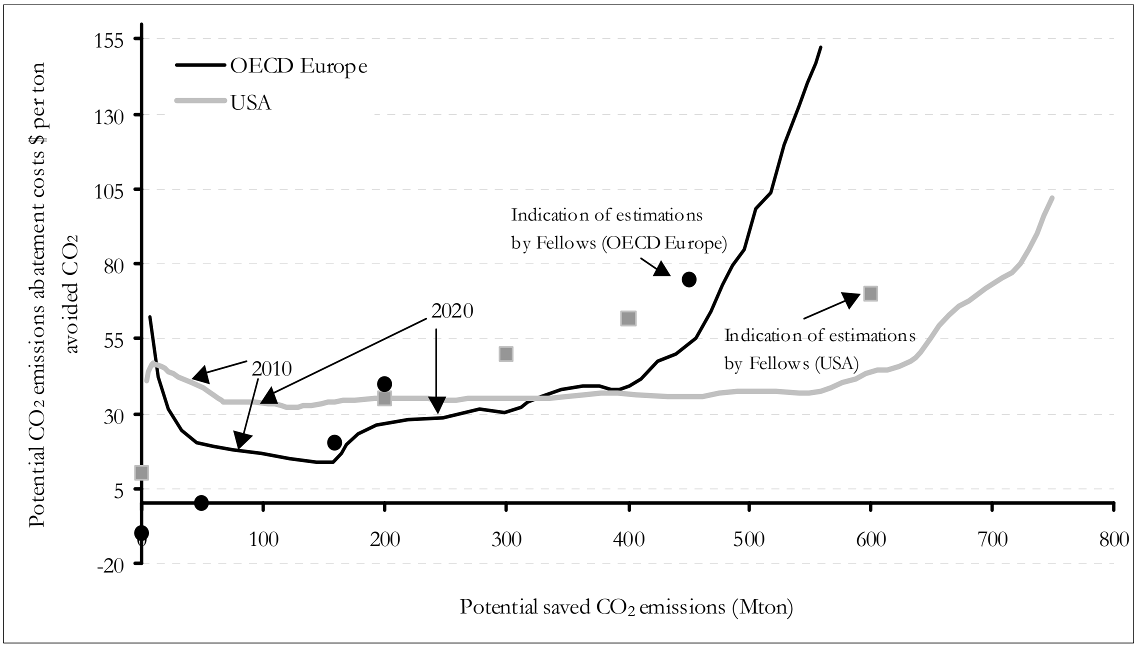


Figure 14: The potential CO_2 abatement cost for wind electricity with increasing wind power penetration (Experiment B). For comparison, also results of Fellows (2000) are shown.

[1] The potential CO_2 emissions abatement costs are calculated as follows: (simulated Δ kWh generation costs)/simulated Δ CO_2 emissions)

6. Sensitivity analysis (Experiment B)

Our results depend of course on the assumptions and constrained setting of the experiments. Therefore we conduct a one-factor sensitivity analyses to study how sensitive they are for: 1. the 'mismatch coefficient' (φ); 2. the technical potential of wind electricity production; 3. the Load Supply Curve of wind electricity production within a month; 4. the progress ratio as a measure for technological learning and 5. the multiplier that accounts for the additional on-site costs for administration, etc. (see Section 2). The results are shown in Figure 16.

1. The 'mismatch coefficient'

The default value of φ is 0.5. For the sensitivity analysis, we varied this value from 0.3 to 1.0 (Figure 9). The results show that this parameter is important: varying the φ-value cause a more than proportional increase in discarded electricity, and hence in wind electricity and CO_2 emissions abatement costs. Changing φ varies the penetration and overall production costs of wind electricity in a similar way.

2. Depletion; the technical potential

The technical potential used as default is based on assumptions regarding the power density of the turbines (MW km^{-2}) and the land-use suitability, see Chapter 5. These assumptions are to some extent arbitrary and depend on social values. Therefore four extreme situations for the technical potential with extreme settings of the power density and the land-use suitability have been analysed. Here we refer to the lowest and highest technical potential of this analysis: for the USA from $4 \cdot 10^2$ to $515 \cdot 10^2$ TWh y^{-1} and in OECD Europe from $0.8 \cdot 10^2$ to $104 \cdot 10^2$ TWh y^{-1} as compared to default values of $206 \cdot 10^2$ (USA) and $41 \cdot 10^2$ TWh y^{-1} (OECD Europe). In case of low technical potential, all available sites are exploited including the sites with lower wind speed. Consequently, the overall wind electricity costs increase mainly because of the depletion of the available wind resources. At low technical potential levels, the full use of this potential takes place within the timeframe considered in both regions. The opposite occurs with high technical potentials. From sites with high wind speeds, more electricity can be produced as there is more land available and the power density is higher, resulting in a higher average load factor. On the other hand, this also implies higher discarded amounts of electricity. Overall, in our setting, a higher technical potential than our default to produce wind electricity has only a marginal impact on the wind electricity penetration and the overall wind electricity costs.

3. The Load Supply Curve of wind electricity; geographical dispersion

If wind turbines are placed far apart in areas with different wind regimes, which is likely within the two regions considered, the monthly Load Supply Curve of the wind power supply is smoothened (Section 3). We assume two extremes, shown in Figure 15. This variation influences the amount of discarded electricity. In general, if wind farms are barely dispersed, there is more wind electricity discarded and this occurs already at low electricity penetration compared to the default situation. Thus overall wind electricity costs increase and less electricity is absorbed in the system. The opposite occurs if wind farms are geographically more dispersed.

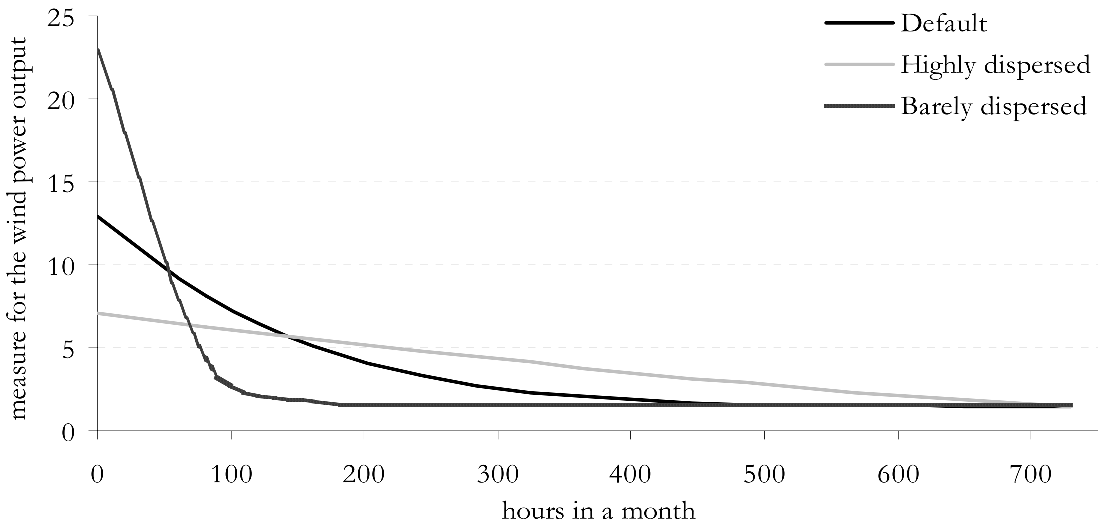


Figure 15: Assumptions regarding the monthly Load Supply Curve of wind power resulting from the assumed geographical dispersion, as used in the sensitivity analysis.

4. Technological learning; declining capital costs

For the sensitivity analysis we varied the progress ratio from 0.85 to 0.95, causing lower, resp. igher wind turbine electricity generation costs. The electricity absorbed by the system is identical to the default situation. As global learning was assumed, the variation between the two regions is identical.

5. Costs multiplier for additional on-site costs

As is explained in Section 2, we have multiplied our static cost-supply curve with a factor that accounts for costs like overhead, administration, etc. This factor is uncertain and varied around the default value, from about 5 ¢ kWh^{-1} (cost low) and 11 ¢ kWh^{-1} (cost high). This does not have an effect on the penetration but reduces the costs proportional for until wind electricity is discarded. If overall production costs of wind electricity are lower, the additional costs due to discarded electricity are also lower.

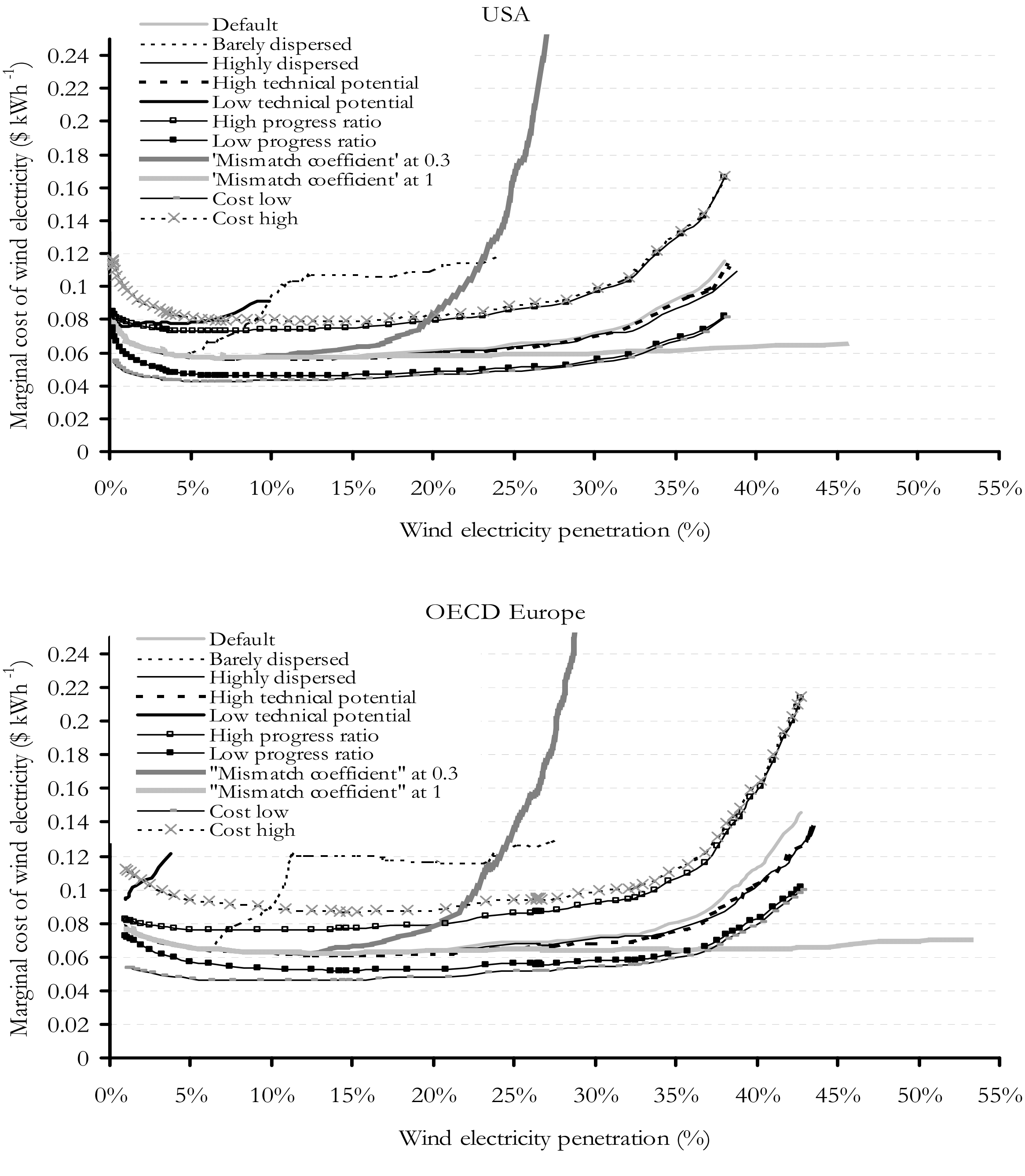


Figure 16: Sensitivity analysis for four parameters influencing the electricity penetration and cost of wind electricity if wind capacity increases in the USA and OECD Europe from the year 2000 to 2050 (Experiment B).

7. Discussion

As we made a comparison with results from literature in Section 5 already, we focus our discussion on the value of the analyses from this study.

Our analysis is based on the use of a highly aggregated (semi) dynamic model using Load Duration Curves at a monthly level. The analysis was done using a constant demand for electricity. This is a significant limitation compared to analyses of the development and operation of present and future national electricity systems at hourly basis, causing higher uncertainties in our results. The impact of these constrains needs to be analysed further.

We have analysed the discarded electricity using a 'mismatch coefficient', which includes interconnection, transmission capacity and load following capabilities. The value of the coefficient has not been related to the load following capacity of the park. Furthermore, the 'mismatch coefficient' is kept constant over the analyses. This may not be correct as the load following capacity increases due to the installation of good load following capacity like peaking plants. This would reduce the discarded electricity and the overall cost of wind electricity and increases the maximum electricity penetration level.

The constant electricity demand as function of time assumed in our study has an impact on the results. All scenarios on the future electricity system assume an increase in electricity demand. This would imply that we overestimate the amount of discarded wind electricity in our study. Therefore, also the overall wind electricity costs are expected to be overestimated at this point. Furthermore, more CO_2 emissions can be abated and the associated costs are assumed to be lower.

The approach used in this study is also simplified in the limitations to include the load following capacity into the system when generating electricity in a reliable manner. This influences the estimates of the amount of discarded wind electricity and the requirements of spinning reserve and back-up capacity. Further analysis on this issue is required to strengthen the conclusions that can be drawn from this study.

The approach is based o the concept of centralised planning of investments and operational strategy. In an increasing liberalised and privatised electricity sector, this may not be a good representation. The operation strategy is not applied at a whole region or country, but to smaller units. This reduces the load following capacity of the system.

The constant fuel and capital costs of conventional power plants have an impact on the system costs analysed, and thus on the CO_2 emissions abatement cost estimates. Furthermore, one may expect different market shares of power plants if fuel and capital cost developments are taken into account.

The forced penetration paths that have been constructed are of course hypothetical, although linked to targets and compared to historical growth rates, not unrealistic. However, we have not assumed simultaneous improvements of the electricity system. One may expect that if wind (or solar PV) is forced in the system (e.g. due to stringent climate policy) more storage capacity and transmission capacity will be installed also, reducing the impact of discarded electricity on the system

The assumed costs of wind electricity in the year 2000 are based on static cost-supply curves of wind electricity and on additional estimates on the costs of administration, insurance, distribution, etc. These additional estimates are based on the Dutch situation, of course, these figures may not apply for other countries or on a regional scale. Other values for these costs do affect the cost-supply curves of wind electricity in absolute numbers, but not the conclusions regarding costs reductions and cost increase as function of the supply. CO_2 emissions abatement costs may of course be different.

We use a simple method to estimate of the additional transmission costs. Also we have not included costs for transmission capacity increases, the assumptions made are subject for discussion and may cause variation of the transmission costs. This may vary the cost of wind electricity with a few dollarcents per kWh.

We have not included the potential of offshore wind electricity. This underestimates the potential of CO_2 emission reduction and overestimates the cost increase caused by depletion of the wind resources. Further analyses including this electricity source are especially of importance for OECD Europe.

During the experiments a global learning curve for intermittent capacity was used. However, the rest of the world was assumed to have zero wind (and solar PV) capacity. This causes an underestimation of the learning rate and consequently an overestimation of the electricity costs compared to a situation where the rest of the world also invests in renewables.

We have focused our analysis on the overall production costs of wind electricity amongst others because more data are required. For solar PV more research is required, e.g. on the capacity credit in larger system, related to the geographical dispersions.

Finally, we should mention neglecting storage capacity. It was illustrated that investments in storage capacity could reduce the discarded electricity significantly as we have shown in Section 5.

These remarks have to be taken into account when considering the results of our study. However, our approach enables to focus on the impact of independent parameters. In a full dynamic model these investigations would not have been possible. Furthermore, the aggregation level used in this study allows analyses at the scale of the USA and OECD Europe as one system. This approach can therefore be used in global or regional energy models such as TIMER 2.0, to study for instance the cost of CO_2 emission abatement under different power regimes and to simulate the competitiveness of renewables in a dynamic system.

8. Summary and conclusions

In this study we have explored the dynamics of electricity production and associated costs of wind (and solar PV) electricity with increasing penetration into the electricity systems of the USA and OECD Europe. Also the amount of fuels saved and the abatement costs of CO_2 emissions have been analysed. The analyses have been done under constraining assumptions, which limits the conclusions to be drawn but improves the analysis of the factors that influence the cost of wind electricity.

With increasing penetration wind production costs may further fall thanks to technological learning. However, this effect is counteracted by:

1. The depletion effect, accounting for a transition to sites with lower wind speeds and less solar irradiance. This effect may cause a cost increase of 25 to 50% counteracting the larger part of the expected gains from technological learning.
2. Back-up capacity, accounting for the additional capital costs that have to be made to maintain system reliability.
3. Discarded electricity, due to a system falure to absorb all wind or solar PV electricity produced, given the (estimated) supply and demand fluctuations and generation and transmission capabilities. At about 20% electricity penetration, about 750 TWh y^{-1} produced in the USA and 500 TWh y^{-1} in OECD Europe wind electricity is discarded. If wind electricity penetrates over about 30%, discarded electricity is found to be the most significant factor for cost increase, accounting for 50% of the overall wind electricity cost. Options to store the discarded electricity, which could reduce these costs, are not considered.

The use of wind electricity would mainly avoid use of natural gas and coal in both regions. However, the CO_2 emission abatement costs differ in both regions due to the more rapid wind electricity cost increase in OECD Europe. Lowest levels of CO_2 abatement costs in the USA are found at about 15 - 35 \$ ton CO_2^{-1}.

The results are very sensitive to the technical potential in the region and to system parameters, such as transmission capacity and geographical dispersions of installed wind and solar PV capacity within a region. The technical potential is assumed to depend mainly on social- and geographical factors like the suitable area and the power density of the wind turbines. If social acceptance is low, the technical potential is low and wind can barely penetrate. On the other hand, wind could become attractive in terms of electricity production contribution and costs and CO_2 abatement if social acceptance for wind turbines is high and the system is technically optimal, with high transmission and interconnection capacity and sufficient low-cost storage capacity.

Part 5

Summing up

CHAPTER EIGHT

SUMMARY AND CONCLUSIONS

Energy plays a crucial role in socio-economic developments at international, national, local and individual level. At present there are aspects in the use and supply of energy (i.e. the energy system) that are incompatible with the goal of sustainable development. Firstly, there is a disparity in access to affordable energy, increasing risks of social instability. One may think of differences in access to fossil fuel reserves, but also in the fact that more than two billion people cannot access affordable energy services. Secondly, the energy-related emissions of small particles, nitrogen, sulphur and greenhouse gases can cause a severe impact on public health, nature and the climatic system. Also, increasing reliance on imported energy makes regions become further vulnerable to supply disruptions. Therefore, energy plays a crucial direct or indirect role in the achievement of Millennium Development Goals (MDGs) formulated at the Millennium Summit organised by the United Nations General Assembly held in 2000. Also in the context of sustainable development, debated at the World Summit on Sustainable Development (WSSD) in September 2002 in Johannesburg, energy was one of the key issues.

One of the pathways to follow in order to achieve the goals for sustainable development is an increased reliance on renewable energy, amongst others solar, wind and biomass energy, because:

- They lead to a diversification of energy sources by increasing the share of a diverse mixture of renewable sources, and thus to an enhanced energy security.
- They are more widely available compared to fossil fuels and therefore reduce the geopolitical dependency of countries as well as minimise spending on imported fuels.
- They contribute less to local air pollution (except for some biomass applications) and therefore reduce the human health damages.
- Many renewable energy technologies are well suited to small-scale off-grid applications and hence can contribute to improved access to energy services in rural areas.
- They can balance the use of fossil fuels and save these for other applications and future use.
- They can improve the development of local economies and create local jobs.
- They do not give rise to greenhouse gas (GHG) emissions to the atmosphere. This also holds for the use of biomass, if produced in a sustainable way, as the emitted carbon has been fixed before in the process of photosynthesis. Biomass energy can then be considered as carbon (dioxide) neutral.

In this thesis, the central research question is: what can be the contribution of renewable energy sources to the present and future world and regional energy supply system. The focus is on wind, solar PV and biomass energy (energy crops) for electricity generation. The results are constructed in order to be used in the energy model TIMER 1.0 (developed at the National Institute of Public Health and the Environment (RIVM)), which is part of the modelling Framework IMAGE 2.2 (Integrated Model to Assess the Global Environment). This model is one of those used for the construction and evaluation of SRES energy scenarios by the Intergovernmental Panel on Climate Change (IPCC).

Quite a few previous studies have analysed the potential of wind, solar PV and biomass energy. The additional insights gained in this thesis are based on our approach to assess the global and regional potential of wind, solar PV and biomass energy in a uniform way using a grid cell approach. It includes changes in land-use patterns and the construction of cost-supply curves of electricity from renewable sources for the assessment of the economic potential. To analyse the potential we use the following categories:

- The **theoretical** potential: this is the theoretical limit of the primary energy contribution from the resource. For solar-driven sources this is the solar energy irradiated on earth or solar energy converted to wind or biomass.
- The **geographica**l potential: this is the theoretical potential limited to the amount of energy available at areas that are considered accessible and suitable for this production.
- The **technical** potential: this is the geographical potential reduced by the losses of the conversion of the primary energy to secondary energy carriers
- The **economic** potential: this is the total amount of technical potential derived at cost levels that are competitive with other energy supply options.
- The **implementation** potential: this is the total amount of the technical potential that is implemented in the energy system. Subsidies and other policy incentives can give an extra push to the implementation potential, but e.g. social barriers can reduce the implementation potential. The implementation potential can be both higher and lower than the economic potential however, can never exceed the technical potential.

The main objective of this thesis is to assess the geographical, technical and economic potential of wind, solar PV and biomass electricity. The potentials are analysed at a global and regional level, for seventeen world-regions similar as used in the IMAGE 2.2 model to make future use of the results for scenario analysis with the TIMER 1.0 and the IMAGE 2.2 model possible. For the assessment of the economic potential, we construct cost-supply curves. As the economic potential also depends on the way renewables are integrated in the electricity system, we also explore the overall costs of wind electricity with increasing penetration levels of the installed wind capacity into the system.

Except for Chapter 2, all potential assessments have been conducted using climatic and land-use data at grid-cell level of 0.5°x 0.5° (longitude x latitude). This geographical aggregation level is consistent with the level used in the terrestrial environment system of the IMAGE 2.2 model. The results are aggregated to the regional level. For the biomass energy potential assessment we have used four land-use scenarios to evaluate potential land availability.

This thesis starts in *Chapter 2* with an exploration of the range of the future potential of biomass for energy at a global scale. The study is done to gain insight in the factors that influence the potential biomass availability for energy purposes rather than give exact numbers. Six biomass resource categories for energy are identified: energy crops on surplus cropland, energy crops on degraded land, agricultural residues, forest residues, animal manure and organic wastes. Furthermore, specific attention is paid to the competing biomass use for material. The analysis makes use of a wide variety of existing studies. The main conclusion of the study is that the range of the global potential of primary biomass (in about 50 years) is very broadly quantified at anything between nill and 1150 EJ y^{-1}. Energy crops from surplus agricultural land have the largest potential contribution at about (nill – 1000 EJ y^{-1}) that is the result of land availability and biomass productivity. The biomass productivity - assumed to range from 10 – 20 ton ha^{-1} y^{-1}, is mainly determined by local factors, like soil quality, climate, water availability and management. The land availability is amongst others determined by land requirements for food demand. This is a function of the future diet, population growth, but most important, the food production system. It is concluded that in order to achieve high biomass energy potentials, considerable transitions are required in the agricultural system, especially in the way meat and dairy products are being produced and consumed. Application of high production levels implies that the knowledge available in the western countries is diffused world-wide. As indicated by the range, a shortage of agricultural land may also occur, e.g. when the world population and food intake increase sharply (the latter accompanied by a high share of meat and dairy products) and the agricultural technology development stagnates.

Chapter 2 provides insight in the factors that determine the biomass energy potential. It concludes the energy crops have the largest range of the geographical potential. These insights have been used in *Chapter 3* where we have analysed the geographical and technical potential of energy short rotation crops for the year 2050-2100 on a regional and global level. Future developments of land-use patterns are estimated using four scenarios, based on the IPCC Special Report on Emission Scenarios (SRES): A1, A2, B1 and B2, and using the IMAGE 2.2 model. The scenarios vary according to population and economic growth, technological change, social behaviour; the value given to environmental and ecological issues and the level of globalisation, resulting in different future land-use patterns. The geographical potential is the product of the available area for energy crops and the productivity. Three categories of potential available areas are distinguished: 1) abandoned agricultural land, 2) low-productive land and 3) rest land not required for food, forest or bioreserves. The results on the geographical potential are summarised in Table I. In absolute terms, the Former USSR has the highest potential, reaching levels in 2050 of about 70 (B2) to 125 (A1) EJ y^{-1}. Depending on the scenario, interesting regions with significant potentials are China, South America and Africa. The potential at low-productive land is negligible.

Table I: The global geographical and technical potential for the years 2050 and 2100 for three land-use categories and four land-use scenarios (EJ y^{-1})

	A1		**A2**		**B1**		**B2**	
	2050	2100	2050	2100	2050	2100	2050	2100
At abandoned agricultural land								
Primary biomass	409	847	129	243	398	656	279	448
Biomass fuel	225	466	71	134	219	361	153	246
Biomass electricity (PWh y^{-1})	82	171	26	49	80	132	56	90
At low-productive land								
Primary biomass	5	2	9	4	6	4	8	5
Biomass fuel	3	1	5	2	3	2	4	3
Biomass electricity (PWh y^{-1})	1	0	2	1	1	1	2	1
At 'rest land'								
Primary biomass	243	266	173	148	47	39	35	32
Biomass fuel	134	146	95	81	26	21	19	18
Biomass electricity (PWh y^{-1})	49	54	35	30	9	8	7	6

The results are highest for the A1 and B1 scenarios. Both scenarios describe a world with decreasing population growth at the second half of the century and a high technical development. The food productivity levels are high because of high management levels and high crop intensities. The A2 scenario has the lowest geographical potential. A2 describes a world with rapid population growth up to 15 billion people in the year 2100. It furthermore experiences less technical development and is oriented towards regional market-based economic development. The technical potential shows that in all scenarios considered energy crops can supply about 4 – 8 times the present world electricity consumption. Similar applies for the technical potential of liquid fuel from biomass.

Chapter 4 deals with the cost-supply curves of primary and secondary biomass energy. For the land-use scenarios used in *Chapter 3*, we have explored the regional and global cost-supply curves of short rotation energy crops at abandoned agricultural land and at rest land in the long term (2050). We have included four cost categories: land, transportation, labour and capital costs. These are assumed to evolve differently over time. Labour costs (wages) are assumed to evolve according to the GDP developments. Labour and capital inputs are assumed to increase proportionally with the productivity increase. With rising income, capital-labour substitution is assumed. Furthermore, thanks to innovations, specific capital and labour costs are assumed to decline with increasing production. The estimations have been based on grid cell data on the productivity of short rotation energy crops and available land over time as well as assumptions regarding the capital and the labour input required to reach these productivity levels.

It is concluded that large amounts of biomass grown at abandoned agricultural land and rest land: 130 to 270 EJ y^{-1} (about 40 to 70% of the present world primary energy consumption) may be produced at costs below 2 \$ GJ^{-1} by 2050 (present upper limit of cost of coal). Interesting regions because of their low production costs and significant potentials are the Former USSR, Oceania, East and Western Africa and East Asia. Such low costs presume significant land productivity improvements over time and cost reductions due to technological learning and capital-labour substitution.

An assessment of biomass liquid fuel cost, using the primary biomass energy costs, shows that the future costs of biomass liquid fuels may be about twice present diesel production costs, although this may change in the long term. Biomass derived electricity costs are estimated to be slightly higher than future electricity baseload cost. However, they may be competitive with future production costs of fossil fuel based electricity combined with physical CO_2 sequestration. The present world electricity consumption of 15.7 PWh y^{-1} may be supplied by biomass in 2050 at costs between 0.04 – 0.045 \$ kWh^{-1} in A1 and B1 and between 0.044 and 0.054 \$ kWh^{-1} in A2 and B2. At costs below 0.06 \$ kWh^{-1}, about 18 (A2) to 53 (A1) PWh y^{-1} can be supplied

The cost-supply curves are quite sensitive to some input parameters, for instance to the elasticity that accounts for the substitution of capital for labour. If mechanisation, and consequently capital-labour substitution, stagnates the production costs in the year 2050 could be twice as high as when this substition is assumed in the A1 scenario. To enhance the insight in the economic potential and competitive position of biomass energy, more research and more input data are required.

The next chapter (*Chapter 5*) focuses on wind energy. The regional and global geographical and technical potential of onshore wind energy is assessed using a grid cell approach. For the economic potential the regional supply cost curves of wind electricity are presented. The global technical potential of wind electricity is estimated to be 96 PWh y^{-1}: about 6 times the present (2001) world electricity consumption. To realise this potential, an area of 1.1 Gha is required when the wind turbines are installed at an average power density of 4 MW km^{-2} at geographically available areas. This is similar to the total global grassland area or to an area with the size of about China, with wind turbines installed at a power density 15 times higher than presently on average in Denmark. The regionally highest technical potential of onshore wind energy is found for the USA: 20.7 PWh y^{-1}. Lowest figures are found for South and South East Asia. In most regions the technical potential exceeds the current electricity consumption. The highest surplus is found in East Africa where the technical potential exceeds the present consumption level more than 300 times. In OECD Europe, the technical potential of wind electricity is about 2 times the present electricity consumption. In Eastern Europe the technical potential does not exceed the present consumption level.

Globally, roughly an amount equal to the present (2001) global electricity consumption may come available at costs less than 0.07 \$ kWh^{-1}, spread over most regions. At costs of 0.06 \$ kWh^{-1} or below, about 7 PWh y^{-1} wind electricity may be generated, half of the present world electricity consumption. These cost figures are based on state of the art technology. This potential is found mainly in Canada, USA, South America, Former USSR and OECD Europe. The actual estimate of the technical potential of onshore wind energy (for given cut-off costs) depends critically on assumptions about acceptable wind power density (W km^{-2}) and land-use constraints.

In *Chapter 6* we have assessed the global and regional geographical, technical and economic potential of electricity production by PV using a grid cell approach. The global technical potential of grid-connected (centralised and decentralised) PV is assessed at a value of about $3.7 \cdot 10^2$ PWh y^{-1}, or about 23 times the present world electricity consumption. For more than 98% it consists of centralised PV applications. At cut-off costs of 1 \$ kWh^{-1}, the technical potential at present is about $3.6 \cdot 10^2$ PWh y^{-1}. At cut-off costs below 0.5 \$ kWh^{-1}, this figure is reduced to $0.7 \cdot 10^2$ PWh y^{-1}. The present global electricity consumption can be generated at costs between 0.44 and 0.46 \$ kWh^{-1}. These cost figures are based on state of the art technologies. It should be noted that this figure does not include grid-connection, transmission, distribution and storage costs. Potentially high contributions, exceeding the present regional electricity consumption almost 1000 - 4000 times, are found in North, East and West Africa and Australia. In Japan, OECD Europe and Eastern Europe, the relative potential is much less, about 0.6 to 2 times the present regional electricity consumption. The potential highly depends on the available area for PV modules, which at regional level can be less than 1% of the total area, as well as the conversion efficiency of PV modules and performance ratio of PV systems. The assumptions regarding the suitability of land for PV system made in this study result in an available area for centralised PV systems of 1.7% of the terrestrial area on earth (2.3 million km^2, i.e. about the size of Sudan) and 0.11% for decentralised PV applications (0.15 million km^2). Depending on future achievements in technology development, like an increase of the conversion efficiency of PV modules and an improvement of the performance ratio of PV systems, the technical potential of centralised PV applications may increase with about a factor 2. The technical potential of the decentralised systems might increase more due to an increase in roof-top areas. It is also estimated that it may become possible to generate the present consumption at a cost below 0.06 \$ kWh^{-1}, taking into account potential future cost reduction. However, this would imply that regions like Northern Africa and Australia would export large amounts of electricity. This would require high transmission costs. To estimate the real economic potential of PV electricity, these costs need to be included.

In *Chapter 7* we have explored, under simplified conditions, the dynamics of electricity production and associated costs of wind (and solar PV) electricity with increasing penetration of these options into regional electricity systems, for the USA and OECD Europe, using a highly-aggregated electricity model called TIMER-EPG, and a constrained setting of the total system. Also the amount of fuels saved by the use of renewables and the related abatement costs of CO_2 emissions were analysed. The analyses were done under highly constrained system boundaries and focused on wind electricity production, which limits the types of conclusions that can be drawn, but improves the understanding of factors that influence the development of the overall cost of wind electricity and the amount of wind electricity absorbed in the system independently.

With increasing penetration wind production costs may further fall thanks to technological learning. However, this effect is counteracted by:

1. The depletion effect, accounting for a transition to sites with lower wind speeds and less solar irradiance. This effect may cause a cost increase of 25 to 50% counteracting the larger part of the expected gains from technological learning.
2. Back-up capacity costs, cvaused by additional capital costs that have to be made to maintain system reliability.
3. Discarded electricity, due to a system failure to absorb all wind or solar PV electricity produced, given the (estimated) supply and demand fluctuations and generation and transmission capabilities. At about 20% electricity penetration, about 750 TWh y^{-1} produced in the USA and 500 TWh y^{-1} in OECD Europe wind electricity is discarded. If wind electricity penetrates over about 30%, discarded electricity is found to be the most significant factor for cost increases compared to the other two factors, accounting for 50% of the overall wind electricity cost. Options to store the discarded electricity, which could reduce these costs, are not considered.

The use of wind electricity would mainly avoid use of natural gas and coal in both regions. However, the CO_2 emission abatement costs differ in both regions due to the more rapid wind electricity cost increase in OECD Europe. Lowest levels of CO_2 abatement costs in the USA are found at about 15 - 35 \$ ton CO_2^{-1}.

The results are very sensitive to the technical potential in the region and to system parameters, such as transmission capacity and geographical dispersions of installed wind and solar PV capacity within a region. The technical potential is assumed to depend mainly on social- and geographical factors like the suitable area and the power density of the wind turbines. If social acceptance is low, the technical potential is low and wind can barely penetrate. On the other hand, wind could become attractive in terms of electricity production contribution and costs and CO_2 abatement if social acceptance for wind turbines is high and the system is technically optimal, with high transmission and interconnection capacity and sufficient low-cost storage capacity.

In summary, we can conclude that the renewable electricity sources studied in this thesis have a potential to generate several times more electricity than the present electricity demand at costs in the range of present electricity costs. Solar PV has the most significant technical potential, but is at present not available at competitive costs in grid connected options. In the longer term, costs of solar PV may come down at cost levels comparable to conventional electricity, especially in sunny areas. The costs depend in the case of biomass electricity strongly on the technological development of the agricultural sector, on the labour wages, the capital-labour ratio and the land rental costs. Costs of wind electricity are already nearly competitive and the wind electricity sector has increased considerably the last decades. However, to what extent the overall costs of wind electricity can decrease further with increasing penetration levels, depends amongst others on the available storage capacity and interconnection of the system.

The spatially explicit calculations done in this study provide interesting new insights concerning the potential of renewable energy sources. This thesis considers on a grid-cell level, next to climatic characteristics, also characteristics of land-use and soil quality, when estimating the future potential of renewables. In particular for the assessment of the future potential of biomass energy, the demand for agricultural land is of high importance as these are expected to be planted at abandoned agricultural land. Land area required to generate the wind electricity potential depends on social factors, but default values in this thesis indicate that to generate 6 times the present electricity production about 1.1 Gha is needed, about the size of China. To generate about 23 times the present electricity production with solar PV, an area of 0.23 Gha is needed, about 20% of China. To generate biomass derived electricity equal to 5 times the present electricity production, in the A1 scenario (highest potential) at abandoned agricultural area, about 1.3 Gha is needed, about 120% of the area of China.

The potentials of the sources vary over the regions. For wind electricity, highest potentials at low costs are found in Canada, the USA, South America, the Former USSR, Oceania and OECD Europe. For solar PV, large potentials at relatively low costs are found in Africa, Oceania, the Middle East and South Asia. For biomass, the regional attractiveness is different for the four scenarios used. However, in all scenarios the Former USSR, Africa, the USA, Oceania and Canada are regions with high geographical potential levels of primary biomass at relatively low costs.

When considering the results of this thesis one should notice that only for the assessment of the technical potential of biomass energy we have conducted scenario simulations over time. It was stated that for the other sources land-use changes are not such an important factor. For biomass this is an important improvement compared to previous studies.

However, one may argue that a significant increase of agricultural land also can change the results for wind and solar PV.

Another interesting aspect of this thesis, is the use of the different categories of potentials, which increases insight in the factors that determine the potential, e.g. land availability versus costs. Furthermore, the use of cost-supply curves has proven to be good tools to indicate the economic potential at a regional scale and to compare the cost and availability of renewables with other energy options.

Based on the considerations mentioned above, some recommendations are made:

- To increase the level of completeness concerning the potential of renewable energy sources, this study can be extended with other renewable energy sources that may become available at low costs, e.g. offshore wind electricity and small-scale hydro power.
- The assessment of the biomass potential has been conducted at a world and regional scale. Therefore, studies at a local or national scale are required, to investigate where energy plantations can be established within in these regions. It is recommended to include land-use developments in these local studies. At this level, other detailed information can be included as well, like land property and availability of technology. Such analyses may also provide more insight in factors like the capital-labour substitution coefficient.
- We have investigated the geographical potential of energy crops using different land-use scenarios including demand for agricultural land. We have not analysed the potential competition for land for biomass for energy or for food. This competition may have an impact on the price for food, which should be investigated at a regional and global level.
- In this thesis we have not analysed the potential competition for land that may occur among the renewable energy technologies. An integrated analysis can indicate the areas where potential competition may occur and may be a basis for the development of incentives for multifunctional land-use. This analysis can use data from this thesis.
- Based on the results of this thesis it can be concluded that when long-term costs of intermittent electricity sources are investigated, one should include the cost dynamics related to the integration of these sources into the electricity system and grid. This may change the results of various long-term scenarios where high shares of renewables are included. At a regional level, these costs are explored in this thesis. It would be interesting to study these costs with a dynamic electricity system, i.e. including electricity demand and cost developments of all electricity produyction technologies.
- This thesis does not consider the implementation potential of renewable electricity technologies sources, although some social aspects are taken into account, e.g. the land-use suitability factor. To what extent the potentials that are estimated are being

used in the future is outside the scope of this thesis. Some insight in these questions can be gained using energy models such as the TIMER 2.0 model.

SAMENVATTING EN CONCLUSIES

Energie speelt een cruciale rol bij sociaal-economische ontwikkelingen op internationaal, nationaal, lokaal en individueel niveau. We kunnen niet zonder energie om voedsel te koken, ons te verwarmen, ons te verplaatsen en te communiceren over grote afstanden, materialen te maken en onze producten te fabriceren, et cetera. Het functioneren van het huidige energiesysteem, dat wil zeggen het geheel aan productie, conversie en gebruik van energie, is niet in overeenstemming met het streven naar duurzame ontwikkeling van de samenleving. Op de eerste plaats bestaat er een schrijnende ongelijkheid in de toegang tot moderne energiedragers. Meer dan twee miljard mensen – eenderde van de wereldbevolking – hebben geen toegang tot (betaalbare) energiediensten. Zij zijn voor hun energievraag vooral afhankelijk van het gebruik van traditionele biomassa, met name brandhout. De overige vier miljard – tweederde van de wereldbevolking – nemen ongeveer 90% van het wereldenergiegebruik voor hun rekening, voornamelijk door het gebruik van fossiele brandstoffen.

Verder zijn de fossiele brandstoffen slechts in een beperkt aantal regio's van de wereld economisch winbaar. Veel landen zijn in toenemende mate afhankelijk van de import van (fossiele) energiebronnen, met het gevolg dat ze steeds kwetsbaarder worden voor mogelijke verstoringen in de aanvoer van deze bronnen. Een andere schaduwzijde van het huidig energiegebruik is gerelateerd aan de luchtverontreiniging door de uitstoot van stoffen zoals zwavel- en stikstofoxiden, roetdeeltjes en kooldioxide. Deze emissies zijn schadelijk op lokale en mondiale schaal. Men kan denken aan luchtvervuiling binnenshuis, smogvorming, verzuring van het milieu en versterking van het broeikaseffect met mogelijke gevolgen voor het klimaat. Energie speelt direct en indirect een cruciale rol bij het verwezenlijken van een groot aantal van de Millennium Ontwikkelingsdoelstellingen – Millennium Development Goals (MDGs) – die in 2000 vastgesteld zijn door de Verenigde Naties. Energie was ook een van de kernpunten waarover afspraken zijn gemaakt tijdens de World Summit on Sustainable Development (WSSD) in september 2002 in Johannesburg.

Een van de te volgen energiestrategieën om tot een duurzamer ontwikkeling van de samenleving te komen is een toenemend gebruik van hernieuwbare energiebronnen. Het gaat hierbij om energiebronnen zoals wind, biomassa en zonne-energie. Er zijn verschillende redenen waarom het stimuleren van hernieuwbare energiebronnen belangrijk is om een duurzamere samenleving op te bouwen:

- Door een toenemend aandeel van verschillende (hernieuwbare) energiebronnen voor het opwekken van energie, dat wil zeggen diversificatie van het aanbod, zal de energiezekerheid toenemen.
- Het gebruik van hernieuwbare energiebronnen spaart fossiele brandstoffen voor toekomstige energietoepassingen, of voor gebruik buiten de energievoorziening.
- Hernieuwbare energiebronnen zijn overal ter wereld beschikbaar. Door het gebruik van energiebronnen uit de eigen regio, zal de geopolitieke afhankelijkheid van een beperkt aantal landen met kolen, olie en gasvoorraden afnemen.
- De meeste hernieuwbare energiebronnen leiden tot een vermindering van lokale en regionale luchtverontreiniging. Dit vermindert tevens de schadelijke invloed die het gebruik van energie heeft op de volksgezondheid, met name op de luchtwegen, en op de ontwikkeling van vegetatie.
- Het gebruik van hernieuwbare energiebronnen kan de sociaal-economische ontwikkeling op lokaal niveau stimuleren, bijvoorbeeld door het creëren van banen.
- Hernieuwbare energiebronnen leiden niet tot uitstoot van broeikasgassen die bijdragen aan een versterking van klimaatveranderingen. Biomassa-energie vormt hierop een uitzondering, aangezien bij de verbranding van biomassa (bijvoorbeeld hout) wel koolstofdioxide wordt uitgestoten. Echter, als biomassa op duurzame wijze wordt geproduceerd, is de koolstofdioxide die wordt uitgestoten eerst vastgelegd bij het fotosyntheseproces en wordt deze opnieuw vastgelegd bij de vorming van nieuwe biomassa. Biomassa-energie kan dan ook als koolstofdioxideneutraal worden beschouwd.
- De meeste hernieuwbare energietechnologieën zijn in potentie ook zeer geschikt voor kleinschalige, ‘stand-alone’ toepassing. Hierdoor kunnen ze bijdragen aan het verbeteren van de toegang tot energiediensten in rurale gebieden over de hele wereld. Voorbeelden zijn de zonnepanelen die elektriciteit leveren voor verlichting in huizen of telecommunicatiedoeleinden, alsmede de kleinschalige biomassavergassers in bijvoorbeeld China, die via een generator hele dorpen voorzien van elektriciteit.

In dit proefschrift staat de vraag centraal naar de potentiëlen van hernieuwbare energiebronnen om regionaal en mondiaal in de huidige en toekomstige energiebehoefte te voorzien. Daarbij hebben we ons beperkt tot de potentiëlen van zonne-energie, windenergie en biomassa-energie (voornamelijk energiegewassen). Ook hebben we ons gericht op het opwekken van elektriciteit met behulp van deze bronnen. De resultaten zijn toegankelijk gemaakt voor gebruik in het zogenaamde TIMER-model. Dit energiemodel maakt deel uit van het IMAGE-model van het Rijksinstituut voor Volksgezondheid en Milieu (RIVM) en wordt onder meer gebruikt om scenariostudies uit te voeren ten behoeve van het ‘Intergovernmental Panel on Climate Change’ (IPCC)[58].

[58] Intergouvernementele panel over klimaatverandering.

De meerwaarde van onze studie ten opzichte van andere studies in dit veld is dat de potentiëlen op een vergelijkbare wijze zijn geanalyseerd, dat dit is gedaan binnen de context van een model dat ook landgebruik meeneemt, en dat de analyses zijn uitgevoerd in hoge mate van detail. Bij het analyseren van het potentieel van zonne-energie, windenergie en biomassa-energie zijn in dit proefschrift verschillende niveaus onderscheiden:

- Het **theoretisch** potentieel is de theoretische limit van de beschikbaarheid van de primaire bron. Voor de bronnen zon, wind en biomassa is dit de jaarlijkse hoeveelheid zonne-instraling, windenergie en biomassaproductie.
- Het **geografisch** potentieel is het theoretisch potentieel beperkt tot dat deel dat vanuit sociaal-geografische overwegingen in principe benut kan worden voor de omzetting naar bruikbare energie. Hier speelt landgebruik een grote rol.
- Het **technisch** potentieel is de hoeveelheid energie uit het geografisch potentieel die na omzetting in secundaire energiedragers, hier elektriciteit, beschikbaar kan komen om te voorzien in onze energiebehoeften.
- Het **economisch** potentieel is dat deel van het technische potentieel dat opgewekt kan worden tegen concurrerende kosten.
- Het **implementatie**potentieel is de totale hoeveelheid secundaire energie die naar verwachting daadwerkelijk wordt opgenomen in het energiesysteem. Hierbij spelen naast economische ook investerings, institutionele, bestuurlijke, maatschappelijke en ecologische overwegingen een rol.

Dit proefschrift richt zich op de inschatting van het theoretisch, geografisch, technisch en economisch potentieel van zonne-, wind- en biomassa-energie toegespitst op elektriciteitsopwekking. De potentiëlen zijn zowel mondiaal als in de zeventien regio's waarin we de wereld hebben verdeeld, in kaart gebracht. Bij het bepalen van het economisch potentieel hebben we ons beperkt tot het bepalen van zogenaamde 'cost-supply' curven, oftewel kosten-aanbod curven. Deze geven aan hoeveel elektriciteit uit zonne-, wind-, en biomassa-energie beschikbaar komt bij een bepaalde kostprijs. Omdat het economisch potentieel ook afhangt van de manier waarop deze in een energiesysteem kan worden geïntegreerd, hebben we bovendien de kosten van windelektriciteit als functie van de penetratiegraad van windvermogen bekeken, waarbij we ons beperken tot West-Europa en de V.S.

In dit proefschrift, (met uitzondering van hoofdstuk 2), zijn voor de hele wereld gegevens over landgebruik, klimatologie en waar nodig populatie gebruikt op een gridcelniveau van 0.5° x 0.5°, wat op de evenaar overeenkomt met 55 x 55 km^2. Ook de potentiëlen van zonne-, wind- en biomassa-energie zijn op deze schaal geanalyseerd. De resultaten zijn geaggregeerd naar de zeventien regio's. De regioverdeling komt overeen met die van het mondiale 'Integrated Assessment Model' IMAGE 2.2, waarvan het energiemodel TIMER

1.0 onderdeel uitmaakt. De resultaten van de potentieelstudies zijn daarom goed in de modellen te gebruiken.

Dit proefschrift begint in *hoofdstuk 2* met een verkennende studie naar de (toekomstige) marges van het geografisch potentieel van biomassa-energie op wereldschaal. Deze studie is exploratief van aard en is met name uitgevoerd om inzicht te krijgen in de factoren die de beschikbaarheid van biomassa voor energietoepassingen beïnvloeden. Er is daarom gekozen voor een simpele benadering. Er zijn zes verschillende biomassabronnen onderscheiden: energiegewassen op onbenutte landbouwgrond, energiegewassen op marginale gronden, reststromen uit landbouw, reststromen uit bosbouw, dierlijk mest en organisch afval. Er is tevens aandacht besteed aan de concurrentie van biomassa die voor materiaaltoepassingen wordt gebruikt. De marges zijn verkend door extreme waarden te nemen voor invoerparameters als: populatiegroei, de opbrengst van voedsel-, en energiegewassen, de vraag naar biomassa voor materiaaltoepassingen en het dieet dat in de toekomst wordt gevolgd. De waarden van deze parameters zijn ingeschat op basis van uitgebreid literatuuronderzoek. Geconcludeerd is dat, afhankelijk van de veronderstellingen, de marges in het potentieel voor biomassa-energie op lange termijn (ongeveer het midden van de 21ste eeuw) zeer ver uiteen lopen, van ongeveer 0 tot 1150 EJ per jaar[59]. Dit komt overeen met zo'n 0 tot 285 procent van het huidige mondiale energieverbruik. Energiegewassen op onbenut landbouwgrond geven de grootste marge als functie van de landbeschikbaarheid en gewasproductiviteit. De biomassaproductiviteit is ingeschat op zo'n 10 tot 20 ton biomassa per hectare per jaar en wordt met name bepaald door lokale factoren zoals bodemkwaliteit, klimatologische omstandigheden, water-beschikbaarheid en managementaspecten van de teelt. De beschikbaarheid van land hangt erg af van de vraag naar landbouwgronden. Dit wordt bepaald door het dieet, de bevolkingsgroei en de wijze van voedselproductie. Geconcludeerd is dan ook dat om hoge biomassa potentiëlen te verkrijgen, grootschalige transities in de landbouwsector nodig zijn, met name in de wijze waarop vlees en melkproducten worden geproduceerd. Dit vereist een kennisoverdracht vanuit het efficiëntere westen naar minder efficiëntere regio's in de wereld. Een tekort aan landbouwgrond, en dus een laag biomassa potentieel is ook goed denkbaar. Dit is mogelijk als de populatie sterk blijft stijgen, er in toenemende mate vlees wordt geconsumeerd en de technologische ontwikkeling in de landbouw achterblijft. De studie geeft aan dat grootschalige beschikbaarheid van biomassa voor de energievoorziening zeker niet vaststaat. De beschikbaarheid zou hoog, maar ook zeer laag uit kunnen vallen; om hier meer inzicht in te krijgen is meer en gedetailleerder onderzoek nodig.

In *Hoofdstuk 3* wordt verder gebouwd op de verkennende studie naar het geografisch potentieel van biomassa voor energiedoeleinden gebruik makend van de inzichten

[59] Eén exajoule (EJ) is 1 x 10^{18} J. Ter vergelijk, in het jaar 2000 was het primaire energiegebruik in Nederland ongeveer 3 EJ en in de wereld zo'n 400 EJ.

uithoofdstuk 2. We beperken ons tot energiegewassen, met een meer gedetailleerde analyse op gridcelniveau. Het geografisch en technisch potentieel van energiegewassen is als functie van de tijd bekeken voor de periode 2050 – 2100. We bekijken de toekomstige ontwikkelingen in de landgebruikspatronen door vier scenario's te onderscheiden. Deze scenario's, genaamd: A1, A2, B1 en B2 zijn ontwikkeld door het IPCC ('Intergovernmnetal Panel on Climate Change') in het 'Special Report on Emission Scenarios[60]'. Het IMAGE 2.2 model is gebruikt om de scenario's te kwantificeren. Deze scenario's verschillen onderling in bevolkings-, en economische groei, technologische vooruitgang, sociale waarden, in de grondhouding ten aanzien van ecologie en economie en in de mate van globalisering die wordt nagestreefd. Het geografisch potentieel is het product van de beschikbare hoeveelheid land en de productiviteit van energiegewassen op deze gronden. Er zijn drie typen landgebruik onderscheiden die beschikbaar zijn voor energieplantages: energie gewassen op onbenutte landbouwgrond, op gedegradeerde of lage-opbrengstgronden en op overige, thans niet-commercieel aangewende gronden. De laatste categorie omvat (extensieve) graslanden in bijvoorbeeld Mongolië, en Zuid-Amerika, maar ook delen van de savannegebieden in Afrika. Het mondiale potentieel op de drie landgebruikstypen is samengevat in Tabel I. Energiegewassen op onbenutte landbouwgronden hebben op termijn het grootste geografische potentieel. Op regionale schaal wordt een hoog geografisch potentieel gevonden in het GOS (de voormalige Sovjet-Unie), in Oost-Azië (voornamelijk China), in Zuid-Amerika en in Afrika.

Tabel I: Het mondiale geografisch en technisch potentieel van biomassa voor de jaren 2050 – 2100 voor de vier scenario's in exajoulen per jaar

	A1		**A2**		**B1**		**B2**	
	2050	2100	2050	2100	2050	2100	2050	2100
Op onbenutte landbouwgrond								
Primaire biomassa (hout)	409	847	129	243	398	656	279	448
Vloeibare brandstof uit biomassa	225	466	71	134	219	361	153	246
Elektriciteit uit biomassa (PWh y^{-1})	82	171	26	49	80	132	56	90
Op lage-opbrengstgronden								
Primaire biomassa (hout)	5	2	9	4	6	4	8	5
Vloeibare brandstof uit biomassa	3	1	5	2	3	2	4	3
Elektriciteit uit biomassa (PWh y^{-1})	1	0	2	1	1	1	2	1
Op overige, thans niet-commercieel aangewende gronden								
Primaire biomassa (hout)	243	266	173	148	47	39	35	32
Vloeibare brandstof uit biomassa	134	146	95	81	26	21	19	18
Elektriciteit uit biomassa (PWh y^{-1})	49	54	35	30	9	8	7	6

De resultaten zijn het hoogst voor de A1- en B1-scenario's. Beide gaan uit van een wereld waarin de wereldbevolking na een aanvankelijke toename daalt in het tweede deel van de eeuw. Tevens is er sprake van een hoge technologische groei in deze scenario's. De

60 Speciaal rapport over emissiescenario's.

voedselgewassen worden dan ook tegen hoge opbrengsten geproduceerd vanwege goed management. Het A2-scenario resulteert in het laagste biomassapotentieel. Het A2-scenario beschrijft een wereld met een snelgroeiende bevolking tot wel 15 miljard mensen in 2100. De technologieontwikkeling is laag en de wereld is sterk regionaal en economisch georiënteerd. Grootschalige handel in voedselproducten is niet verondersteld zodat voedselvoorziening binnen de regio moet plaatsvinden. In zo'n toekomstige wereld is de druk op het landgebruiksysteem bijzonder groot.

Hoofdstuk 4 gaat over de kosten-aanbodcurven van biomassa-energie voor het jaar 2050. Voor de landgebruiksscenario's uit *hoofdstuk 3* worden de regionale en mondiale kostenaanbod curven geconstrueerd van houtige korte-omloopenergiegewassen die geteeld worden op onbenutte landbouwgrond of overige, thans niet-commercieel aangewende gronden. Vier verschillende kostenfactoren zijn mee genomen, welk worden verondersteld zich in de tijd verschillend te ontwikkelen: land, transport, arbeids en kapitaalkosten. Arbeids en kapitaalinzet, zoals de hoeveelheid manjaren arbeid per jaar, worden verondersteld proportioneel met de productiviteit toe of af te nemen. Arbeidskosten worden verondersteld zich te ontwikkelen in lijn met het gemiddelde BNP in de regio. Wel is aangenomen dat bij toenemende arbeidslonen kapitaal-arbeidsubstitutie plaatsvindt. Dit houdt in dat als arbeid duurder wordt, er mechanisatie optreedt waardoor het aandeel arbeid in het productieproces afneemt. Verder is aangenomen dat bij toenemende productie, de kapitaal- en arbeidskosten dalen als gevolg van innovaties in de productiesystemen, waarbij men kan denken aan efficiëntere oogstmachines. De studie laat zien dat mogelijk grote hoeveelheden energiegewassen (ongeveer 130 – 270 EJ per jaar) in de toekomst kunnen worden geproduceerd tegen kosten die vergelijkbaar zijn met de huidige prijs van steenkool (tot 2 $ per GJ). Regio's met relatief lage kosten en hoge potentiëlen zijn het GOS, Australië, Oost- en West-Afrika en Oost-Azië (China). De meest aantrekkelijke regio's zijn verschillend per scenario. De genoemde lage kosten kunnen alleen worden bereikt door significante ontwikkelingen in de opbrengst van energiegewassen en kostendalingen als gevolg van technologisch leren en kapitaal-arbeidsubstitutie. Als we deze getallen gebruiken om de kosten van biobrandstoffen in te schatten komen we tot kostenniveaus die zo'n twee keer zo hoog zijn als huidige dieselproductiekosten. Elektriciteit uit biomassa zou mogelijk op grote schaal kunnen concurreren met CO_2-neutrale alternatieve opties in de elektriciteitssector, zoals elektriciteit uit fossiele bronnen waarbij gebruik is gemaakt van CO_2-afvangst en -opslag. De huidige wereldelektriciteitsconsumptie kan in 2050 worden geproduceerd tegen kosten van 4 – 4.5 ¢ per kWh in de A1- en B1-scenario's, en ongeveer 4.5 en 5.5 ¢ per kWh in de A2-en B2-scenario's. Beneden de 6 ¢ per kWh, kan zo'n 18 (A2) tot 53 (A1) keer de huidige elektriciteitsconsumptie worden geproduceerd.

In *hoofdstuk 5* concentreren we ons op elektriciteit uit wind. Er is een inschatting gemaakt van het regionale en mondiale geografische, technische en economische potentieel van elektriciteitsopwekking met windturbines. Daarbij hebben we ons beperkt tot terrestrische systemen. Ook in deze studie zijn kosten-aanbodcurven bepaald. Het mondiale technische potentieel van windelektriciteit is geschat op zo'n 96 TWh (terrawattuur) per jaar, dit is 6 keer het huidige wereldelektriciteitsgebruik. Om dit potentieel te realiseren is een gebied van 1.1 Gha nodig, waarbij de windturbines worden neergezet met een dichtheid van 4 MW km^{-2}. Dit is een gebied zo groot als China, waarbij de turbines geplaatst zijn met een dichtheid die 15 keer hoger is dan de huidige turbinedichtheid in Denemarken. Op regionale schaal is het hoogste potentieel gevonden voor de V.S. en lage waarden voor Zuid- en Zuidoost-Azië. Met de hedendaagse stand van de technologie kan het huidige mondiale elektriciteitsverbruik worden geproduceerd uit windenergie tegen kosten die tussen de 5 en 7 ¢ per kWh bedragen. Gemiddelde huidige kosten voor conventionele elektriciteit zijn 3 - 4 ¢ kWh^{-1}. Echter, kostendalingen van windelektriciteit zijn te verwachten voor de toekomst.

In *hoofdstuk 6* onderzoeken we het potentieel van elektriciteitsopwekking uit zonne-energie gebruikmakend van fotovoltaïsche (PV) systemen. Opnieuw is gekeken naar de kosten-aanbodcurven op mondiale en regionale schaal. Het technische potentieel bij de hedendaagse stand van de technologie wordt mondiaal geschat op zo'n 23 keer het huidige elektriciteitsverbruik wereldwijd. Hiervoor is een gebied nodig van zo'n 0.2 Gha. Dit komt overeen met een gebied zo groot als Soedan volgelegd met zonnecel-panelen. Het relatieve potentieel kan op regionaal niveau veel hoger zijn. In Afrika en Australië is het technische potentieel wel 1000 tot 4000 keer het elektriciteitsverbruik in deze regio's. Maar in Japan en West-Europa is het technische potentieel beperkt tot 0.6 en 2 keer het huidige elektriciteitsverbruik. Het huidige mondiale elektriciteitsverbruik kan echter alleen worden geproduceerd uit PV tegen kosten die veel hoger zijn dan wanneer windenergie of biomassa zou worden gebruikt, namelijk zo'n 44 tot 46 ¢ kWh^{-1}. Momenteel is zonne-energie te duur om op grote schaal concurrerend te zijn. Echter op lange termijn worden daarentegen grote technologische ontwikkelingen verwacht die de kosten significant kunnen reduceren tot zo'n 6 ¢ per kWh afhankelijk van de omstandigheden. Beneden de 6 ¢ per kWh zou dan een hoeveelheid elektriciteit kunnen worden opgewekt gelijk aan het huidige mondiale elektriciteitsgebruik. Grootschalig gebruik van zonne-energie zou wel betekenen dat Noord-Afrika en Australië grote hoeveelheden elektriciteit moeten gaan exporteren, wat additionele kosten met zich mee zou brengen.

In *hoofdstuk 7* worden voor West-Europa en de V.S. met behulp van het TIMER-EPG model (een elektriciteitsmodel) de kostenontwikkelingen van intermitterende bronnen (wind- en zonne-energie) verkend bij een toenemende penetratiegraad van deze bronnen in het elektriciteitssysteem. Hierbij is vooral naar windelektriciteit gekeken. Tevens is onderzocht hoeveel fossiele brandstof kan worden bespaard door windenergie en wat de daaraan gerelateerde kosten per vermeden ton CO_2 zijn. Bij deze analyses is veel dynamiek van het model, constant gehouden om een beter zicht te krijgen op de invloed van veranderingen in penetratiegraden van windenergie op de totale windenergie kosten en de hoeveelheid windenergie die kan worden opgenomen in het elektriciteitssysteem.

Bij toenemende penetratie van windvermogen in het systeem dalen in eerste instantie de totale kosten van windenergie als het gevolg van leergedrag. Echter, deze kostendaling wordt tegengewerkt door:

1. Het uitputtingseffect. Dit houdt in dat bij toenemende penetratiegraden steeds minder goede locaties zullen worden gebruikt, resulterend in oplopende kosten. Als 40% van de elektriciteitsvraag door windelektriciteit wordt bedekt, stijgen de kosten zo'n 25 tot 35% indien geen dalende kosten als gevolg van leergedrag worden aangenomen.
2. Additionele kapitaalkosten voor 'back-up' capaciteit, dat wil zeggen het extra vermogen dat geïnstalleerd moet worden om de betrouwbaarheid van het systeem te garanderen.
3. Verliezen van windenergie als gevolg van een beperking van de hoeveelheid windenergie die kan worden opgenomen door het systeem. In onze studie wordt windenergie weggegooid vanaf een penetratiegraad van zo'n 20%. Deze penetratiegraad is gelijk aan een productie van 500 (Europa) tot 750 (V.S.) TWh y^{-1}, ongeveer 10 (Europa) tot 70 (V.S.) keer de huidige elektriciteitsproductie van windturbines. Bij een penetratiegraad van 40% zijn de additionele kosten als gevolg van het de onbenutte windelectriciteit zo'n 50%.

De additionele kosten ten gevolge van het 'weggooien' van windelektriciteit zijn groter dan de andere twee factoren bij een penetratiegraad boven 30%.

Het gebruik van windenergie bespaart mogelijk voornamelijk gas en kolen in beide regio's. De CO_2-besparingskosten verschillen per regio. Dit komt omdat de elektriciteitsparken in beide regio's verschillen. De laagste kosten om een ton CO_2 te besparen is ingeschat op 15 en 35 $ per vermeden ton CO_2 in respectievelijk Europa en de V.S. De resultaten zijn echter erg gevoelig voor het technisch potentieel van de regio's (berekend in hoofdstuk 5 en 6) en systeemparameters zoals de transmissie en interconnectiecapaciteit (d.w.z. de mate van doorkoppeling met elektriciteitsystemen van buurlanden), opslagcapaciteit en de geografische verspreiding van de opgestelde windturbines. Windenergie zou een zeer aantrekkelijke energiebron kunnen zijn die tegen lage kosten beschikbaar kan komen en daarbij CO_2 kan besparen, bij hoog technisch potentieel (dat onder meer afhankelijk is van sociale acceptatie), als er goede opslagmogelijkheden zijn en een goede doorkoppeling met elektriciteitssystemen van buurlanden.

Samenvattend kunnen we concluderen dat de in dit proefschrift bestudeerde energiebronnen technologisch voldoende potentieel hebben om significant bij te dragen aan de toekomstige elektriciteitsvoorziening. Met elk van deze bronnen kan een meervoud van het huidige elektriciteitsverbruik worden geproduceerd. Zonne-energie heeft het grootste technische potentieel maar is niet op grote schaal beschikbaar tegen lage kosten. Verwacht wordt dat de kosten van zonne-energie binnen deze eeuw kunnen dalen tot niveaus in de orde van de huidige productiekosten van elektriciteit. Wind- en biomassa-elektriciteit zouden wel op korte termijn in voldoende mate tegen relatief lage kosten kunnen worden geproduceerd. Daarbij hangen de kosten van biomassa-energie vooral af van de technologische vooruitgang in de landbouw, de arbeidskosten, de kapitaal-arbeidverhouding en de landkosten. De kosten van windelektriciteit zijn op dit moment al betrekkelijk laag en bijna concurrerend. In hoeverre de kosten van windelektriciteit bij verregaande penetratie kunnen verder afnemen hangt zeer af van de beschikbare opslagcapaciteit, gezien het fluctuerende karakter van windenergie.

De ruimtelijk expliciete berekeningen die in dit proefschrift zijn uitgevoerd, geven nieuwe inzichten in het potentieel van hernieuwbare energiebronnen. In dit proefschrift zijn naast klimatologische karakteristieken ook gegevens over land en het gebruik van land op geografisch gedetailleerde schaal meegenomen. Deze aanpak is belangrijk gebleken, aangezien de toekomstige beschikbaarheid van hernieuwbare energiebronnen, met name biomassa-energie, sterk afhankelijk is van de toekomstige vraag naar land. Deze vraag is onder meer afhankelijk van ontwikkelingen in de bevolkingsgroei, het dieet, de landbouw, de bosbouw en de waarde die gehecht wordt aan natuur. Extreme aannames over deze invoerparameters laten zien dat de marges van het potentieel van biomassa-energie zeer uiteenlopen.

In dit onderzoek zijn hoge potentiëlen voor de winning van energie uit hernieuwbare bronnen gevonden in regio's met grote hoeveelheden beschikbaar land, zoals het GOS, Australië, Afrika en de V.S. Voor elk type technologie om de hernieuwbare energie te winnen is aangenomen dat het gebruikstype van het land waarop deze technologie bij voorkeur wordt geplaatst, verschillend is. Tevens is de geschiktheid van een landgebruikstype voor het plaatsen van een technologie verschillend voor de bekeken technologieën. Hierdoor varieert het aandeel van de verschillende bronnen over de regio's. Voor windelektriciteit kunnen hoge beschikbaarheden tegen relatief lage kosten worden gerealiseerd in Canada, de V.S., Zuid-Amerika, het GOS, Australië en West-Europa. Voor zonne-elektriciteit worden bij de laagste opwekkosten grote potentiëlen gevonden in Afrika, het Midden-Oosten, Australië en Zuid-Azië. Voor biomassa is de aantrekkelijkheid van de verschillende de regio's afhankelijk van het scenario voor de ontwikkeling van economie, demografie en landgebruik, dat wordt gevolgd, hoewel het GOS, Afrika, de V.S., Australië en Canada in alle scenario's interessante gebieden zijn. Zij hebben een hoog potentieel voor de teelt van energiegewassen tegen relatief lage kosten.

Bij het analyseren van de resultaten van dit proefschrift dient opgemerkt te worden dat veranderingen in landgebruikspatronen zijn meegenomen, echter alleen voor biomassa-energie. Beargumenteerd is dat dit minder van belang is voor de andere bronnen. Naast de ruimtelijk expliciete methode, is ook de gestructureerde aanpak ten aanzien van de verschillende categorieën van potentiëlen informatief gebleken. Deze indeling verhoogt het inzicht in het belang van de verschillende factoren die een rol spelen en de beschikbare hoeveelheid hernieuwbare energie beperken, bijvoorbeeld de beschikbare hoeveelheid land bij windenergie en de kosten bij zonne-energie. Tevens biedt het gebruik van de kosten-aanbod curven een goede basis om het economisch potentieel te schatten door de curven te vergelijken met andere beschikbare energiebronnen.

Op basis van bovengenoemde overwegingen en de resultaten van dit proefschrift, doen we enkele aanbevelingen voor verder onderzoek:

- Om te komen tot een meer volledige beschirjving van het wereldpotentieel van hernieuwbare energie, kan de potentieelstudie uitgebreid worden met analyses naar het potentieel van hernieuwbare energiebronnen die mogelijk interessant zijn in termen van potentiële beschikbaarheid en kosten. Men kan denken aan offshore windenergie en kleinschalige waterkracht.
- We hebben een analyse uitgevoerd naar de toekomstige regionale en mondiale beschikbaarheid van biomassa voor energietoepassingen, gebruik makend van informatie op gridcelniveau. Vergelijkbare studies op lokale of nationale schaal zijn nodig om locaties te identificeren waar energieplantages zouden kunnen worden neergezet. Deze studies zouden dan ook meer gedetailleerde informatie mee kunnen nemen over bijvoorbeeld landeigenaarschap en over de technologieën die ter plaatse beschikbaar zijn. Zulke meer lokale studies kunnen ook een beter inzicht verschaffen in onzekere factoren in onze studies, zoals de kapitaal-arbeidsubstitutiecoëfficiënt.
- Gezien de resultaten van dit proefschrift, kan worden aanbevolen dat, wanneer lange-termijnkosten van wind- en zonne-energie worden bestudeerd, het belangrijk is ook de additionele kosten voor de integratie in het net in rekening te brengen. In dit proefschrift zijn deze kosten onderzocht op regionale schaal door de vraag naar elektriciteit constant te houden. Het is tevens interessant een verdergaande analyse te doen waarbij ook dynamische vraag wordt meegenomen en verschillende scenario's wat betreft vraag en aanbod worden verkend.
- Een geïntegreerde analyse van de beschikbaarheid van land waarbij de drie bronnen samen worden bekeken, kan nieuwe inzichten geven in gebieden waar concurrentie tussen de drie bronnen zou kunnen optreden. Dit kan een aanleiding zijn voor het ontwikkelen van en het nadenken over, mogelijkheden voor multifunctioneel landgebruik.
- Aangezien dit proefschrift gaat over potentiële beschikbaarheid waarbij een aantal institutionele en sociale factoren buiten beschouwing zijn gelaten, moeten de potentieelschattingen gezien worden als bovengrenzen van wat in de praktijk gerealiseerd kan worden. Voorbeelden van mogelijke barrières bij het benutten van het potentieel zijn horizonvervuiling als het gaat om het plaatsen van windturbines en zorg over vermindering van biodiversiteit bij grootschalige toepassingen van energieplantages. In hoeverre de potentiëlen ook daadwerkelijk benut kunnen worden, is niet bestudeerd in dit proefschrift. Dit zou wel verder onderzocht kunnen worden binnen de context van de scenario's opgesteld door het IPCC, gebruikmakend van energiemodellen zoals het TIMER 2.0 model.

- Aangezien de resultaten van dit proefschrift dezelfde regionale aggregatie hebben als het TIMER 2.0 model, zouden in vervolgonderzoek geïntegreerde analyses kunnen worden uitgevoerd waarbij de concurrentie van hernieuwbare energiebronnen met conventionele energiebronnen in verschillende scenario's wordt bestudeerd als functie van de tijd.

REFERENCES

ABB, 1998, Renewable energy. Status and prospects, Baden-Dattwil.

Abed, K. A. and A. A. El-Mallah, 1997, Capacity factor of wind turbines, Energy, 22(5), pp: 487-491.

Ackermann, T. and L. Soeder, 2002, An overview of wind energy-status 2002, Renewable & sustainable energy reviews, pp: 667-128.

AEA Technology, 2001, Comparison of public acceptibility of energy from waste and energy from biomass residues in 5 EU states, Oxfordshire, pp: 210.

Agterberg, A. and A. Faaij, 1998, Bio-energy trade: possibilities and constraints on short and longer term, Utrecht University, Department of Science, Technology and Society.

Ahmed, K., 1994, Renewable energy technologies. A review of the status and costs of selected technologies, Washington, Worldbank, pp: 169.

Alcamo, J., R. Leemans, E. Kreileman, 1998, Global change scenarios of the 21st century. Results from the IMAGE 2.1 model, Oxford, Pergamon, pp: 296.

Alsema, E., 2003, Personal communication on BOS costs, February 2003, Utrecht University.

Alsema, E. and M. van Brummelen, 1993, Het potentieel van pv-systemen in OECD landen, Utrecht University, Department of Science, Technology and Society, pp: 53.

Alsema, E. A. and E. Nieuwlaar, 2000, Energy viability of photovoltaic systems, Energy policy, 28, pp: 999-1010.

Alsema, E. A., A. J. M. van Wijk, W. Turkenburg, 1983, The capacity credit of grid-connected photovoltaic systems, In: Fifth E.C. Photovoltaic solar energy conference, Athens (Greece), D. Reidel Publisher Company.

Amous, S., 1999, The role of wood energy in Africa, Tunis/Rome, APEX-ebbd.

Anonymous, 2002a, Grid stability and expansion challenges, Wind Power Monthly, October, pp: 2.

Anonymous, 2002b, Impressive capacity figures for Minnkota in US, Wind Power Monthly, April, p: 1.

Anonymous, 2002c, Wind weakening system security. Spain's isolated grid, Wind Power Monthly, July 2002, p: 1.

Anonymous, 2003a, Eon use forecasting model for predicting wind, Wind Power Monthly, February, 2003, p: 1.

Anonymous, 2003b, Tararua wind farm at top of output league table, Wind Power Monthly, April, p: 1.

Argote, L. and D. Epple, 1990, Learning curves in manufacturing, Science, 247 (February), pp: 920-924.

Audus, H., 2000, The treatment of technology development in energy models, Int. J. Global Energy 13(1-3), pp: 58-68.

AWEA, 1998, Wind energy and climate change, available at. *www.awea.org*, pp: 15.

AWEA, 2000, Wind energy outlook, Washington, American Wind Association, pp: 4.

Azar, C. and G. Berndes, 1999, The implication of carbon dioxide abatement policies on food prices, In: Sustainable agriculture and environment globalisation and the impact of trade and liberalisation, Eds: A. K. Dragun and C. Tisdell, Edward Edgar Publisher, pp: 153 - 168.

Azar, C. and E. D. Larson, 2000, Bioenergy and land-use competition in Northeast Brazil, Energy for sustainable development, 4(3), pp: 51-58.

Baltus, C. W. A., E. A. Alsema, A. Reinders, J. Boumans, R. J. C. van Zolingen, B. C. Middelman, 1997, Aanbevolen werkwijze voor de monitoring van netgekoppelde PV-systemen in Nederland, Utrecht**,** pp:45.

Battjes, J. J., 1994, Global options for biofuels from plantations according to IMAGE simulations, Interfacultaire Vakgroep Energie en Milieukunde (IVEM), Rijksuniversiteit Groningen, The Netherlands.

de Beer, J., 1998, Potential for industrial energy-efficiency improvement in the long term, Utrecht University, pp: 277.

Belward, A. and T. Loveland, 1995, The IGBP-DIS 1 km land cover project, In: Remote Sensing in Action, Eds: C. P.J. and Y. C. Robertson. Southampton, Univerity of Southampton, pp: 1099-1106.

Berndes, G., 2002, Bioenergy and water-the implications of large-scale bioenergy production for water use and supply, Global Environmnetal Change, 12, pp: 253 - 271.

Berndes, G., M. Hoogwijk, R. van den Broek, 2003, The contribution of biomass in the future global energy system: a review of 17 studies, Biomass and Bioenergy, 25(1), pp: 1 - 28.

Betcke, J., 1995, High voltage direct current transmission: wind by wire, Utrecht University, Departemnet of Science, Technology and Society, pp: 41.

Betcke, J. W. H., V. A. P. van Dijk, L. A. M. Ramaekers, R. J. C. van Zolingen, 1998, Evaluation of irradiation measurements on tilted planes at PV systems in the Netherlands, In: Second World Conference and Exhibition on Solar Energy Conversion, Vienna, pp: 4.

Betcke, J. W. M., W. G. J. H. M. van Sark, W.C. Turkenburg, 2003, Evaluation of the performance of PV system designs in The Netherlands in 1991-2002, technical monitoring and simulation, submitted to Progress in Photovoltaics.

Beurskens, H. J. M., 1999, Trends in the development and implementation of wind energy technology, In: AWEA Conference, Burlington USA.

Biewinga, E. E. and G. van der Bijl, 1996, Sustainability of energy crops in Europe; a methodology developed and applied, Utrecht, CLM, pp: 209.

Bouwman, A. F., B. Eickhout, I. Soenario, 2004, Exploring changes in world ruminant production systems, to be submitted to Agricultural Systems.

BP, 2002, BP statistical review of world energy 2002, available at: *www. bp.com.*

Brand, A. J. and J. K. Kok, 2003, Aanbodvoorspeller duurzame energie, Petten, ECN, pp: 90.

British Wind Energy Association, 2000, Planning for wind energy. A guide for regional targets. London, BWEA, pp: 23.

van den Broek, R., A. Faaij, A. van Wijk, T. Kent, M. Bulfin, K. Healion, G. Blaney, 1997, Willow firing retrofitted irisch peat power plants, Biomass and Bioenergy, 12(2), pp: 75 - 90.

van den Broek, R., A. van Wijk, W. Turkenburg, 2000, Farm-based versus industrial eucalyptus plantations for electricity generation in Nicaragua, Biomass and Bioenergy, 19(5), pp: 295 - 310.

van den Broek, R., 2000, Sustainability of biomass electricity systems. An assessment of costs, macro-economic and environmental impacts in Nicaragua, Ireland and the Netherlands, Utrecht University, pp: 215.

van den Broek, R., S. Teeuwisse, K. Healion, T. Kent, A. van Wijk, A. Faaij, W. Turkenburg, 2001, Potentials for electricity production from wood in Ireland, Energy, 26, pp: 991 - 1013.

van den Broek, R., A. van Wijk, W. Turkenburg, 2002, Electricity from energy crops in different settings. A country comparison between Nicaragua, Ireland and the Netherlands, Biomass and Bioenergy 22(2), pp: 79 - 98.

Brower, M. C. and M. W. Tennis, 1995, Catching a steady breeze: puytting wind power to work on electric utility systems, The Electricity Journal, March, pp: 32 - 41.

Bruton, T. M., J. M. Woodcock, B. Garrard J. Alonso, J. Nijs, A. Räuber, A. Vallêra, H. Schade, E. Alsema, R. Hill, B. Dimmler, 1996, Multi-Mega upscaling of silicon and thin film solar cell and modules manufacturing, ' MUSIC FM', Sunbury-on-thames, pp: 24.

BTM, C. A., 2001, International wind energy development, World market update, 2000, BTM Consult Aps, pp: 65.

Bucher, K., 1997, Site dependence of the energy collection of PV modules, Solar Energy, 47, pp: 85 -94.

Bundesverband Wind Energie, 2003, German wind power still flying high, Osnabrück**,** p: 1.

Bundesverband WindEnergie, 2001, Windenergie 1995 - 2000, Osnabrück.

Butti, K. and J. Perlin, 1980, Golden thread, London, Marion Boyars Publishers Ltd.

Cabooter, Y., L. DeWilde, M. Langie, 1997, An inventory of locations suitable for wind energy in Flanders region, V.U.B, O.D.E., pp: 7.

Cabooter, Y., L. Dewilde, M. Langie, 1999, An inventory of locations suitable for wind energy in Flanders regions, In: European Wind energy Conference, Nice, France.

Centraal Bureau voor de Statistiek, 2002, StatLine, available at: *www.cbs.nl*, Voorburg/Heerlen, CBS.

Chabot, B., 1999, From costs to prices: how to determine tariffs to secure a private development of wind power, In: European Wind Energy Conference, Nice, France.

Chapman, J. and S. Wise, 1998, Expanding wind power: Can Americans afford it? pp: 25.

Chum, H. L. and R. P. Overend, 2001, Biomass and renewable fuels, Fuel processing technology, 71, pp: 187 - 195.

Coelman, B. T., 1996, Mogelijkheden voor kleinschalige energie-opwekking met geteelde biomassa, Wageningen, CPV, IMAG-DLO, ECN.

Cooper, 1969, The absoprtion of solar radiation in solar stills, Solar Energy, 12(3).

Criqui, P., 1996, International markets and energy prices, the POLES model, In: Models for energy policy, Eds: J.B. Lesourd, J. Percebois and F. Valette. London, New York, Routledge, pp: 253 (14 - 29).

Dalton, T. J., W. A. Master, K. A. Foster, 1997, Production cost and input substitution in Zimbabwe's smallholder agriculture, Agricultural Ecnomics, 17, pp: 201 - 209.

Danish Wind Industry Association, 2002, Wind energy policy in Denmark, status 2002, available at *www.windpower.org*.

Danish Wind Industry Association, 2001, available at*: www.windpower.dk*.

David, J. and H. Herzog, 2000, The cost of carbon capture, In: 5th international conference of greenhouse gas control technologies (GHGT-5), Cairns, Australia.

Davis, S. C., 2001, Transportation Energy Book, Oak Ridge, DOE, pp: 197.

De la Torre Ugarte, D. G., M. E. Walsh, H. Shapouri, S. P. Slinsky, 2000, The economic impacts of bioenergy crop production on U.S. Agriculture, Tennessee, APAC, DOE-ORNL, pp: 40.

Decker, B. and U. Jahn, 1997, Performance of 170 grid connected PV plants in Northern Germany-analysis of yields and optimization potentials, Solar Energy, 59(4 - 6), pp: 127 - 133.

Dessus, B., B. Devin, F. Pharabob, 1992, World potential of renewable energies, Paris, CNRS - PIRSEM, pp: 70.

Dodge, D. M., 2001, Illustrated history of wind power development, TelosNet.

Döös, B. R. and R. Shaw, 1999, Can we predict the future food production? A sensitivity analysis, Global Enviromental Change, 9(4), pp: 261 - 283.

Dornburg, V., 1999, A System analysis of biomass energy systems in relation to scale, Utrecht University, Department of Science, Technology and Society.

Dornburg, V. and A. Faaij, 2001, Efficiency and economy of wood-fires biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies, Biomass and Bioenergy, 21, pp: 91 - 108.

Dornburg, V., G. Termeer, A. Faaij, 2003, Economic and greenhouse gas emission analysis of bio-energy production using multi-product crops. Case studies for the Netherlands and Poland, submitted to Biomass and Bioenergy.

Duffie, J. A. and W. A. Beckman, 1991, Solar engineering of thermal process, 2nd edition, New York, John Wiley & Sons, Inc.

ECE/FAO, 2000, Forest Products Annual Markets Review, 1999-2000, ECE/FAO, pp: 3.

Edmonds, J. A., M. A. Wise, R. D. Sands, R. A. Brown, H. Kheshgi, 1996, Agriculture, land use and commercial biomass energy, Pacific Northwest National laboratory, pp: 25.

EIA, 1999, Assumptions to the annual energy outlook 1999. Renewable Fuels Module, pp: 9.

Elliot, D. L., C. G. Holladay, W. R. Barchet, H. P. Foote, W. F. Sandusky, 1986, Wind energy resource atlas of the United States, Golden, Colorado, Pacific Northwest Laboratory, pp: 210.

Elliot, D. L. and M. N. Schwartz, 1993, Wind energy potential in the United States, Pacific Northwest Laboratory.

den Elzen, M. and S. Both, 2002, Modelling emissions trading and abatement costs in FAIR 1.1. Case study: The Kyoto Protocol under the Bonn-Marrakesh Agreement, Bilthoven, pp: 67.

EPIA and Greenpeace, 2002, Solar generation, Brussels, pp: 26.

Ericsson, K. and L. J. Nillson, 2003, International biofuel trade. A study of the Swedich import, Biomass and Bioenergy, in press.

European Commission, 1999, Wind Energy: the Facts, Luxembourg, European Commission.

EWEA, 2001, European Review: the top 12 markets, Wind directions, available at *www.ewea.org.*

EWEA, 2003, 86 Million Europeans to get power from the wind by 2010. Wind industry sets bigger target for Europe, Brussel, p: 1.

EWEA and Greenpeace, 2002, Windforce 12, A blueprint to achieve 12% of the world's electricity from wind power by 2020, pp: 50.

Faaij, A., C. Harmelinck, M. Tijmensen, 2000, Long term perspectives for production of fuels from biomass: integrated assessment and R&D priorities. Preliminary results, In: First World Conference and Exhibition on Biomass for Energy and Industry, Sevilla.

Faaij, A., B. Meuleman, R. van Ree, 1998, Long term perspectives of biomass integrated gasification/combined cycle (BIG/CC) technology: costs and efficiency and a comparison with combustion, Utrecht University, Department of Science, Technology and Society, pp: 93.

FAO, 1981, Report on the Agro-Ecological Zones Project. Volume 3: Methodology and results for South and Central America, World Soil Resources, Rome.

FAO, 1996, World livestock production systems. Current status, issues and trends, Rome**,** pp: 83.

FAO, 1997, Statistics on prices paid by farmers for means of production, Rome.

FAO, 2000, Agriculture: Towards 2015/2030. Technical Interim report, Rome.

FAO, 2001, Forestry statistics, available at: *www.fao.org.*

FAO, 2003, FAOSTAT, Agricultural statistics, available at: *www.fao.org.*

Faundez, P., 2003, Potential cost of four short-rotation silvicultural regimes used for the production of energy, Biomass and Bioenergy, 24(4-5), pp: 373 - 380.

de Feber, M. and D. Gielen, 2000, Mogelijke toekomstige wereldwijde vraag naar biomassa als materiaalbron, In: Beschikbaarheid biomassa voor energieopwekking, GRAIN: Global restrictions on biomass Availability for Import to the Netherlands, Utrecht.

Fellows, A., 2000, The potential of wind energy to reduce carbon dioxide emissions, Glasgow, Garrad Hassan, pp: 146.

FGW and ISET, 2000, Increasing the penetration of wind energy in the European electricity network, Fordergesellschaft Windenergie, Institut fur Solar Energieversorgungstechnik, pp: 47.

Fischer, G. and L. Schrattenholzer, 2001, Global bioenergy potentials through 2050, Biomass and Bioenergy, 20(3), pp: 151 - 159.

Fujino, J., K. Yamaij, H. Yamamoto, 1999, Biomass-Balance Table for evaluating bioenergy resources, Applied energy, 63, pp: 75 - 89.

Gardner, P., H. Snodin, A. Higgins, S. McGoldrick, 2003, The impacts of increased levels of wind penetration on teh electricity systems of the Republic of Ireland and Northern Ireland. Glasgow, Garrad Hassan and Partners, pp: 103.

German Advisory Council on Global Change (WBGU), 1999, World in transition. Conservation and sustainable use of the biosphere, Bremerhaven, WBGU, pp: 441.

Giebel, G., 2000a, On the benefits of distributed generation of wind energy in Europe, University of Oldenburg, pp: 104.

Giebel, G., 2000b, Equalizing effects of the wind energy production in Northern Europe determined from reanalysis data, Roskilde, Risoe, pp: 20.

Gielen, D., S. Bos, M. de Feber, T. Gerlach, 2000, Biomass for Greenhouse Gas Emission Reduction. Task 8: Optimal emission reduction strategies for Western Europe, Petten.

Gielen, D. J. and H. Yagita, 2002, The long-term impact of GHG reduction policies on global trade: A case study for the petrochemical industry, European Journal or Operational Research, 139, pp: 665-681.

Goldemberg, J., 2000, World Energy Assessment, New York, United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council, pp: 508.

Goldemberg, J. and T. B. Johansson, to be published, Energy and the Challenge of sustainability. The 2003 overview update.

Goldemberg, J., T. B. Johansson, A. K. N. Reddy, R. H. Williams, 1988, Energy for a sustainable world, New York, John Wiley & sons.

Graham, R., L. E. Lichtenberg, V. O. Roningen, H. Shapouri, M. E. Walsh, 1995, The economics of biomass production in the United States, In: Second Biomass Conference of the Americas: Energy, Environment, Agriculture, and Industry, Portland, NREL.

Grainger, A., 1988, Estimating areas of degraded tropical lands requiring replenishment of forest cover, The International Tree Crops Journal, pp: 531 - 61.

Graveland, C., A. F. Bouwman, B. de Vries, B. Eickhout, B. Strengers, 2002, Projections of multi-gas emissions and carbon sinks, and marginal abatement cost functions modelling for landuse related sources, Bilthoven, RIVM, pp: 92.

Green, M. A., 1982, Solar cells: Operating principles, technology and system applications, Kensington, The University of New South Wales.

Green, M. A., 2000, Photovoltaics: technology overview, Energy Policy, 28, pp: 989 - 998.

Green, M. A., K. Emery, K. Emery, D. L. King, S. Igari, W. Warta, 2003, Solar cell efficiency tables (Version 21), Progress in photovoltaics research and applications, 11, pp: 39 - 45.

Grubb, M. J., 1988, The economic value of wind energy at high power system penetrations: ananalysis of models, sensitivity and assumptions, Wind engineering, 12(1), pp: 1 - 26.

Grubb, M. J. and N. I. Meyer, 1993, Wind energy: Resources, systems, and regional strategies, In: Renewable energy: Sources for fuels and electricity, Eds: T. B. Johansson, H. Kelly, A. K. N. Reddy and R. H. Williams, Washington, D.C., Island Press, pp: 157 - 212.

Grübler, A., 1998, Technology and global change, Laxenburg, Cambridge University Press.

Grübler, A., M. Jefferson, A. McDonald, S. Messner, N. Nakicenovic, H-H. Rogner, L. Schrattenholzer, 1995, Global Energy Perspectives to 2050 and Beyond, World Energy Council (WEC)/International Institute for Applied Systems Analysis (IIASA).

Hakes, J., 2000, Long term world oil supply, Washington, EIA, pp: 27.

Hall, D. O., F. Rosillo-Calle, R. H Williams, J. Woods, 1993, Biomass for energy: supply prospects, In: Renewable energy: Sources for fuels and electricity, Eds: T.B.Johansson, H. Kelly, A. K. N. Reddy and R. H. Williams, Washington, Island Press, pp: 1160.

Hamelinck, C., A. Faaij, H. den Uil. H. Boerrigte, 2003a, Production of FT transportation fuels from biomass: technical options, process analysis and optimisation and development potential, Energy, the International journal, submitted.

Hamelinck, C., R. A. A. Suurs, A. Faaij, 2003b, International bioenergy transport costs and energy balances, Utrecht, Utrecht University, Copernicus Institute, pp: 53.

Harmon, C., 2000, Experience curves of photovoltaic technology, Laxenburg, IIASA, pp: 17.

van de Haspel, B, R. Winter, F. Corten, 1993, Een methodiek voor de analyse van het potentieel van zonnecellen op daken en gevels in Nederland, Delft, CE, pp: 50.

Heilman, P. and R. J. Norby, 1998, Nutrient cycling and fertility management in temperate short rotation forest systems, Biomass and Bioenergy, 14(4), pp: 361 - 370.

Heller, M., G. A. Keoleian, T. A. Volk, 2003, Life cycle assessment of a willow bioenergy cropping system, Biomass and Bioenergy, 25(2), pp: 147-165.

Hillring, B., 1999, Price formation on the Swedish woodfuel market, Biomass and Bioenergy, 17, pp: 445 - 454.

Hoffman, W., 2001, PV solar electricity: one among the new millenium industries, In: 17th European Photovoltaic Solar Energy and Conference, Munich.

Hofman, Y., D. de Jager, E. Molenbroek, F. Schilig, M. Voogt, 2002, The potential of solar electricity to reduce CO_2 emissions, Utrecht, Ecofys, pp: 106.

Holdren, J. P. and K. R.Smith, 2000, Energy, the environment and health, In: World Energy Assessment, Eds: J. Goldemberg, Washington D.C., pp: 61 - 110.

Hoog Antink, E., 2000, PV Offshore: A pre-feasibility study of a large-scale offshore photovoltaic system, Leusden, ETC Energy, Utrecht University, pp: 64.

Hoogwijk, M., 1998, Crop modelling of Eucalyptus plantations in Nicaragua, Utrecht University, Department of Science, Technology and Society, pp: 31.

van Hooijdonk, G., 2002, Future prospects for ethanol production from ligno-cellulosic biomass. Utrecht, Utrecht University, Copernicus Institute, Science Technology and Society, pp: 78.

Houghton, R. A., 1990, The future role of tropical forests in affecting the carbon dioxide concentration of the atmosphere, Ambio, 19(4), pp: 204 - 209.

Houghton, R. A., J. Unruh, P.A. Lefevre, 1991, Current land use in the tropics and its potential for sequestering carbon, In: Technical workshop to explore options for global forestry management, Bangkok, Thailand, International Institute for Environment and Development.

Hughes, E. E. and G. A. Wiltsee, 1995, Comparative evaluation of fuel costs from energy crops, In: Second Biomass Conference of the Americas: Energy, Environment, Agriculture and Industry, Portland, Oregon, NREL.

IEA/OECD, 2000a, Trends in photovoltaic applications in selected IEA countries between 1992 and 1999, Paris.

IEA/OECD, 2000b, Experience curves for energy technology policy, Paris, pp: 127.

IEA/OECD, 2001a, Potential for building intergated photovoltaics, Paris, pp: 11.

IEA/OECD, 2001b, OECD balances of non-OECD countries 1999 - 2000, Paris.

IEA/OECD, 2002a, World energy Outlook 2002, Paris, pp: 523.

IEA/OECD, 2002b, Energy Statistics & Balances, Paris.

IEA/OECD, 2003, Key World Energy Statistics, Paris.

IEPE, 1998, Technology improvement dynamics database developed under the EU-DG Research Sapient project, Grenable, pp: 40.

IMAGEteam, 2001, The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st Century, CDRom, Bilthoven, National Institute for Public Health and the Environment.

de Jager, D., A. P. C. Faaij, W. O. Troestra, 1998, Kosten-effectiviteit van transportbrandstoffen uit biomassa, Utrecht, NOVEM, pp: 82.

Johansson, T. B., H. Kelly, A. K. N. Reddy and R. H. Williams, 1993, Renewable fuels and electricity for a growing world economy. Defining and achieving the potential, In: Renewable energy: Sources for fuels and electricity, Eds: T. B. Johansson, H. Kelly, A. K. N. Reddy and R. H. Williams. Washington, D.C., Island Press, pp: 1 - 71.

Junginger, M., 2000, Experience curves in the wind enery sector. Use analysis and recommendations. Utrecht University, Department of Science, Technology and Society, pp: 33.

Junginger, M., A. Faaij, W. Turkenburg, 2003, Global experience curve for wind farms, Energy Policy, in press.

Junginger, M., A. Faaij, R. van den Broek, A. Koopmans, W. Hulscher, 2001, Fuel supply strategies for large-scale bio-energy projects in developing countries, Electricity generation from agricultural and forest residues in Northeastern Thailand, Biomass and Bioenergy, 21(4), pp: 259 - 275.

Kaltschmitt, M., G. A. Reinhardt, T. Stelzer, 1997, Life cycle analysis of biofuels under different environmental aspects, Biomass and Bioenergy, 12(2), pp: 121 - 134.

Kelly, H., 1993, Introduction to photovoltaic technology, In: Renewable energy: sources for fuels and electricity, Eds: T. B. Johansson, H. Kelly, A. K. N. Reddy and R. H. Williams, Washington D.C., Island Press, pp: 297 - 336.

Kemp-Benedict, E., C. Heaps, P. Raskin, 2002, Global scenarios group futures. Technical notes. Stockholm, Stockholm Environmeny Institute, Global Scenario Group, pp: 264.

Kgathi, D. L. and M. B. M. Sekhwela, 1998, Southern Africa's Savannas: Sustainable management of natural resources, Botswana, University of Botswana, pp: 15.

King Hubbert, M., 1971, The energy resources of the earth, Scientific American, 225, pp: 60-84.

Kunte, A., K. Hamilton, J. Dixon, M. Clemens, 1998, Estimating national wealth: Methodology and results, Indicators and environmental valuation. Washinton, D.C., The World Bank, pp: 44.

Kurokawa, K., 2003, Energy from the desert: feasibility of very large scale photovoltaic power generation (VLS-PV) systems, London, James & James.

Kurokawa, K., T. Takashima, T. Hirasawa, T. Kichimi, T. Imura, T. Nishioka, H. Itsuka, N. Tashiro, 1997, Case studies of large-scale PV systems distributed around desert area of the world, Solar Energy Materials and Solar Cells, 47, pp: 189 - 196.

Laali, A. R., A. Louche, L-J Meyer, 1996, Influence of wind farm capacity, turbine size and wind speed on production cost: analysis of the actual market trend, In: European Union Wind Energy Conference, Göteborg.

Larson, E. D. and H. Jin, 1999, Biomass conversion to Fischer-Tropsch Liquids: Preliminary Energy Balances, In: Fourth biomass conference of the Americas, Oakland, Elsevier Science ltd., Oxford.

Larson, E. D. and R. H. Williams, 1995, Biomass plantation energy systems and sustainable development, In: Energy as an instrument for socio-economic development, Eds: J. Goldemberg and T. B. Johansson. New York, United Nations Development Programme¸ pp: 16.

Lashof, D. A. and D. A. Tirpak, Eds., 1990, Policy options for stabilizing global climate, New York, Washington, Philadelphia, London, Hemisphere Publishing Corporation.

Laukamp, H., 2002, Photex. Cost reduction potential for residential PV systems, Freiburg, Fraunhofer-Institut, pp: 5.

Lazarus, M., 1993, Towards a Fossil free Energy Future, Boston, Stockholm Environment Institute, pp: 240.

Leach, G., 1995, Global land & food in the 21st century. Trends and issues for sustainability. Stockholm, Stockholm Environmental Institute, pp: 90.

Leemans, R., A. van Amstel, C. Battjes, E. Kreileman, S. Toet, 1996, The land cover and carbon cycle consequences of large-scale utilization of biomass as an energy source, In: Global change scenarios of the 21 the century, Eds: J. Alcamo, R. Leemans and E. Kreileman, Oxford, Pergamon, pp: 235 - 257.

Leemans, R. and G. J. van den Born, 1994, Determining the potential distribution of vegetation, crops and agricultural productivity, In: IMAGE 2.0: Integrated modeling of global climate change, Ed: J. Alcamo, Dordrecht, Kluwer Academic Publishers.

Leemans, R., B. Eickhout, B. Strengers, L. Bouwman, M. Schaeffer, 2002, The consequences of uncertainties in land use, climate and vegetation responses on the terrestrial carbon, Science in China (Series C), 45, pp: 126 - 142.

Lefevre, T., J. L. Todoc, G. R. Timilsina, 1997, The Role of Wood Energy in Asia, Bangkok/Rome, Asian Institute of Technology, pp: 107.

Lemming, J., P. E. Morthorst, L. H. Hansen, P. D. Andresen, P. H. Jensen, 1999, O&M costs and economical lifetime of wind turbines, In: European Wind energy conference, Nice.

Lesourd, J. B., 2001, Solar photovoltaic systems: the economics of a renewable energy resource, Environmental modelling and software, 16, pp: 147 - 156.

Leutz, R., T. Ackermann, A. Suzuki, A. Akisawa, T. Kashiwagi, 2001, Technical offshore wind energy potentials around the globe, In: European Wind Energy Conference and Exhibition, Copenhagen, Denmark.

Lewandowski, I., 2001, Energiepflanzenproduktion, In: Energie aus Biomass. Grundlagen, Techniken und verfahren, Eds: M. Kaltschmitt and H. Hartmann, Berlin, Springer, pp: 57 - 93.

Loveland, T. R. and A. S. Belward, 1997, The IGBP-DIS global 1 km cover data set Discover. First results, Int. J. Remote Sens., 18, pp: 3289 - 3295.

Luyten, J. C., 2001, personnal communication on the food security factor, December 2001, Washington.

Luyten, J. C., 1995, Sustainable world food production and environment, Wageningen, AB-DLO Delft Hydraulics.

Lynd, L. R., 1996, Overview and evaluation of fuel ethanol from cellulosic biomass: technology, economics, the environment, and policy, Annual reviews, energy environment, 21, pp: 403 - 465.

Lysen, E. H., 1982, Introduction to wind energy, Amersfoort, SWD, Steering Committee Wind Energy Developing Countries, pp: 310.

Mackay, R. M. and S. D. Probert, 1998, Likely market-penetrations of renewable energy technologies, Applied Energy, 59(1), pp: 1 - 38.

Manne, A., R. Mendelsohn, R. G. Richels, 1995, MERGE: A model for evaluating regional and global effects of GHG reduction policies, Energy policy, 23(1), pp: 17 - 34.

Marrison, C. I. and E. D. Larson, 1995, Cost versus scale for advanced plantation-based biomass energy systems in the USA and Brazil, In: Second Biomass Conference of the Americas, Portland OR.

Matthies, H. G., C. Nath, T. E. Schellin, A. D. Garrad, M. A. Wastling, D. C. Quarton, J. Wei, M. Scherweit, T. Siebers, 1995, Study of offshore wind energy in the EC, Brekendorf, Verlag Natuerliche Energie.

Maycock, P., 2002, The world PV market. Production increases 36%, Renewable energy world, 5, pp: 147 - 161.

Maycock, P., 2003, Global PV shipments, PV News, pp: 22.

McDonald, A. and L. Schrattenholzer, 2001, Learning rates for energy technologies, Energy Policy 29, pp: 255 - 261.

McDonald, A. and L. Schrattenholzer, 2002, Learning Curves and Technology Assessment, International Journal of Technology Management, 23(7/8), pp: 718 - 745.

Messner, S. and L. Schrattenholzer, 2000, MESSAGE-MACRO: linking an energy supply model with a macro-economic module and solving it iteratively, Energy, 25, pp: 267 - 282.

Milligan, M. R., 2002, Modeling utility-scale wind power plants part 2: Capacity credit, Golden, National Renewable Energy Laboratory, pp: 21.

Moreira, J. R. and J. Goldemberg, 1999, The alcohol programme, Energy Policy, 27, pp: 229 - 245.

Morthorst, P. E., 1998, Wind power development-status and perspectives, Roskilde, Risoe National Laboratory, pp: 27.

Nakicenovic, N., 2000, Special Report on Emission Scenarios, Cambridge University Press.

National Wind Coordinating Committee, 1997, Wind energy resources, Wind energy series, pp: 4.

Neij, L., 1999, Cost dynamics of wind power, Energy, 24, pp: 375 - 389.

New, M., M. Hulme, P. Jones, 1997, A 1961-1990 mean monthly climatology of global land areas, Norwich, Climate Research Unit.

New, M., M. Hulme, P. Jones, 1999, Representing twentieth century space-time climate variability, Part I: Development of a 1961-91 mean monthly terrestrial climatology, American Meteorological Society March 1999, pp: 820 - 856.

de Noord, M., 1999, Large scale offshore wind energy: Costs analysis and integration in the Dutch electricity market, Petten, ECN.

Oliver, M. and T. Jackson, 2000, The evolution of economic and environmental cost of crystalline silicon photovoltaics, Energy Policy, 28, pp: 1011 - 1021.

Oliver, M. and T. Jackson, 2001, Energy and economic evaluation of building-integrated photovoltaics, Energy, 26, pp: 431 - 439.

Pantaleo, A., A. Pellerano, M. Trovato, 2003, Technical issues on wind energy integration in power systems: projections in Italy, In: 2003 European Wind Energy Conference, Madrid, EWEA.

Parente, V., J. Goldemberg, R. Zillis, 2002, Comments on experience curves for PV modules, Progress in photovoltaics reserach and applications, 10(8), pp: 571 - 574.

Payne, A., R. Duke, R. Williams, 2001, Accelerating residential PV expansion: supply analysis for competitive electricity markets, Energy Policy, 29, pp: 787 - 800.

Perlack, R. D., 1995, Determination of the potential market size and opportunities for biomass to electricity projects in China, Tennessee, Oak Ridge National Laboratory, pp: 5.

Perlack, R. D. and L. Wrights, 1995, Technical and economic status of wood energy feedstock production, Energy, 20(4), pp: 279 - 284.

Perlack, R. D., L. Wright, M. A. Huston, W. E. Schramm, 1995, Biomass fuel from woody crops for electric power generation, Washington, ORNL.

Petersen, E. L., I. Troen, S. Frandsen, K. Hedefaard, 1981, Windatlas for Denmark, Roskilde, Risoe, pp: 229.

Phillips, V. D., W. Liu, R. A. Merriam, L. Bain, 1995, Short-rotation forestry as alternative land use in Hawaii, Biomass and Bioenergy, 8(4), pp: 235 - 244.

Pimentel, D., G. Rodrigues, T. Wane, R. Abrams, K. Goldberg, H. Staecker, E. Ma, L. Brueckner, L.Trovato, C. Chow, U. Govindarajulu, S. Boerke, 1994, Renewable energy: Economic and environmental issues, BioScience, 44(8).

Rangarajan, S., 1998, Wind energy resource survey in India, Bangalore, Indian Institute of Tropical Meteorology, Field Reserach Unit.

Rehfeldt, K., B. Schwenk, J. P. Molly, 1997, Sensitivity study of different parameters concerning the energy generating costs of wind turbines, In: European WInd energy Conference, Dublin.

Rogner, H., 2000, Energy sources, In: World Energy Assessment, Ed: J. Goldemberg, New york, UNDP, pp: 136 - 171.

Roos, A. and C. Rakos, 2000, The limits of modelling. Experiments with bioenergy in practise. Could models have predicted this outcome?, Biomass and Bioenery, 18, pp: 331 - 340.

Rosegrant, M. W., M. S. Paisner, S. Meijer, J. Witcover, 2001, 2020 Global food outlook, Washington D.C., IFPRI, pp: 18.

Rosenqvist, H., 2002, Personnal communication on energy crop production cost in Sweden, Luleå University of Technology.

Rosenqvist, H., A. Roos, E. Ling, B. Hektor, 2000, Willow growers in Sweden, Biomass and Bioenergy, 18(2), pp: 137 - 145.

RWEDP, 1997, Regional Study on Wood Energy Today and Tomorrow, Bangkok, Regional Wood Energy Development Program, pp: 168.

van Sambeek, E. J. W., T. J. de Lange, W. J. A. Ruijgrok, E. A. Pfeiffer, 2003, Onrendabele toppen van duurzame elecktriciteitsopties, Petten, ECN, KEMA, pp: 23.

Schaeffer, G-J., 2003, Experience curve as policy tool. The case of PV, EU-Extool, IEA EXCETP, Paris.

Schulz, H., 1999, Short history and present trends of Fischer-Tropsch synthesis, Applied Catalysis 186, pp: 3 - 12.

Shapouri, H., P. Gallagher, Graboski, 2000, The USDA 1998 U.S. ethanol cost of production survey, Washinton, USAD, Office of Energy Policy and New Uses, Iowa State University,Colorado School of Mines.

Sharma, S. C., 1991, Technological change and elasticities of substitution in Korean agriculture, Journal of development economics, 35, pp: 147 - 172.

Shell, 1995, The evolution of the world's energy system 1860-2060: extracts of a study by Shell International, London.

Silva de la Maza, P., 1998, Personal communication, Chichigalpa, Project leader Forestry Project San Antonio, April 1998.

Sims, R. E. H., H.-H. Rogner, K. Gregory, 2003, Carbon emission and mitigatoin cost comparison between fossil fuel, nuclear and renewable resources for electricity generation, Energy Policy, 31, pp: 1315 - 1326.

Snik, A., 2002, Experience curves for photovoltaic energy technology, Utrecht University, Department of Science Technology and Society, pp: 43.

Solarbuzz, 2002, SolarBuzz module prices, available at *www.solarbuzz.com*.

Sørensen, B., 1999, Long term scenarios for global energy demand and supply. Four global greenhouse mitigation scenarios, Roskilde University, pp: 213.

Sørensen, B., 2000, Renewable Energy. 2nd edition, Academic Press.

Stevens, M. J. M. and P. T. Smulders, 1979, The estimation of the parameters of the Weibull wind speed desitribution for wind energy utilization purposes, Wind engineering, 3(2), pp: 132 - 145.

Strauss, C. H., S. C. Grado, P. R. Blankenhorn, T. W. Bowersox, 1988a, Economic evaluations of muliple rotation SRIC biomass plantations, Solar Energy, 41(2), pp: 207 - 214.

Strauss, C. H., S. C. Grado, P. R. Blankenhorn, 1988b, Developing financial and energy accounting models for woody biomass systems, Solar Energy, 42(5), pp: 379 - 386.

Strauss, C. H. and L. L. Wright, 1990, Woody biomass production costs in the United States: An economic summary of commercial populus plantations systems, Solar Energy, 45(2), pp: 105 - 110.

Strengers, B., 2001, The Agricultural Economy Model in IMAGE 2.2., Bilthoven, National Institute of public health and the environment (RIVM), pp: 52.

Sudha, P., H. I. Somashekhar, S. Rao, N. H. Ravindranath, 2003, Sustainable biomass production for energy in India, Biomass and Bioenergy, 25(5), pp: 501 - 515.

Swisher, J. and D. Wilson, 1993, Renewable energy potentials, Energy, 18(5), pp: 437 - 459.

Tijmensen, M. J. A., A. P. C. Faaij, C. Hamelinck, M. Hardeveld, 2002, Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification, Biomass and Bioenergy, 23(2), pp: 129 - 152.

Toivonen, R. M. and L. J. Tahvanainen, 1998, Profitability of willow cultivation for energy production in Finland, Biomass and Bioenergy, 15(1), pp: 27 - 37.

TueWind Solutions, 2001, Wind energy resource atlas of South East Asia, New York.

Turhollow, A., 1994, The economics of energy crop production, Biomass and Bioenergy, 6(3), pp: 229 - 241.

Turhollow, A., 2000, Cost of producing biomass from Riparian buffer strips, Oakridge, ORNL.

Turkenburg, W. C., 2000, Renewable energy technologies, In: World Energy Assessment, Ed: J.Goldemberg, Washington D.C., UNDP, pp: 220 - 272.

Tuskan, G. A., 1998, Short-rotation woody crop supply systems in the United States: what do we know and what do we need to know?, Biomass and Bioenergy, 14(4), pp: 307 - 315.

UNEP, 2002, Global Environmental Outlook 3, London, pp: 416.

United Nations Population Division: Department of Economic and Social Affairs, 2002. World Urbanization Prospects: The 2001 Revision. New York, pp: 318.

Vaessen, P. T. M., 2003, Personnal communication on indicative costs of electricity transmission, KEMA, November 2003.

Varian, H. R., 1996, Intermediate microeconomics. A modern approach, New York, W.W. Norton and Company.

Venendaal, R., U. Jorgensen, C. A. Fosters, 1997, European energy crops: A synthesis, Biomass and Bioenergy, 13(3), pp: 147 - 185.

Vleeshouwers, L. M. 2000, Yield increases of biomass energy crops: a look to the future, In: Sustainable energy - new challenges for agriculture and implications for land use, Wageningen University.

de Vries, B., J. Bollen, L. Bouwman, M. den Elzen, M. Janssen, E. Kreileman, 2000, Greenhouse-gas emissions in a equity, environment and service-oriented world: an IMAGE-based scenario for the next century, Technological Forecasting and Social Change, 63(2-3), pp: 137 - 174.

de Vries, B. J. M., D. P. van Vuuren, M. A. Janssen, M. den Elzen, 2002, The Targets IMage Energy model Regional (TIMER) ,Technical documentation. Bilthoven, RIVM, pp: 188.

van Vuuren, D. P., H. J. M. De Vries, M. Hoogwijk, B. van Ruiven, 2004, TIMER 2.0 - Technical documentation. Bilthoven, RIVM, in preparation.

Walsh, M. and R. Graham, 1995, Biomass feedstock supply analysis: Production costs, land availability, yields. Oackridge, Tennessee, ORNL.

Walsh, M. E., 1998, U.S. Bioenergy crop economic analyses: status and needs, Biomass and Bioenergy, 14(4), pp: 341 - 350.

Walsh, M. E., 2000, Method to estimate bioenergy crop feedstock supply curves, Biomass and Bioenergy, 18, pp: 283 - 289.

Wan, Y.-h. and B. K. Parsons, 1993, Factors relevant to utility integration of intermittent renewable technologies, Golden, National Renewable Energy Laboratory, pp: 106.

Weingart, J. M., 1978, The Helios strategy: An heretical view of the potential role of solar energy in the future of a small planet, Technological forecasting and social change, 12, pp: 273 - 315.

Wieringa, J. and P. J. Rijkoort, 1983, Windklimaat van Nederland, Den Haag, Staatsuitgeverij.

van Wijk, A., 1990, Wind energy and electricity production, Utrecht University, pp: 197.

van Wijk, A. J. M. and J. P. Coelingh, 1993, Wind power potential in the OECD Countries, Utrecht University, Department of Science, Technology and Society, pp: 35.

Williams, R. H., 1995, Variants of a low CO_2 -emitting energy supply system (LESS) for the world - prepared for the IPCC Second Assessment Report Working Group IIa, Energy Supply Mitigation Options, Richland, Pacific Northwest Laboratories, pp: 39.

Williams, R. H. and E. D. Larson, 1993, Advanced gasification-based biomass power generation, In: Renewable energy: Sources for fuels and electricity, Eds: T. B. Johansson, H. Kelly, A. K. N. Reddy and R. H. Williams, Washington D.C.

Windstats, 2000, Windstats newsletter, 13(1).

Wirsenius, S., 2000, Human use of land and organic materials. Modelling the turnover of biomass in the global food system, Chalmers University, pp: 255.

World Commission on Protected Areas (WCPA), 2000, Protected areas: Benefits beyond boundaries, WCPA in Action, Gland, IUCN, pp: 19.

World Energy Council, 1994, New renewable energy resources. A guide to the future, London, Kogan Page Limited.

Worldbank, 2000, World development indicators, Washington.

WRR, 1992, Ground for choices: four perspectives for the rural areas in the European Community (In Dutch), Den Haag, pp: 150.

Yamaguchi, M., 2001, Present status and prospects of photovoltaic technologies in Japan, Renewable and sustainable energy reviews, 51, pp: 13 - 135.

Yamamoto, H., J. Fujino, K. Yamaji, 2001, Evaluation of bioenergy potential with a multi-regional global-land-use-and-energy model, Biomass and Bioenergy, 21, pp: 185 - 203.

Yamamoto, H., K. Yamaij, J. Fujino, 1999, Evaluation of bioenergy resources with a global land use and energy model formulated with SD technique, Aplied energy, 63, pp: 101 - 113.

van der Zwaan, B. and A. Rabl, 2003, Prospects for PV: a learning curve analysis, Solar energy, 74, pp: 19 - 31.

Zweibel, K., 1999, Issue in thin film PV manufacturing costs reduction, Solar energy materials and Solar cells, 59, pp: 1 - 18.

van Zyl, J., N. Vink, T. Fenyes, 1987, Labour-related structural trends in South African maize production, Agricultural economics, 1, pp: 241 - 258.

DANKWOORD

Veel mensen zijn de afgelopen vier jaren betrokken geweest bij dit proefschrift. Op deze plek wil ik iedereen bedanken voor hun directe en indirecte bijdragen. Allereerst is dit proefschrift totstandgekomen met veel inzet van mijn beide promotoren, Wim Turkenburg en Bert de Vries. Wim, ik heb je leren kennen als een gedreven wetenschapper met een grote inhoudelijke kennis en een ongekend kritisch vermogen. Ik dank je voor je steeds weer grondige commentaren en je geduld, vooral aan het einde. Bert, ik bewonder je creativiteit en analytisch vermogen. Je bijdrage op conceptueel niveau is bijzonder groot geweest en ik dank je hiervoor, als wel voor je vertrouwen en enthousiasme.

Ik wil ook alle co-auteurs van hoofdstukken en overige papers bedanken. Allereerst André Faaij voor zijn bijdrage aan drie verhalen. André, dank voor alle discussies, je visie en aanstekelijk enthousiasme. Aansluitend een woord van dank voor Detlef van Vuuren. Detlef, je hebt een grote bijdrage geleverd aan hoofdstuk 7, maar ook je suggesties, discussies en opmerkingen ten aanzien van mijn werk gedurende de gehele periode waren waardevol, mijn dank hiervoor. Even waardevol is ook dat je altijd een vrolijke en leuke collega bent geweest. Ik wil ook Bas Eickhout, Richard van den Broek, Göran Berndes, Jobert Winkel, Jan Coelingh en Dolf Gielen bedanken. Bas, dank voor je bijdrage aan alle hoofdstukken, maar in het bijzonder aan het derde, ook jij dank voor de gezelligheid. Richard, voor je bijdrage aan hoofdstuk 2, het beantwoorden van velerlei vragen en je interesse. Göran, thanks for your contribution to Chapter 2. I really enjoyed the time in Göteborg and our close collaboration. Jan, bedankt voor je bijdrage aan hoofdstuk 5 en alle ondersteuning gedurende de hele periode.

Ik wil al mijn collega's bij zowel NW&S en KMD bedanken voor hun belangstelling, discussies en de altijd weer prettige en gezellige sfeer. Jullie zijn met te velen om bij naam te noemen, maar DANK jullie allen! Om toch een paar uitzonderingen te maken, wil ik Martin en Jethro als (oud)-kamergenoten bedanken voor alle discussies over windturbines en zonne-instraling. Jethro, ik mis de maandagochtendgesprekken! Ook hier een woord van dank voor Penny met wie ik veel cursussen heb gevolgd en drie maanden in Mödling tijdens de zomerschool bij het IIASA een kamer heb gedeeld. Een belangrijke periode tijdens mijn promotieonderzoek. Penny, ik waardeer je attentheid, humor en interesse. Ik kijk uit naar jouw boekje. Ook een dankjewel voor de collega's in het supply-cluster, voor jullie discussies, antwoorden op mijn vragen en samenwerking; met name Carlo, Roni,

Wilfried, ErikA, Jinke, Edward. Tenslotte wil ik Rineke bedanken voor de hulp bij 'M' en de GIS-software.

Een proefschrift schrijven is een aanslag op je sociale omgeving. Daarom wil ik hier ook enkele personen bedanken die de afgelopen maanden op het persoonlijke vlak veel hebben moeten inleveren. Hélène, lieve meid, dank voor je vrolijkheid, openheid, zorg en liefde. Esther, voor je vriendschap, enthousiasme, en constructieve inzichten. Heleen, dank voor je lach, avonturier, je hebt me weer verrast! Liisa, thanks for sharing your thoughts with me. You have proven that even if we do not live next door, we can still be close friends. I am looking forward to your thesis! Dank voor jullie vriendschap, gezelligheid en interesse, Ivo (dank ook als reisgenoot), Danielle, Jeroen en natuurlijk de chemiewinkeliers Nico, Marc, Arjan, Marjan en Ingeborg. Tenslotte, Carola en Liesbeth, stoere, slimme vriendinnen vanaf dag één. Na lang als drie blonde meiden achterin gezeten te hebben, stonden we nu al twee keer vooraan. Fijn dat jullie de derde keer achter mij willen staan.

Tenslotte wil ik mijn familie bedanken. Lieve Judith, en Jeroen, dank voor jullie belangstelling en attentheid. Jeroen, dank ook voor het lezen van het gehele manuscript en alle waardevolle suggesties. Lieve P&M, jullie zorg, steun en interesse is steeds mijn hele leven al onvoorwaardelijke geweest. Het heeft me altijd een gevoel van vrijheid en veiligheid gegeven dat ongeacht de keuzes die je maakt, er altijd twee mensen zijn die je steunen. Bedankt voor alles, jullie zijn schatten! Tenslotte: Twan, mijn lief. Zonder jou was dit proefschrift er ook wel geweest, maar was ik niet zo vrolijk gebleven…. Dank voor je begrip, zorg, liefde en relativeringsvermogen. Ik ben blij met je!

CURRICULUM VITAE

Ik ben op 22 november 1974 geboren in Enschede en heb mijn jeugd in Oldenzaal doorgebracht. In 1993 behaalde ik daar mijn VWO-diploma aan het Thijcollege, waarna ik scheikunde ging studeren aan de Universiteit Utrecht. Tijdens mijn studie heb ik me ingezet als vrijwilliger bij de Chemiewinkel, waar ik ondersteuning heb verleend bij maatschappelijke problemen op milieuchemisch gebied. Na een stage atmosferische chemie heb ik tijdens een lange wandelvakantie in Nepal in 1996 besloten ook de kopstudie milieukunde te gaan volgen. Mijn wens te willen afstuderen op het gebied van 'energie en ontwikkeling' leidde in 1998 tot een afstudeeronderzoek bij de sectie Natuurwetenschap en Samenleving (NW&S) van de faculteit Scheikunde. Hiervoor heb ik in Nicaragua een gewasgroeimodel ontwikkeld voor de eucalyptusplantages van een suikerfabriek, die gebruikt zouden worden voor elektriciteitsopwekking. Inmiddels zijn daar de eerste bomen geoogst en levert de suikerfabriek energie uit biomassa aan het elektriciteitsnet. Hierna heb ik bij het adviesbureau Ecofys mijn tweede afstudeeronderzoek uitgevoerd, dat betrekking had op het Kyoto-instrument 'Clean Development Mechanism'. In 1999 heb ik beide studies afgerond en ben ik bij NW&S begonnen aan mijn promotieonderzoek naar de mondiale beschikbaarheid van zonne-, wind-, en biomassa-energie. Over dit onderzoek, dat ik voor een belangrijk deel heb uitgevoerd bij het Rijksinstituut voor Volksgezondheid en Milieu (RIVM), heb ik mondelinge presentaties gehouden in Brussel, Göteborg, Amsterdam, Madrid en Norwich. In het kader van mijn onderzoek heb ik tevens in de zomer van 2001 gedurende drie maanden een zomerschool gevolgd aan het International Institute of Applied System Analysis (IIASA) in Oostenrijk.