Fraunhofer IWES

Institut für Elektrische Energietechnik
Rationelle Energiewandlung

Erneuerbare Energien und Energieeffizienz

Renewable Energies and Energy Efficiency

Band 14 / Vol. 14

Herausgegeben von / Edited by
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Bioenergy and renewable power methane in integrated 100% renewable energy systems

Limiting global warming by transforming energy systems

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This work has been accepted by the faculty of Electrical Engineering and Computer Science of the University of Kassel as a thesis for acquiring the academic degree of Doktor der Ingenieurwissenschaften (Dr.-Ing.).

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Defense day 23rd September 2009

Bibliographic information published by Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie;
detailed bibliographic data is available in the Internet at http://dnb.d-nb.de.

Zugl.: Kassel, Univ., Diss. 2009
ISBN print: 978-3-89958-798-2
ISBN online: 978-3-89958-799-9
URN: urn:nbn:de:0002-7998

www.upress.uni-kassel.de

Cover design: Grafik Design Jörg Batschi, Kassel
Printed in Germany

Abstract

The two major challenges in global energy systems are to reduce energy-related greenhouse gas emissions and to maintain energy supply security. This thesis presents one solution to both problems. It proposes strategies for the transformation of current energy systems into 100% renewable, stable and almost emission-free energy systems without making use of nuclear energy or carbon capture and storage.

Within renewable energy systems, one is facing two difficulties: On the one hand, the fluctuating renewable sources need to be matched with the energy demand, on the other hand, a substitution for high energy density fuels in heat and transport has to be found. Therefore, this thesis examines bioenergy and the newly developed 'renewable power methane' or 'renewable methane' concerning their potential to solve these problems.

First, bioenergy is analyzed in the broader context of climate change, energy systems and land use in order to estimate the sustainable potential of global bioenergy. Then, a techno-economic and ecologic analysis of 78 bioenergy pathways is done in order to identify the strategic role of bioenergy in future energy systems. The potential is linked with this analysis to identify the range of maximum greenhouse gas reduction potential of bioenergy (2.5-16 Gt $CO_{2\text{-eq.}}$ yr^{-1}). Due to land-use competition and emissions from land-use, residues are to be favored as biomass source over energy crops. However, the limited bioenergy potential will neither be sufficient to balance fluctuating renewable power nor to fully replace fossil fuels in heat and transport.

Second, to solve this bioenergy bottleneck, a new approach of converting renewable power into methane via hydrogen and CO_2 methanation is developed. Several integrated concepts with CO_2 from air, biomass, and fossil fuels are designed. In this way, renewable power can be stored in the natural gas network and used temporarily and spatially flexible for balancing power, for process heat and for long-distance transportation. It can be produced basically anywhere where water, air and renewable power are available and thus decrease import dependence on fossil fuels. It can recycle CO_2 in the energy system or even act as carbon sink in combination with CO_2 storage.

Third, the necessary transformation of energy systems is performed. The key elements are direct renewable power generation, renewable electromobility, heat pumps, renewable power methane and overcoming traditional biomass. By integrating smart power networks, heat networks and natural gas networks, a full renewable energy supply is possible. Several 100% renewable energy systems are developed, reducing global energy-related emissions by 95%. The 100% renewable power supply was simulated with an hourly resolution. Finally, the role of such a transformation in global climate protection is analyzed. It has to take place until 2050 in order to limit global warming to 2°C.

Therefore, there is not much time left for the transformation to start.

Zusammenfassung

Die beiden zentralen Herausforderungen in der globalen Energiewirtschaft sind die Reduktion der energiebedingten Emissionen und der Erhalt der Versorgungssicherheit. Diese Arbeit bietet einen Lösungsansatz für beide Probleme. Sie zeigt auf, wie der Umbau der Energiesysteme hin zu einer stabilen, nahezu emissionsfreien 100% Versorgung mit erneuerbarer Energie gestaltet werden kann, ohne auf Technologien wie Kernenergie oder die CO_2 Sequestrierung zurückgreifen zu müssen.

Innerhalb erneuerbarer Energiesysteme gibt es zwei Kernprobleme: Einerseits gilt es, das fluktuierende Angebot von erneuerbaren Energien auf den variablen Energiebedarf anzupassen; andererseits gestaltet es sich besonders im Verkehrssektor als schwierig, einen erneuerbaren Energieträger mit hoher Energiedichte als Ersatz für fossile Kraftstoffe zu finden. In dieser Arbeit werden zwei Optionen, die das Potenzial zur Lösung dieser beiden Probleme haben, untersucht: Bioenergie und das neu entwickelte „renewable power methane“ – Methan aus regenerativem Strom – erneuerbares Methan – erneuerbares Gas.

Zunächst wird die Bioenergie im globalen Kontext Klimawandel, Energiesystemen und Landnutzung untersucht, um daraus das nachhaltige Bioenergiepotenzial abzuleiten. Die Ergebnisse einer umfassenden Analyse von 78 Biokonversionspfaden werden mit dem identifizierten Bioenergiepotenzial kombiniert, um das maximale Treibhausgasvermeidungspotenzial von Bioenergie abzuleiten (2.5-16 Gt $CO_{2\text{-eq.}}$ a^{-1}). Die Nutzung von Reststoffen und Abfällen ist dem Anbau von Energiepflanzen vorzuziehen, da Landnutzungskonkurrenzen und -emissionen vermieden werden können. Trotz vorhandenen Potenzials wird die Bioenergie nicht ausreichen, um die fluktuierende Stromeinspeisung von erneuerbaren Energien auszugleichen oder fossile Kraftstoffe im Wärme- und Transportsektor vollständig zu ersetzen.

Um diesen Engpass zu lösen, wurde ein neuer Ansatz zur Stromspeicherung entworfen, in dem regenerativer Strom über Wasserstoff und einer CO_2-Methanisierung zu einem Erdgassubstitut umgewandelt wird. So kann erneuerbarer Strom im Erdgasnetz gespeichert und räumlich-zeitlich flexibel als Regel- und Reserveenergie, aber auch im Fernverkehr eingesetzt werden. Wird das CO_2 aus der Luft gewonnen, kann ein klimaneutrales, erneuerbares ‘Erdgas’ aus Wasser, Luft und regenerativem Strom praktisch überall auf der Welt hergestellt werden, was die Importabhängigkeit von fossiler Energie erheblich reduziert. Mit dem neuen Konzept kann CO_2 im Energiesystem rezykliert oder eingelagert werden, was eine Kohlenstoffsenke schafft.

Durch den Ausbau und die Integration der Energienetze (Strom, Wärme, Gas) wird eine 100% erneuerbare Energieversorgung und die Senkung der energiebedingten Emissionen um 95% möglich. Verschiedene Strukturen von 100% erneuerbaren Energiesystemen werden entworfen und eine rein erneuerbare Stromversorgung für das Jahr 2050 mit stündlicher Auflösung simuliert. Abschließend wird die Rolle einer solchen Transformation im Klimaschutz diskutiert. Die skizzierte Transformation des Energiesystems muss bis 2050 erfolgen, um die globale Erwärmung langfristig annähernd auf 2°C zu begrenzen. Damit dieses Ziel erreicht werden kann, muss die Transformation heute beginnen.

Resumen

La reducción de gases de efecto invernadero y garantizar el abastecimiento energético global constituyen los dos mas grandes desafíos en las sistemas de energía. Esta tesis presenta una solución a ambos problemas, proponiendo estrategias para la transformación de los actuales sistemas energéticos en sistemas 100% renovables, estables y libres de emisiones invernadero sin promover la utilización de la energía nuclear ni la captura y almacenamiento de carbono.

Dentro de los sistemas de energía renovables se encuentran dos problemas: por un lado las fuentes de energía son variables y deben poder cubrir la demanda, por otro lado es difícil poder sustituir las combustibles fósiles en sectores como el transporte y el calor. Esta tesis examina el poder de la bioenergía y del novedoso concepto de la "renewable power methane" – metano renovable – gas renovable – respecto de su potencial para resolver los problemas planteados.

Primero, la bioenergía es analizada de una forma amplia en el contexto del cambio climático, los sistemas energéticos y el uso de tierras, con el objetivo de identificar el potencial global sustentable de bioenergía. Luego, es analizado el aspecto técnico-económico y ecológico de 78 posibilidades de bioenergía con la intención de identificar el rol estratégico de la bioenergía en el futuro. El potencial esta combinado con este análisis con la intención de identificar el rango máximo de reducción de gases de efecto invernadero que puede alcanzar la bioenergía (2.5-16 Gt $CO_{2\text{-eq.}}$ a^{-1}). Dada la competencia por el uso de tierra y las emisiones que el mismo uso de tierra genera, los residuos generados son una fuente de biomasa más favorable que las propias plantas energéticas. De todos modos, el limitado potencial de las bioenergías no es suficiente para balancear las fluctuantes energías renovables como así tampoco para reemplazar a los combustibles fósiles en áreas como la calefacción o el transporte.

Segundo, para poder resolver este cuello de botella respecto de las bioenergías, una nueva propuesta para convertir energía renovable en metano vía hidrógeno y la metanización del CO_2 es desarrollada. Varios conceptos integrados fueron diseñados. De esta manera, las energías renovables pueden ser almacenadas en las redes de gas natural y utilizadas temporal y espacialmente de una manera flexible para balance de energía, para procesos térmicos y para transportes de larga distancia. El metano renovable puede ser producido básicamente en cualquier lugar donde se encuentre agua, aire y energía renovable, reduciendo de este modo la dependencia de los combustibles fósiles. El mismo metano renovable puede reciclar CO_2 en el sistema de energía o inclusive puede extraerlo de la atmósfera.

Tercero, la transformación de los sistemas de energía es desarrollada. Los elementos fundamentales son la generación de energía renovable directa, la electromovilidad renovable, las bombas caloríficas, el metano renovable y la posibilidad de superar la biomasa tradicional. Una alimentación con 100% energías renovables es posible si las redes energéticas (electricidad, calor y gas natural) son combinadas. Varios sistemas 100% de energía renovable son desarrollados, obteniendo como resultado una reducción del 95% las emisiones de gases de efecto invernadero. El sistema eléctrico de 100% energía renovable esta simulado con alta resolución (1 hora). Finalmente la importancia de una transformación de estas características para el clima global es también analizada. Dicha transformación tiene que ser llevada a cabo hasta 2050 con el objetivo de limitar el calentamiento global en 2°C. Por lo tanto no hay mucho tiempo restante para iniciar la transformación de los sistemas de energía.

Yes, we can.

(Barack Hussein Obama)

Hope is all we need to make change reality.

(treehugger)

Love never fails. It always protects, always trusts, always hopes, never gives up.

(1 Corinthians 7-8)

Acknowledgements

Kwanza, ningesema asante na shukrani kwa mungu. Yeye ni maisha, maisha yetu, maisha ya dunia. Dunia na mbingu ni umoja. Mbingu ni ndani ya kila mtu. Kwa hivyo, tuseme asante. Asante sana.

I would like to thank life=love=god for creativity and all people who have accompanied me throughout the creation of this thesis:

Prof. Dr.-Ing. Jürgen Schmid for the supervision and inspiring support throughout the work and especially for his great confidence, motivation and the freedom to develop new ideas.

Prof. Dr.-Ing. Martin Faulstich for his co-supervision, encouragement and valuable inspiration. Prof. Dr-Ing. Albert Claudi and Prof. Dr.-Ing. Peter Zacharias for joining the commission.

My parents Anneliese and Konrad Sterner, for their unconditional love, giving me this wonderful life, the chance to alter life for the better and the great opportunity to unfold my talents by ideally supporting my education, my music and my ideas.

Special thanks to enable and inspire my work throughout the creation process: Dr. Astrid Schulz, Dr. Benno Pilardeaux, Dr. Alexander Vogel, Dr. Michael Specht, Bernd Stürmer, Jochen Bard, Norman Gerhardt, Amany von Oehsen, Dr. Stefan Bofinger, Mareike Jentsch and Yves-Marie Saint-Drenan.

Thanks for your ideas, inspirations, and support: Berthold Hahn, Dr. Kurt Rohrig, Michael Beil, Katharina Lesch, Patrick Hochloff, Alejandro Gesino, Claudia Erdt, Ritah Mubbala (Uganda), Sham Sundar Subbarao and Dr. VVN Kishore (both India), Franziska Müller-Langer, Anastasios Perimenis, Uwe Fritsche, Kirsten Wiegmann, Jürgen Pettrak, Prof. Dr. Andreas Neyer, Dr. Joachim Nitsch, Dr. Wolfram Krewitt, all workmates at Fraunhofer IWES (Institute for Windenergy and Energy System Technology, Kassel), WBGU (German Advisory Council on Global Change, Berlin) and the University of Kassel.

Dr. Anne Neyer, who supported me throughout the thesis, for her patience, her encouragement and her constant mental support. I dedicate this work to her.

Contents

Acronyms and abbreviations

AF	Allocation factor
API	American Petroleum Institute
ASU	Air Separation Unit
B5	5% Biodiesel blend in fossil diesel
B100	100% Biodiesel blend in fossil diesel
BEMI	Bidirectional Energy Management Interface
BP	British Petroleum - Beyond Petroleum
bpd	barrels per day
BTL	Biomass-To-Liquid
°C	degree Celsius
C3	C3 carbon fixation
C4	C4 carbon fixation
$Ca(OH)_2$	Calcium hydroxide
CCS	Carbon Capture and Storage
ch	chemical
CH_4	methane
CHP	Combined Heat and Power Plant
CO	Carbon monoxide
CO_2	Carbon dioxide
$CO_{2\text{-eq.}}$	Carbon dioxide equivalent according to IPCC definitions (accumulating the effect on climate of all greenhouse gases according to their global warming potentials in a period of 100 years) (IPCC, 2007f)
COP	Coefficient Of Performance
CSP	Concentrating Solar thermal Power
DDGS	Dried Distillers Grains with Solubles
DE	Deutschland – Germany
dLUC	direct Land-Use Change
DME	Di-Methyl-Ether (fuel for (long-distance) transport)
E5	5% bioethanol blend in fossil diesel

E85	85% bioethanol blend in fossil diesel
EJ	Exajoule
FT	Fischer-Tropsch
e.g.	for example
el	electrical
EUR	Euro
FAME	Fatty Acid Methyl Ester
FAO	Food and Agriculture Organization of the United Nations
FLh	Full-load hours (utilization rate of a conversion plant)
g	gram
ΔG	Gibbs free energy (delta)
GHG	Greenhouse gas(es)
GJ	Gigajoule
Gt $CO_{2\text{-eq.}}$	Gigaton CO_2 equivalent
GW	Gigawatt
GWh	Gigawatt hour
h	hour
ΔH	Enthalpy (delta)
H_2	hydrogen
H_2O	water, vapor
ha	hectare
HRL	High Residual Load
ICE	Internal Combustion Engine
i.e.	id est – that is
IEA	International Energy Acency
IFPRI	International Food Policy Research Institute
IGCC	Internal Gasification Combined Cycle power plant
iLUC	indirect Land-Use Change
ISET	Institute for Solar Energy Technology
IWES	Fraunhofer Institute for Windenergy and Energy System Technology (former ISET)

IT	Information Technology
K	Kelvin
kcal	Kilocalories
kg	Kilogram
kJ	Kilojoule
km	kilometer
km^2	square kilometer
KOH	Potassium hydroxide
kW	Kilowatt
kWh	Kilowatt hour
l	litre
LRL	Low Residual Load
LULUCF	Land-Use, Land-Use Changes and Forestry
MJ	Megajoule
μ	chemical potential
MW	Megawatt
MWh	Megawatt hour
N_2O	Nitrous oxide
NaOH	Sodium hydroxide
NaS	Sodium sulphur
NEDC	New European Driving Cycle
OECD	Organisation for Economic Co-operation and Development
PEM	Polymer Electrolyte Membrane
REN21	Renewable Energy Policy Network for the 21st Century
Person-km	Person kilometers traveled (mileage)
PJ	Petajoule
ppm	parts per million
PSA	Pressure-Swing Adsorption
PV	Photovoltaic(s)
R	specific gas constant
RNG	Renewable Natural Gas = ‘real natural’ gas = renewable power methane

RPM	Renewable Power Methane
SimEE	Simulation des Einsatzes von erneuerbaren Energien – simulation of renewable energy in power supply (simulation tool)
SNG	Substitute Natural Gas
SOFC	Solid Oxide Fuel Cell
t	ton(s)
T	Temperature
th	thermal
TJ	Terrajoule
TW	Terrawatt
TWh	Terrawatt hour
UNDP	United Nations Development Programme
US$	United States dollar
WBGU	German Adisory Council on Global Change
yr	year
ZSW	Zentrum fuer Solarenergie- und Wasserstoffforschung

0. Introduction

0.1 Main research questions

One cannot neglect the fact that fossil fuels are depleting and the major cause of anthropogenic global warming. At the same time, nuclear fuels are depleting as well and contain risks and unsolved problems like waste disposal, making their use unfavorable. Further, doubling nuclear power use reduces global greenhouse gas (GHG) emissions only by 4%. Carbon capture and storage (CCS) technology reduces GHG emissions only to a certain extent, it does not reduce fossil fuel dependency, and long-term CO_2 storage facilities are not yet tested. Energy efficiency and energy savings can reduce energy demand and energy-related GHG emissions drastically, but in the long run, energy systems will have to be based on renewables. Therefore, future energy systems will be dominated by renewable energy sources.

The fundamental difference between today's and future energy systems is that the expected main energy sources, namely wind and solar energy, are of a fluctuating, unsteady nature. So far, fossil and nuclear energy supply has been able to meet the flexible energy demand, while fuels basically are stored energy, available for flexible use.

Therefore, one main research question is how to match future energy supply with energy demand at high shares of fluctuating energy sources, i.e. how to balance and integrate wind and solar energy.

Especially the transport sector is challenged and shaped by a high dependency on fossil fuels and high-density energy carriers. The heat sector can use solar and geothermal energy for residential heating and warm water supply, but in some cases the base load is missing and especially process heat is still highly dependent on natural gas. Thus, another main research question is how to replace fossil fuels in heat and transport.

In the power sector, many options are discussed to integrate fluctuating renewable energy sources, for example virtual power plants on the supply side, demand side management on the energy customer side and different transmission and storage options in between. No silver bullet has been found yet and all options face difficulties: Increasing power transmission capacities encounters resistance from local residents, pumped hydro storage or compressed air storage sites are not sufficient or too far away from main power generation sites. This list can be continued.

Bioenergy is an attractive solution to the renewable energy integration challenge. It is renewable, but is has fossil fuel properties like high energy densities and is basically stored chemical energy. It is therefore suitable to substitute fossil fuels in transport, heat and power sectors and particularly interesting for balancing power.

In contrast, bioenergy has experienced a vigorous international discussion on its effect on climate change and sustainability.

Bioenergy use has a vivid history. Since the beginning of humankind, it was the energy source number one: easy to access, easy to use, geographically well-distributed. Until the first industrial revolution some 200 years ago, it was the main energy carrier and accounted for 99% of primary energy demand. During industrialization, biomass has been gradually substituted first by coal at the beginning of the 20th century and by oil and gas later on (Goldemberg, 2000).

One could say, the more prosperous a nation was, the less biomass they used. Among the roughly 60 countries, which use biomass in the traditional way as their main energy source today, most are developing nations. Now as fossil fuels are depleting and climate change is turning into the main threat to humankind, the world starts to look for alternative energy sources again. Bioenergy has gotten popular in industrialized countries, because it is renewable, sustainable and CO_2-neutral at first sight. Therefore, modern bioenergy experienced a boom in the late 1990s and the past 10 years, especially in the transport sector, until food prices increased in 2007 and 2008 worldwide (FAO, 2008b). Society noticed that on one hand there is a competition on land use for food, bioenergy and other products. On the other hand bioenergy, in particular biofuels, are causing more damage to the climate than they can prevent when for example rain forests are destroyed for new energy crops plantations. The question arises, whether biomass is problematic in general or if we have to differentiate more carefully here. While this discussion has a one-sided focus on liquid biofuels, the main global consumption is still traditional biomass. The current challenge is to overcome this inefficient and harmful type of bioenergy use. Nevertheless, biomass for heat, transport and electricity is part of the energy plans of almost all countries and major questions have to be answered from a scientific point of view, how to access and use the source bioenergy sustainably.

The main questions in the scientific bioenergy discussion are:

- How can bioenergy be used sustainably?
- Which role does, can and should bioenergy play in the transformation of energy systems and where does it strategically find its best place?
- Which potential does bioenergy have considering land-use competition and sustainable agriculture and forestry?
- What is the maximum GHG reduction potential of bioenergy?
- In which energy sector does bioenergy have the largest impact in GHG mitigation?
- In which application is bioenergy used most efficiently and at the lowest cost?
- Which parameter can be used to measure the GHG reduction efficiency trans-sectorally for all energy sectors?

- To what extent can bioenergy contribute to stabilizing power networks as balancing power?

In search for answers, a broad system analysis is necessary. Much research has been done on single aspects of bioenergy, but a trans-sectoral analysis and assessment is still missing.

This thesis aims to fill this gap of knowledge and analyzes bioenergy in the context of climate change, energy systems and land-use, including the identification of sustainable biomass sources, biomass potential, conversion technology and the impact and role of biomass in future energy systems and its contribution to climate mitigation.

In the course of creating this thesis, further questions arose out of this analysis, dealing with energy supply in general.

Fundamental questions in the scientific discussion of energy systems are

- As bioenergy is not likely to meet the rising balancing power demand in a 100% renewable energy system, what other options are available?
- How can fluctuating renewable energy be matched with fluctuating energy demand?
- How can surplus renewable power be stored and grid operation stability ensured?
- How can long-distance transport and process heat applications be made independent from fossil fuels and be powered by renewable energy?
- What are the most favorable GHG reduction options?
- How can global warming be limited to 2°C?

A new concept for storing and balancing renewable power is developed in this thesis.

A 100% renewable power supply has been simulated with high temporal resolution. The ‘renewable power methane’ concept is also an answer to the challenge of overcoming fossil fuel dependence in long-distance transport and process heat.

The question “In what time the transformation of energy systems has to happen, to limit global warming to 2°C ?” is answered in a sample scenario, performing the transformation of energy system at constant land use GHG emissions from agriculture and forestry.

0.2 Structure of thesis and new approaches

The thesis is divided into six parts and the annex:

Chapter 1 – Status quo, threats and potentials in climate change, energy systems, land-use

Chapter 1 provides an analysis of bioenergy in the broader context of climate change, energy systems and land-use based on literature review. Thus, the bandwidth of global sustainable bioenergy potential is identified, taking into account effects of land-use competition and land-use change.

New approaches in chapter 1

Data is compiled into global figures on renewable energy, and methods on primary energy balancing are advanced and applied. The GHG reduction potential of doubling the use of nuclear energy is identified. Further, the four elements of a low-carbon energy supply are created and options for climate protection in land-use are confronted and a bandwidth of sustainable bioenergy potential derived from analyzing 15 studies.

Chapter 2 – Analysis of 78 biomass pathways

In chapter 2, an in-depth analysis including calculations for 70 relevant modern bioenergy and main traditional biomass pathways for electricity, heat and mobility is carried out to identify the pathways with the highest efficiency, the lowest production cost, the most positive greenhouse gas balance and the lowest GHG reduction costs. These parameters are contrasted with each other in a synthesis.

New approaches in chapter 2

To some extent, this thesis is one of the first ones dealing with all types of energy from biomass, thus opening the narrow predominant focus on biofuels and putting bioenergy in a broader context. All bioenergy sectors are analyzed in one single synthesis assessment, covering heat, power and transport. Further, for the first time modern bioenergy and traditional biomass pathways are brought together in one single assessment.

Chapter 3 – Integrated assessment

The identified sustainable bioenergy potential of chapter 1 is coupled with optimal bioenergy pathways of chapter 2, and thus a range of the maximum greenhouse gas reduction potential of bioenergy is identified. Moreover, synergies in energy crop use with sustainable land-use are established; stages of sustainable modern bioenergy application are developed according to its strategic functions. In addition, ways of overcoming traditional biomass use in developing countries are outlined.

New approaches in chapter 3

Based on the knowledge of chapter 1 and 2, an integrated assessment of the role of bioenergy in land-use, energy systems and GHG emission reduction is conducted. Further, the new analysis on the optimal stages for using bioenergy in sustainable energy systems is carried out.

Chapter 4 – Renewable power methane (RPM)

A new concept for storing renewable power as methane and its usage in all energy sectors is developed in chapter 4, designing various integration concepts with CO_2 from air, biomass and fossil fuels. In addition, first control concepts for electricity network integration are developed. These concepts are identified as part of the solution for the energy storage problem and enable the use of renewable power in special transport segments and process heat.

New approaches in chapter 4

The 'renewable power methane' (renewable methane, renewable SNG) concepts are based on a new invention that the author developed in collaboration with colleagues from ZSW Stuttgart. The basic idea of CO_2 methanation and linking electricity and natural gas network is from Dr. Michael Specht. In this work, this idea is applied and expanded further to develop integrated concepts with CO_2 from air, bioenergy, waste and fossil plants, the operation concepts in the integrated networks and the stand-alone concept. These concept ideas are patented in Germany by the inventors under pending patent No DE 10 2009 018 126.1 (Specht et al., 09.04.2009). Further, new interconnection concepts with other energy grids have been developed.

Chapter 5 – Development of sustainable energy systems

In chapter 5, five steps of increasing technical energy efficiency are described. These steps are combined with sustainable bioenergy and renewable power methane to design 100% renewable energy system structures. Ultimately, these systems can serve as a carbon sink in combination with atmospheric CO_2 recovery and storage via renewable power methane. A transformation of today's carbon-intensive energy systems into emission-free renewable energy systems is performed, and the role of this necessary transformation in global climate protection is analyzed.

New approaches in chapter 5

Sustainable bioenergy and 'renewable power methane' are included along with energy efficiency measures in the development of 100% renewable energy supply structures. All aspects of this thesis are brought together in the transformation of energy systems towards emission-free energy supply. Concluding, the potential role of such a transformation in keeping the 2°C climate stabilization target is discussed, using latest climate research findings. This chapter is based on two peer-reviewed papers derived from this thesis (Sterner et al., 2008c; Sterner et al., 2008b).

Chapter 6 – Summary and outlook

Besides the summary of this thesis, chapter 6 includes first simulation results of a 100% renewable power supply with high temporal resolution. In a new approach, the developed renewable energy structures are integrated and simulated with the IWES model SimEE with a focus on power storage by renewable power methane concepts. This illustrates future research topics on the integration of renewable power and RPM concepts in energy system modeling and power system planning and operation.

Annex – Methodologies, technical background information and simulation results

In the annex, definitions and technical background information are given on bioenergy related technologies. Moreover, methodologies for primary energy balancing (chapter 1) and analysis and assessment of bioenergy pathways are given, including calculation of technical efficiency, greenhouse gas balances and mitigation costs (chapter 2).

Model descriptions and simulation results of modeling 100% renewable power generation in Germany in the year 2050 conclude the scientific content of the annex.

The triangle of sustainable bioenergy – basis for chapter 1 to 3

The first 3 chapters are based on the triangle of sustainable use of bioenergy, which is described briefly (Figure 0.2-1).

First, bioenergy has to be climate neutral and may not emit more GHG than the fossil reference. Climate protection is a prerequisite for sustainable bioenergy. Second, as bioenergy is a limited resource, it has to be used as efficient as possible. This is determined by a strategic application of bioenergy in energy systems. Third, energy crops should avoid land-use competition as far as possible. The competition for area, water and other resources is crucial for a sustainable use of energy crops. Bioenergy can be only sustainable, if all three elements are in balance.

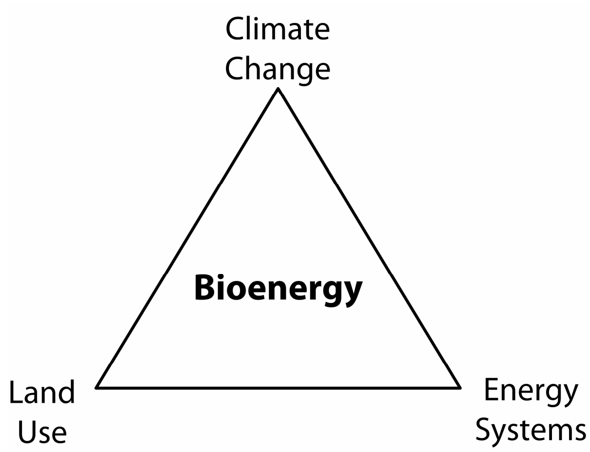

Figure 0.2-1: Triangle of sustainable bioenergy. Source: own compilation.

1. Status quo, threats and potentials in the triangle of bioenergy – climate, energy and land use

In the following chapter, status quo, threats and potentials of the three elements in the triangle for sustainable bioenergy 'climate change', 'energy systems' and 'land use' are analyzed and put in context with bioenergy at the end of each section.

1.1 Climate change – climate protection

There has always been and will ever be climatic changes in the earth's atmosphere. The question that has challenged the scientific discussions is, whether the current climate change is natural or anthropogenic. In-depth analyses show that the human influence is the major cause for the current increase in global mean temperature (IPCC, 2007f).

1.1.1 Status quo

Climatic change – which share is anthropogenic?

There is scientific proof for human influence on climate change. In the course of industrialization, the global mean temperature has increased by 0.8 °C since 1880, more than in the previous 1500 years. According to IPCC scenarios, global mean temperatures might rise between 1.8 - 3.0 °C at low and 3.2 - 7.3 °C at high emissions until 2100, whereby no active climate mitigation scenario was calculated (IPCC, 2007f).

Changing climate is caused by a change in the earth's energy balance, which can happen in three ways: (1) changing the incoming solar radiation, (2) changing the part of solar radiation which is reflected by earth's surface or clouds, aerosols and gases in the atmosphere and (3) changing the infrared radiation from earth backwards to space by e.g. changing the concentration of GHG in the atmosphere (IPCC, 2007f).

GHGs like water vapor, CO_2 and methane have a warming effect on this radiation balance. They do not interfere much with the incoming solar radiation but can have a blocking, absorbing effect on the outgoing longwave infrared radiation and 'close' the atmospheric windows in the spectrum. Without this greenhouse effect of natural GHGs, the global mean temperature would be -18 °C and not +15 °C. Thus, this effect is essential for life on earth but in the same time it is highly sensitive to changes.

According to the laws of physics, doubling the concentration of CO_2 in the atmosphere leads to an increase of global mean temperatures by 1.5-4.5°C (Rahmstorf et al., 2007b), p.29. Since 1750, the concentration of CO_2 has risen by 38% due to human activities, primarily because of the combustion of fossil fuels and deforestation (CDIAC, 2009; IPCC, 2007f), p.97. The intensity of a factor like greenhouse gas that can influence the climate and change the energy balance in the earth-atmosphere system is usually evaluated in terms of its 'radiative forcing'. It is defined as the 'rate of energy change per unit area of the globe as measured at the top of the atmosphere' (IPCC, 2007f), p.135-136.

In 2005 relative to 1750, the global mean 'anthropogenic' forcing was 1.6 (0.6 to 2.4) W m^{-2} whereas the mean 'natural' forcing was 0.12 (0.06 to 0.30) W m^{-2}, which is mainly due to an increased solar output in this period (IPCC, 2007f), p.136. Knowing the rising GHG concentrations by measurements and fossil fuel consumption, 'anthropogenic' forcings can be calculated and compared with temperature trends (Figure 1.1-1a). Neglecting anthropogenic GHGs in modeling global temperature evolution and using only natural GHGs for radiative forcings, the modeled temperature rise does not match the actual temperature rise (Figure 1.1-1b). Therefore, it is evident that the current increase of GHGs and global warming are results of human activities.

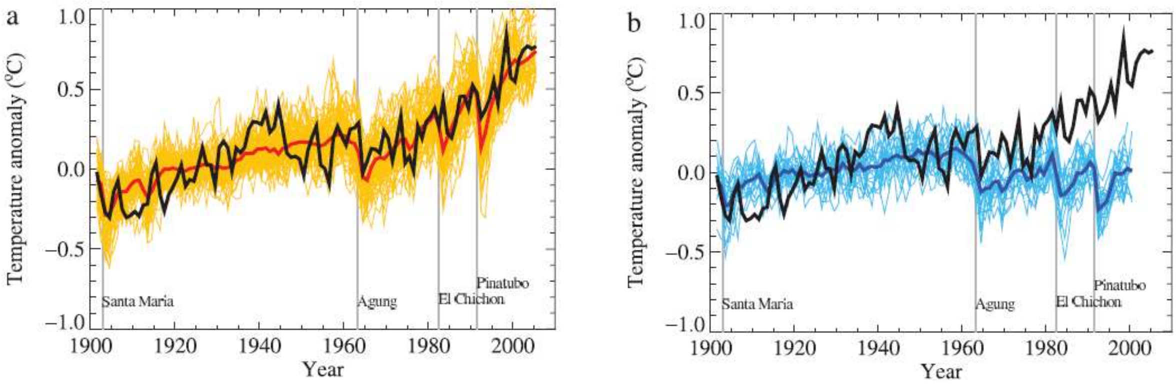

Figure 1.1-1: Temperature anomalies in global mean temperature measured (black line) and modeled as a result of radiative forcing (a – natural and anthropogenic forcings modeled – red line, b - only natural forcing modeled – blue line). The cooling effect of volcanic aerosols can be clearly noted as well as the warming effect of GHGs due to human activities, dominated by combustion of fossil fuels and deforestation. Source and ©: (IPCC, 2007f), p.684.

This correlation can be exceeded into the past. Air bubbles trapped in ice cores give detailed information about temperature and GHG concentration going back until 740,000 years ago. The past 430,000 years - which are the documented best - cover four glacial-interglacial cycles (IPCC, 2007f), p.438. These cycles have been mostly determined by the change of the earth's orbit around the sun (Milakovitch cycles).

Concentrations of carbon dioxide and methane in the atmosphere show a good correlation with air-temperature throughout the recorded time period. Today, the atmospheric concentration of CO_2 and CH_4 exceeds by far the level of past 420,000 years. CO_2 concentration amount to 385 ppm in 2008, far higher than the maximum concentration of 290 ppm in that period with a strong increasing tendency (Trans, 2009; CDIAC, 2009; Petit et al., 1999).

Current greenhouse gas emission trends and shares of land use and energy

The anthropogenic GHG emissions have risen by 70% between 1970 and 2004 up to 49 Gt CO_2-eq. per year. The main driver of GHG emission growth is the energy sector: the emissions of power generation have tripled in this period, the emissions of the transport sector doubled (Figure 1.1-2) (IPCC, 2007d), p.102-109.

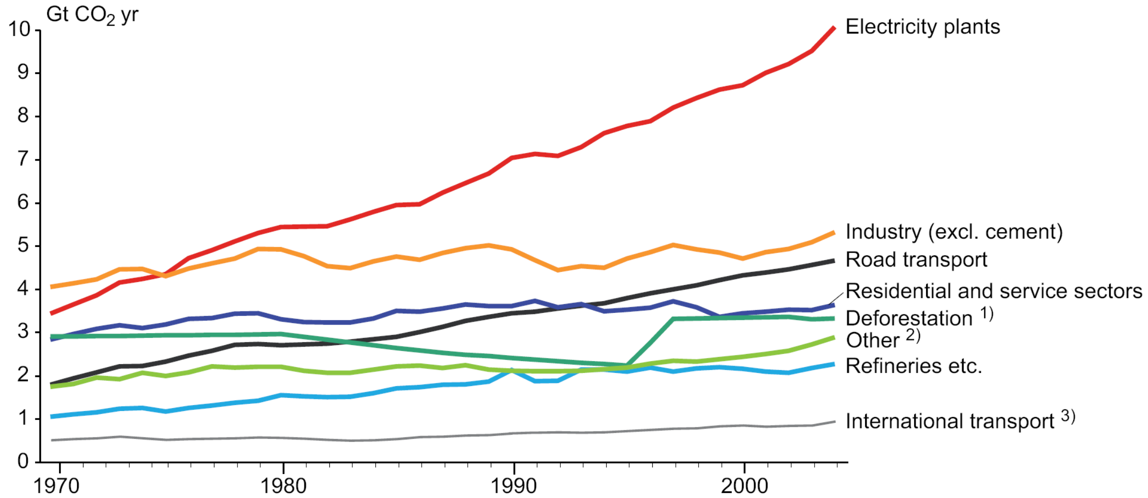

Figure 1.1-2: Growth of global CO_2 emissions in Gt CO_2 per year, (1970-2004) (only direct emissions by sector). [1)] Including fuelwood at 10% net contribution. For large-scale biomass burning, averaged data for 1997-2002 are based on the Global Fire Emissions Database satellite data, including decomposition and peat fires, excluding fossil fuel fires; [2)] Other domestic surface transport, non-energetic use of fuels, cement production and venting/flaring of gas from oil production; [3)] Including aviation and marine transport. Source and ©: (IPCC, 2007d), p.104.

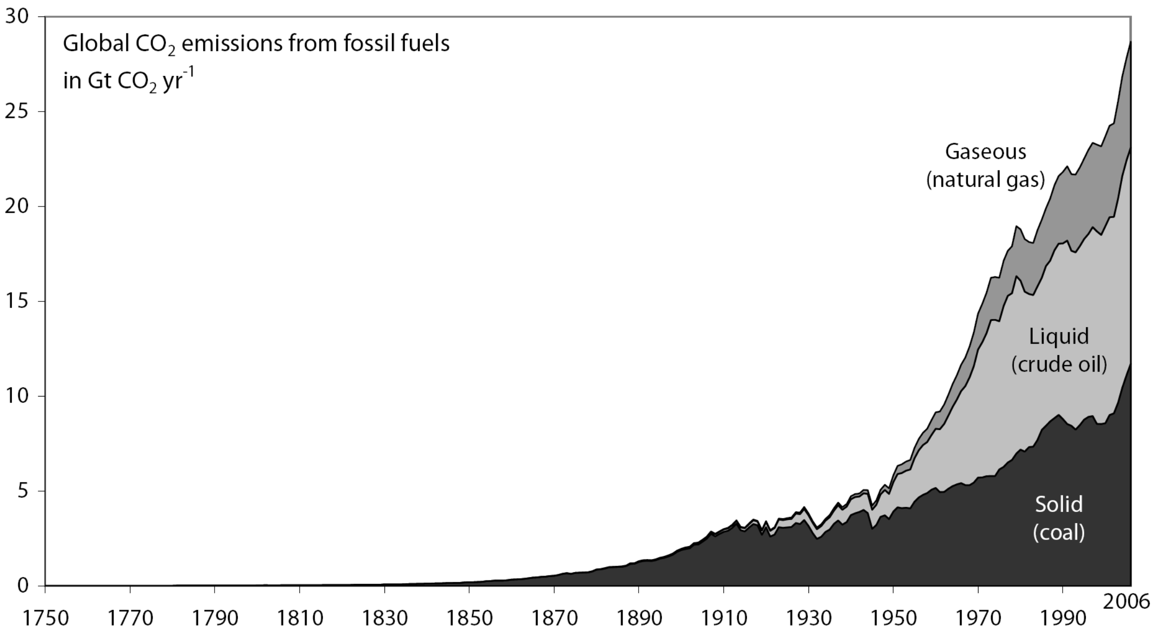

Figure 1.1-3: Growth of global CO_2 emissions from fossil fuels in Gt CO_2 per year (1750-2006), without emissions from gas flaring and cement production. These figures correspond to the light red share in below Figure 1.1-4 a. Source: own compilation, based on data from (Boden et al., 2009).

The combustion of fossil fuels accounted for the largest share (57%) of global CO_2 emissions and shows the strongest increase since 1750 (Figure 1.1-3).

Methane (CH_4) emissions originate from agriculture and fossil energy use and have increased since 1970 by about 40%, whereby CH_4 emissions of fossil energy use showed an increase of 85%. Nitrous oxide (N_2O) emissions have grown about 50%, mainly due the expansion of agriculture and fertilizer use (Figure 1.1-4a) (IPCC, 2007d), p.102-107.

The total global GHG emissions of 2004 split in about 67% energy-related emissions and 33% land-use change emissions, of which agriculture including fertilizers have a share of 13.5% and forestry 17.5%, which is mainly deforestation (Figure 1.1-4b). Energy-related emissions compose of 'energy supply' (power generation, heat supply), 'transport', 'industry' and 'buildings' (heat and power supply) and include in a simplified approach also industry CO_2 sources like steal and cement production. In reality, the industry pie splits in CO_2 from industrial fossil energy use and CO_2 from production of goods from materials that emit CO_2 during their processing. In this thesis, CO_2 from industry processes are only taken into consideration in chapter 4.

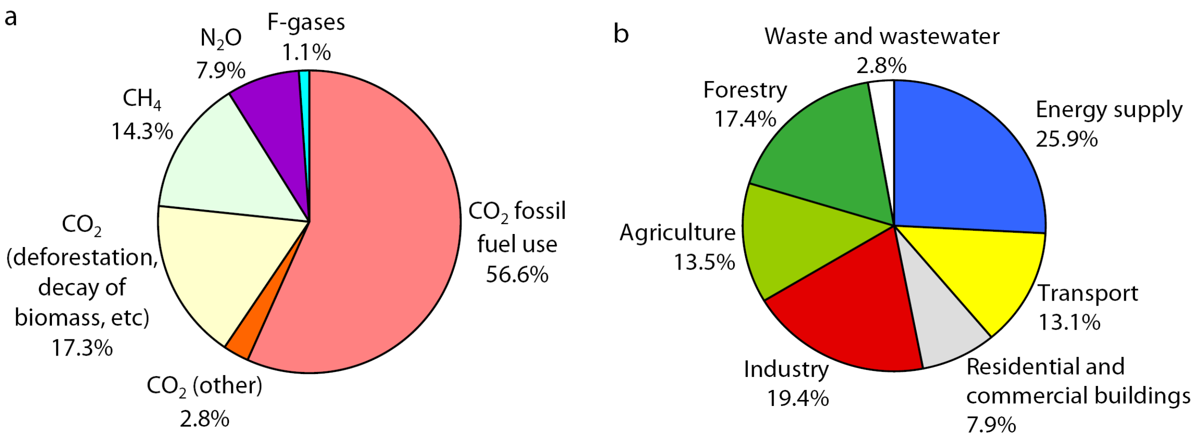

Figure 1.1-4: Share of different anthropogenic GHG emissions in total emissions in 2004 split in (a) GHGs in terms of $CO_{2\text{-eq.}}$ and (b) emission sectors in terms of $CO_{2\text{-eq.}}$ (forestry includes deforestation). Source and ©: (IPCC, 2007g), p.5, adopted from Figure SPM.3

Crucial role of bioenergy

Bioenergy plays a rather crucial role in GHG emissions, since it is affecting not one single but all important emission sources like energy and land use caused by agriculture or forestry. It also affects gases like CO_2 (substituting fossil fuels on one hand, possible support of deforestation and land-use change on the other hand), CH_4 (agriculture and poor combustion of biomass) and N_2O (fertilizers and poor combustion of biomass).

In the Kyoto-protocol, CO_2 emissions of bioenergy are not accounted so far and taken as 'CO_2-neutral', which is not consistent with recent research results, e.g. (Fritsche, 2007; Fritsche et al., 2008c; Jungbluth et al., 2008). GHG emissions related to direct and indirect land-use changes (CO_2, CH_4, N_2O) are not accounted fully (e.g. only from fertilizers) and only in 'Kyoto Annex I countries', i.e. industry nations. In developing countries, no GHG emissions are accounted for bioenergy (production) at all. This is a weakness of the United Nations Framework Convention on Climate Change (UNFCCC) that has to be met in the future.

1.1.2 Threats

Anthropogenic global warming affects natural systems and is a threat to nature and human society.

Observed impacts on nature and human society

Already today, many events are measurable and can be related to global warming. The impacts of climate change can be derived from climatic indicators like temperature, precipitation, sea level and number of extreme weather events (IPCC, 2007f). The increased global mean temperature has caused e.g.

- warming of lakes and rivers
- increasing ground instability in permafrost regions
- earlier timing of spring events
- melting of glaciers and ice sheets
- water stress in some regions

Oceans are affected too. They are taking up one third of the emitted CO_2 while only two-thirds are left in the atmosphere. For that reason, oceans became more acidic, which is increasing coral mortality. Sea level rose by 15-20 cm in the 20th century, which has not been the case in the previous one thousand years. Global warming caused a rise of 3mm per year between 1993-2003 (IPCC, 2007f), p.387, p.410.

Extreme weather events like tropical cyclones, heat waves, draughts and floods have increased in number and intensity in the past decades. The 2003 heat wave in Europe caused about 30,000 to 50,000 deaths. Precipitation patterns have changed in the last decades, resulting e.g. in drier summers in Mediterranean or Southern Africa and more floods like in Mozambique or Bangladesh. In 2005, an extreme hurricane season has brought the catastrophe of New Orleans in the US, while two tropical storms took an unusual way and arrived in Europe in the Iberian Peninsula and the Canary Islands. The increased number and intensity of tropical cyclones is likely due to increased ocean temperatures, which are related directly to global warming (WBGU, 2008).

Projected impacts on nature and human society

The observed impacts are projected to increase and intensify in the future. Major projected threats of global warming are negative consequences like extreme weather events, vanishing water reserves, harvest failures and destroyed living habitats (IPCC, 2007b), p.8-18; (IPCC, 2007c), p.42; (WBGU, 2008), p.55-72.

Global warming is likely to cause

- increased water demand and salinization of freshwater systems
- harvest failures, soil erosion, livestock death due to extreme weather events

- extinction of species, migration of wildlife, loss of biodiversity
- malnutrition, infectious diseases, increased extreme weather-related mortality
- population migration, danger to the security and stability of societies, destruction of property and infrastructure, power outages, increased energy demand for cooling, lower energy demand for heating, declining air quality, reduced quality of life

It is likely that droughts and floods increase in frequency with all their negative impacts on nature and society. Water supply stored in snow cover and glaciers is projected to decline in this century, reducing water availability for more than a sixth of the current global population. Ecosystems may loose their capacity of uptaking carbon and thus amplify global warming. Global food production is assumed to increase with higher local temperatures of 1-3°C, but above this level, it is assumed to decrease again. It is expected, that especially developing countries – which are not the causer - will be affected negatively by climate change, since their capacity to adopt is rather low. Political tensions caused by this injustice are likely to arise. Health related problems like malnutrition and diseases as well as death due to extreme weather events will challenge societies. These projections are based on smooth trends, which allow systematic risk assessments.

Tipping points and non-linear effects can happen beyond an increase of 2-3°C in global mean temperature and are unlike smooth trends hardly predictable. Such events could be the melting of the Greenland ice sheet, the weakening of the thermo-haline circulation in the Atlantic, the collapse of the Amazon rainforest or a transformation of monsoon in South-Asia, which in the worst case influence each other. The melting of the Greenland ice sheet could lead to a break down of the Gulf Stream by flushing melted freshwater into it. This would lead to a sea level increase of approximately 7m, flooding many densely populated coastal regions around the world (WBGU, 2008). If climate protection fails, the global sea level is predicted to rise half a meter by the year 2100 (IPCC, 2007f), p.409 and even significantly more (Rahmstorf et al., 2007a).

All of these predictions reveal the vulnerability of life and nature by the impacts of climate change. Consequently, a comprehensive and ambitious reduction of GHG emissions is the major task for our generation and vital for future generations.

1.1.3 Potentials and necessity for climate protection

The necessary reduction of GHG emissions will challenge humanity. Essential steps will be the transformation of energy systems and the implementation of sustainable land use. To meet these goals, binding international GHG reduction goals and burden sharing among all nations are necessary. Various mitigation technologies like renewable energy are commercially available. Bioenergy affects both major emitting sectors energy and land use and has therefore a special role in climate protection.

Necessary global greenhouse gas reductions

Many research results emerge in the perception that global mean temperatures must not exceed 2°C beyond the pre-industrial level to avoid negative impacts and catastrophes by global warming (Meinshausen et al., 2009; Allen, 2009; WBGU, 2008). This threshold implies the stabilization of GHG concentration in the atmosphere below 450 ppm $CO_{2\text{-eq}}$, which means a necessary reduction of global GHG emissions by 50 to 85% until 2050 in relation to 2000 (Barker et al., 2007), p.39. Meanwhile, the research community discusses the reduction of 100% and 'negative' emissions by removing CO_2 from the atmosphere.

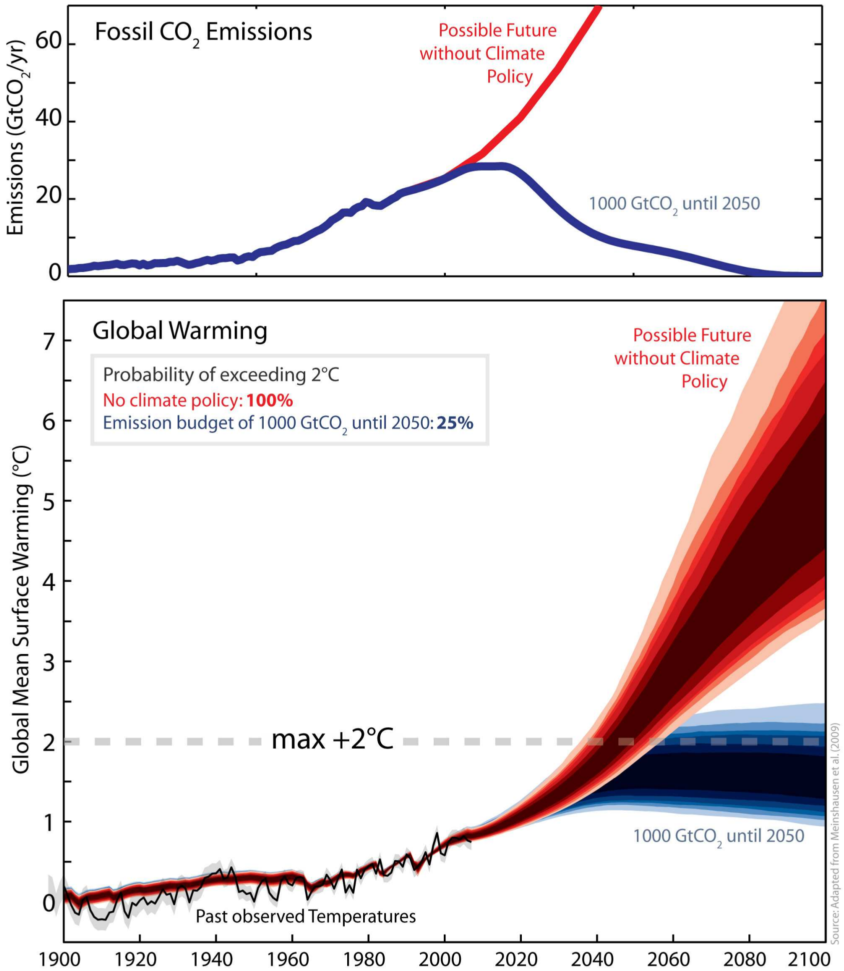

Figure 1.1-5: Two possible future scenarios: One in which no climate policies are implemented (red), and one with strong actions to mitigate emissions (blue). Shown are fossil CO_2 emissions (top panel) and corresponding global warming (bottom panel). The shown mitigation pathway limits fossil and land-use related CO_2 emissions to 1,000 billion tons CO_2 over the first half of the 21st century with near-zero net emissions thereafter. Greenhouse gas emissions of this pathway in the year 2050 are ~70% below 1990 levels. Without climate policies, global warming will cross 2°C by the middle of the century. Strong mitigation actions according to the blue route would limit the risk of exceeding 2°C to 25%. Source and ©: Nature, (Meinshausen et al., 2009).

It is projected that the increase in energy demand and fossil fuel combustion will continue to grow if no measures are taken to reduce emissions (IPCC, 2007d), p.97. Especially CO_2 emissions are crucial, as CO_2 has a very long lifetime and remains longer in the atmosphere than most of the other GHG. To limit global warming to 2°C with a probability of 75%, GHG emissions need to be strongly decreased in the next 40 years; leaving a budget of 1,000 Gt CO_2 (1500 Gt $CO_{2\text{-eq.}}$) for the period 2000-2049 that must not be exceeded (Figure 1.1-5).

Industry nations account for about 20% of the world's total population in 2004, but are responsible for a share of 46% of global GHG emissions. The contrast is quite clear: the nations causing anthropogenic climate change are not the ones that are affected the most. Emissions would multiply if all countries took over the energy and resource intensive lifestyle of the 'developed' nations. Therefore, on one side industrialized countries have to reduce emissions more drastically than developing countries according to the 'polluter pays' principle. On the other side, emerging nations have to design their economic progress climate friendly and avoid mistakes of industrialized countries like a high fossil fuel dependency by e.g. diversifying their energy sources with renewable energies.

GHG reduction implies a fundamental transformation of the energy and transport sector towards a low carbon energy supply and other technological changes in agriculture and forestry including a change of lifestyle and nutrition patterns.

Main potentials for emission reduction

The main anthropogenic GHG sources are the energy sector and land-use. Total emissions split roughly into 2/3 energy-related and 1/3 land-use-related GHG emissions (see also Figure 1.1-4). Therefore, the climate change problem is mainly an energy system problem and the major potential for GHG reduction is the transformation of the energy sector towards emission-free energy sources.

In the near future, three main options are on the hand to reduce GHG in the energy sector: (i) energy efficiency, (ii) renewables, and (iii) fuel switching from coal / oil to natural gas or nuclear power. In the long run, a switch from fossil and nuclear sources to renewables will be inevitable due to depleting resources and unsolved disposal problems. The individual potentials are discussed in chapter 1.2.3.

In the land-use sector, avoided deforestation and improved, less fertilizer intensive land management are the options today available. On a long perspective, a global land use management system is a necessary option to reduce land-use related GHG emissions (WBGU, 2009). The individual potentials are discussed in chapter 1.3.3.

Bioenergy in particular

Bioenergy affects both major climate relevant sectors, namely energy and land use. On the one hand, it can reduce emissions by substituting fossil fuels and offers the possibility of negative emissions through carbon sequestration. On the other hand, it harms the climate on the land-use side, as it is part of agriculture and forestry. For example, bioenergy can lead to more emissions than it is saving by unsustainable land-use change (forest removals for bioenergy plantations) and unsustainable land use management (CO_2 and N_2O in agriculture from soil carbon and fertilizers).

Yet, the effects of climate change can have an accelerating effect on energy crops. By increasing global mean temperatures, timber productivity is projected to increase on a global level. In addition, crop productivity and agricultural yields are assumed to increase in some regions with higher temperatures and a higher share of CO_2 in the atmosphere. Nevertheless, agriculture and forestry may be hit severely by droughts, floods and other extreme weather events, diminishing annual crop yields. The net effect resulting from climate change on agricultural productivity is difficult to predict.

The net effect of bioenergy on climate will be examined in the ecologic analysis of greenhouse gas balances in chapter 2.4. It is necessary to regard climate change, energy and land use in combination when it comes to the impact of bioenergy, which is done in a super-positioned analysis in this thesis.

1.2 Energy systems

Analysis in the previous chapter showed, that the energy sector is the major emitter of anthropogenic GHG and thus the key player in climate mitigation. Consequently, there is a need to adopt and change the energy systems towards sustainability. The age of fossil fuels is at a turning point and the age of renewables is at its come back, since fossil resources are depleting and CO_2 emitting while renewables are renewable and CO_2 free or neutral. The status quo of world energy supply and systems is analyzed in chapter 1.2.1, including shares and trends of bioenergy. Chapter 1.2.2 deals with main challenges within energy systems or caused by them and in chapter 1.2.3 potentials for an efficient and low-carbon energy supply are constituted.

1.2.1 Status quo

1.2.1.1 Shares in global primary energy consumption

The total primary energy consumption increased by 62% between 1980 and 2006 and this rising trend continues. In 2006, global energy demand was around 491 EJ according to the efficiency method (IEA et al., 2008) and 509 EJ according to the substitution method (BP, 2009; REN21, 2008b; OECD, 2008). Both methods are used in energy balances, delivering different results as they evaluate direct generated power from hydro, solar and wind differently. The methods and their fundamental differences are explained in detail in annex A1. The substitution method is - unlike the efficiency method - allowing a physically correct comparison between electrical, thermal and chemical energy and thus used in this work.

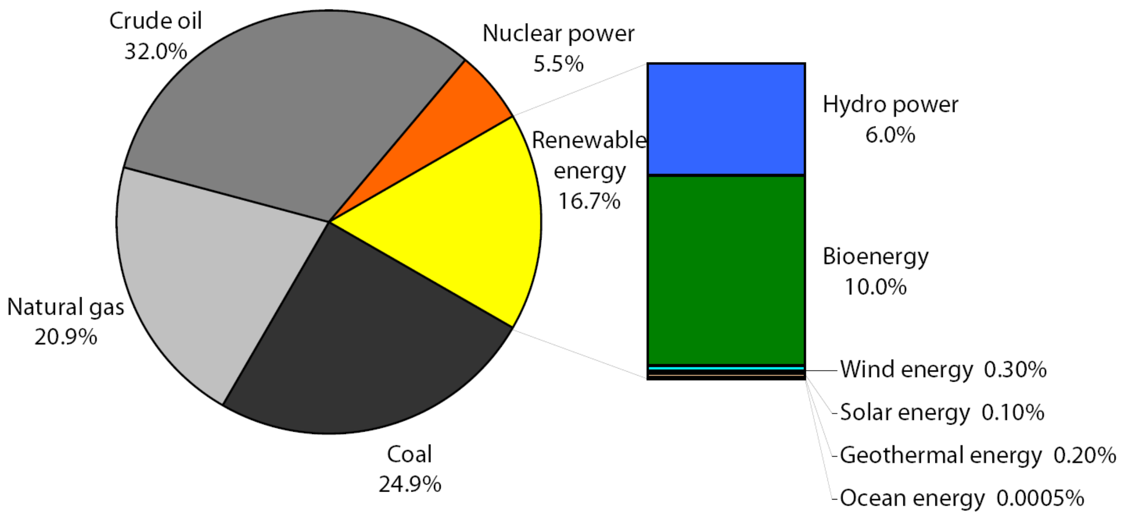

Figure 1.2-1: Global primary energy sources 2006, substitution method. Source: Own compilation, based on data from (IPCC, 2007g; BP, 2009; REN21, 2008b; OECD, 2008).

In 2006, fossil fuels held a share of 77.8% in global primary energy supply, nuclear power 5.5% and renewable energies 16.7% (Figure 1.2-1). Crude oil remains the dominating energy carrier, followed by coal and natural gas. Traditional biomass used for cooking and heating accounted for 8.6% and modern bioenergy for heat, power and transport 1.4%. Hydropower had a slightly higher share than nuclear power. Wind power is growing rapidly but yet a small share of global energy supply. Geothermal energy, solar energy and other renewables like ocean energy are still used to a very small extent (BP, 2009; REN21, 2008b; OECD, 2008).

1.2.1.2 Current trends of fossil, nuclear and renewable energy sources

Crude oil

Global oil production grew by 11% in the decade of 1998-2008 (BP, 2009) and is approaching its peak in the next few years. (Campbell, 2003) or (Schindler et al., 2008) assume that this peak has possibly been reached already. Peak oil passed in more than 20 of about 40 oil producing countries, among them the USA, Norway and Venezuela. Conventional oil production is already declining and the more difficult production of unconventional oil like oil shale is economically not as feasible as conventional oil and thus resulting in far higher emissions. After 'Peak Oil', a steep decline in oil production is forecasted (Schindler et al., 2008). Figure 1.2-2 shows the passed and projected global oil production by the Energy Watch Group, compared to IEA assumptions. The IEA stated in their 'world energy outlook 2008' that oil resources are of a ‚ultimate finite nature' (IEA et al., 2008).

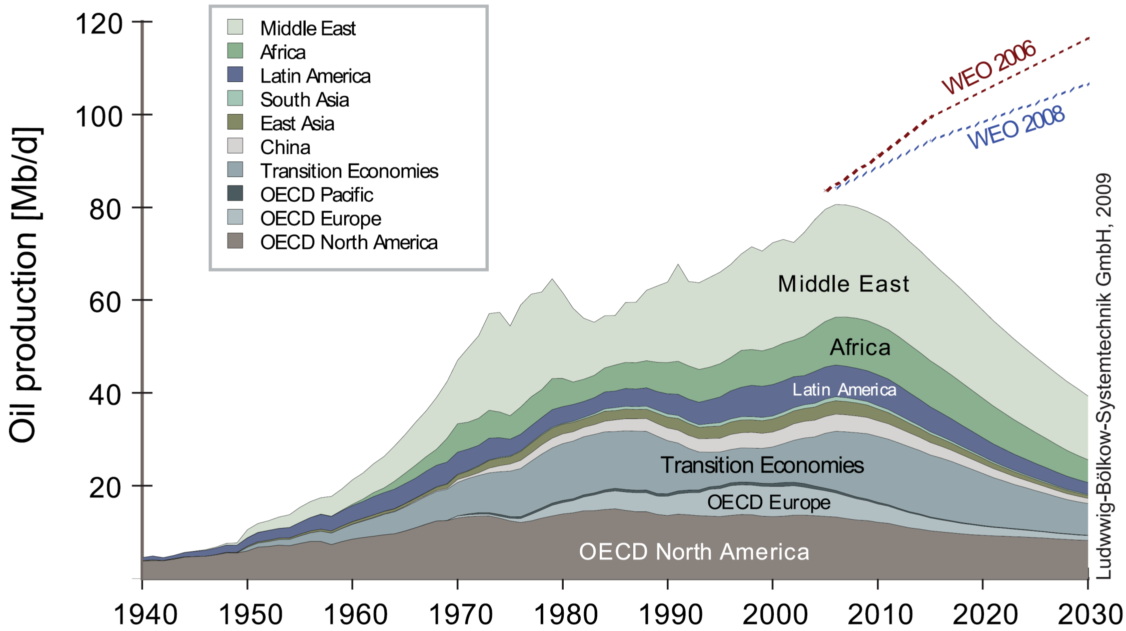

Figure 1.2-2: Global oil production splits in main oil regions compared to projections of the IEA World Energy Outlook (WEA) of 2006 and 2008 Source and ©: LBST, www.lbst.de (Schindler et al., 2008).

Coal

Global was the world's fastest-growing fossil fuel in the last decade, with a growth in consumption by 50% (BP, 2009). An expansion of coal power plants can be noted especially in China and India with evident negative consequences on GHG emissions, since coal has the highest specific emissions per energy unit. Unlike oil or gas, coal will last at current production and consumption rates over many decades to come. However, in China as well as in the USA, coal production is depleting. The global 'peak coal' is predicted to be around 2025 (Schindler et al., 2007).

Natural gas

The production of natural gas increased in the past decade by 33%. The largest reserves are in Russia, Iran and Qatar (BP, 2009). Natural gas has the lowest amount of GHG per energy unit among fossil fuels, can be used flexibly in all energy sectors and will play an important strategic role in technical supply security in future energy systems (see also chapter 1.2.3).

Nuclear power - uranium

Nuclear power generation stagnated in recent years. The number of reactors on the grid has been oscillating between 435 and 440 for the past 15 years. Two thirds of all nuclear power plants are older than 20 years (IAEA PRIS, 2008). The reactors lifetime depends on the reactor type and varies between 20 and 40 years, which is the reason why many old reactors have to be exchanged or their capacity replaced within the next decades. The trusted reserves of uranium last at current utilization rates for another 30 to 70 years, depending on the technology used. There is the possibility to extend the reach of uranium resources by using fast breeding reactors and recycling plants or to switch to alternative nuclear fuels like thorium. However, these options are still future options and not available from the shelf as there is no commercially operated fast breeding reactor yet. In addition, these technologies still deal with severe security problems. Hence, these nuclear alternatives will not play a significant role in the near future (Schindler et al., 2006). In general, any use of nuclear fuels and the operation of nuclear power plants bear substantial risks, which are described in chapter 1.2.2.2.

Wind energy

Windenergy is becoming a solid division of energy supply systems. Installed capacity has shown an exponential growth. In the past decade, it increased twelve-fold from 10 GW to 115 GW. In 2008, the largest power capacity increase was wind power and the USA overtook Germany's leading position in installed wind capacity. In 2009, most probably China will take the lead (WPM, 2009). At good wind sites, wind power is already competitive and in some cases more economic than fossil electricity. The potentials of wind energy are still unexplored. (Lu et al., 2009) estimates that wind power can cover current worldwide consumption of electricity by more than 40 times and total primary energy by 5 times. Windenergy will be in medium term the largest renewable source besides hydro power and bioenergy and an effective climate mitigation tool, as the emissions from producing wind turbines are compensated in less than 3 month of operation and the remaining 20 years of lifetime, wind power is emission-free (EWEA, 2009; GWEC, 2008).

Hydro power

Global hydro power utilization experienced an increase of 20% in the past five years (BP, 2009). In Europe, the potential for large hydro power is largely exploit already, in other continents not yet. Vast expansion of large hydro is controversial and limited by environmental constraints, availability of sites and resettlement impacts. Medium, small and pico hydro power plants are less problematic as they can be integrated better in landscapes without forcing resettlements or water irrigation stress (REN21, 2008b). So far, only a small share of this low-cost emission-free technology is explored globally (see annex Table A3-1) (Goldemberg, 2000), p.156.

Solar energy

On a global scale, solar energy is mainly used for heat applications today. At the end 2006, a solar thermal capacity of 105 GW was installed, over 65% in China. Growth rates in Europe in 2006 have been at over 50%. There is also a trend to use solar energy for solar cooling and climatisation instead of fossil fuel based devices (REN21, 2008b).

Solar power is booming as well with annual growth rates of 60%. An estimated global capacity of about 15 GW of photovoltaics (PV) was installed at the end of 2008. This amount is still insignificant, compared to global capacity of wind or hydro power. PV technology is still a high-cost technology, which is expected to become competitive in the future by technology developments and economies of scale. However, off-grid PV is already competitive in many areas without grid connection and used especially for telecommunication, water pumping and lighting (EPIA, 2009; REN21, 2008b).

After a first boom in the 1970s in the USA, the market for concentrating solar thermal power (CSP) remained stagnant until 2004, when interest in this technology grew again. The global installed capacity of 0.4 GW in 2006 is still minor compared to other technologies. However, plans exist for new installations of about 10 GW in the coming years (Müller-Steinhagen et al., 2008). In contrast to PV, CSP has the advantage of far higher rated capacities at considerably lower cost of generation. A prerequisite for feasible CSPs are very high solar irradiation values. The vision to built CSPs in desert regions and transport solar electricity to metropolitan areas is technically and economically feasible and basically a matter of political will (Czisch, 2005).

Geothermal energy

Similar to solar energy, geothermal energy is mainly used for heat supply via heat pumps by using ambient heat. About 33 GW thermal capacity is installed globally and very high annual growth rates of 30-40% observed.

About 10 GW geothermal power capacity is installed and increases annually by approximately 2 to 3%. Countries with special geographic structures and near to the surface heat sources like Iceland are benefiting from geothermal energy (REN21, 2008b).

Ocean energy and other technologies

In 2008, the installed global tidal power capacity was 0.3 GW. Ocean energy is an example for renewable energy sources which have a large potential, which is basically not utilized yet, just as well as solar active cooling and different forms of geothermal power generation (REN21, 2008b).

1.2.1.3 Current trends and shares of bioenergy in the context with other renewables

Classification of bioenergy

The term 'biofuels' is often mistaken as a synonym for the term 'bioenergy'. In this thesis, the following classification of bioenergy is applied as illustrated in Figure 1.2-3.

'Energy crops' describe all types of plantations done on agricultural or forestry land. 'Residues and waste' can be classified in many categories. The most common are harvesting residues, residues and waste from food production and woody biomass residues. 'Traditional biomass' pathways are all forms of the traditional way of using biomass for heating, cooking and lighting and are mainly found in developing countries. 'Modern bioenergy' pathways are modern conversion processes of biomass into electrical, thermal and mechanical energy for power, heat and transport.

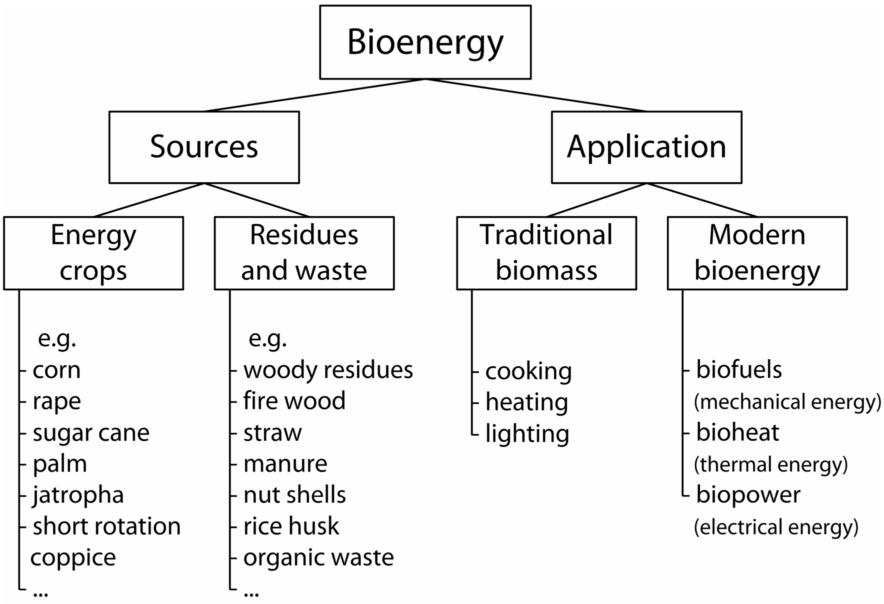

Figure 1.2-3: General classification of bioenergy. Source: own compilation.

Shares of bioenergy

Bioenergy covers about 10% (50.3 EJ) of global total primary energy supply in 2006, whereby 85.6% are 'traditional biomass' for heating and cooking and the far smaller share is 'modern bioenergy' for heat (7.8%), electricity (4.5%) and biofuels, namely bioethanol (1.8%) and biodiesel (0.4%) (Figure 1.2-4). Thus, the main share is still used in a traditional way with inefficient technologies and poor combustion quality. According to (IEA, 2007b), about 2.5 billion people worldwide (38% of world's population in more than 80 developing countries) depend on biomass as their 'primary' energy source. Bioenergy has a share of over 90% of primary energy in about 50 countries. In contrast, modern bioenergy use appears little but has increased strongly during the last decade (GBEP, 2008). The largest consumers of bioenergy are China (9 EJ yr^{-1}) and India (6 EJ yr^{-1}), followed by the USA (2.3 EJ yr^{-1}) and Brazil (2.0 EJ yr^{-1}). The amount of bioenergy consumed in the larger European countries like France and Germany (both around 0.45 EJ yr^{-1}) is rather small (GBEP, 2008).

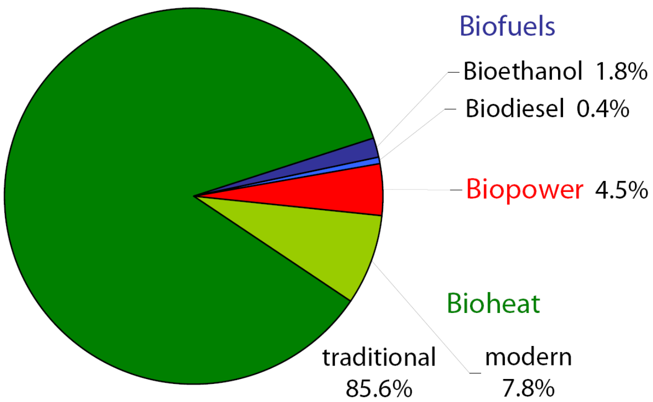

Figure 1.2-4: 2006 global shares of bioenergy for heat, power and fuels, total primary energy: 51.4 EJ. Source: (REN21, 2008b; OECD, 2008).

Bioenergy for heat

Bioenergy plays its most important role in the heat sector. 93.4% of global bioenergy is used for heat purposes. Over 570 million households use it in a traditional way for cooking, heating and lighting. This use is inefficient and harmful to health due to indoor pollution and other dangers. Overcoming traditional biomass use holds a huge potential in resource conservation, health improvement and climate protection (REN21, 2008b). 44% of harvested wood is used as firewood, with a declining trend since the 1990s (FAO, 2006). Unlike, the worldwide use of charcoal has doubled between 1975 and 2000 with a further rising trend as a cause of urbanization in developing countries (MA, 2005e).

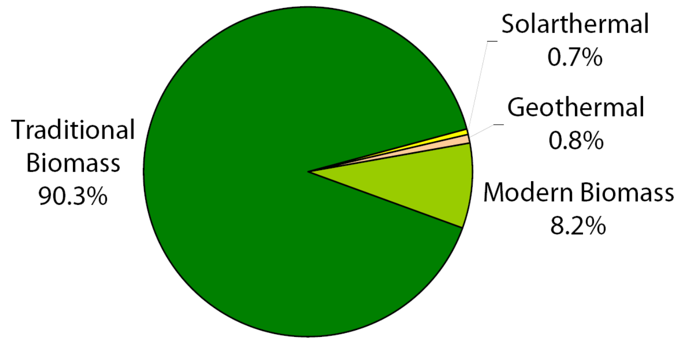

Figure 1.2-5: 2006 global shares of renewable heat. Total primary energy: 48.7 EJ. Source: (REN21, 2008b; OECD, 2008).

Among all renewables used in the heat sector, bioenergy is the dominating source (98.5%) (Figure 0.2-1). In 2006, modern bioheat applications with a thermal capacity of about 235 GW_{th} existed. Modern bioenergy heating systems like pellet heaters are applied in industrialized countries with high woody biomass potentials. In developing countries, about 25 million household use biogas for cooking and lighting from small biogas digesters and many industrial heat processes like drying are run by biomass (REN21, 2008b).

Bioenergy for power and CHP

The extent of bioenergy for electricity (e.g. direct combustion, co-firing, fermentation) is lower than bioenergy for heat. In 2006, biopower plants with a global capacity of 45 GW were connected to the grid, covering 0.4% of global power consumption (REN21, 2008b).

This represents 6.5% of global installed renewable power capacity in 2006 (Figure 1.2-6). About half of these installed capacities are CHP plants. Almost all kinds of biomass can be converted into power (see also annex A4). The most common conversion technologies are direct combustion of solid (woody) biomass in steam turbine power plants or co-firing in coal power plants (IEA, 2007a). Gaseous biofuels like biogas or biomethane from gasification or fermentation generate power in gas turbines, combined-cycle power plants or small CHP units like micro gas turbines

(Krautkremer et al., 2004). Liquid biofuels are also used for power generation in stationary internal combustion engines, especially in CHPs.

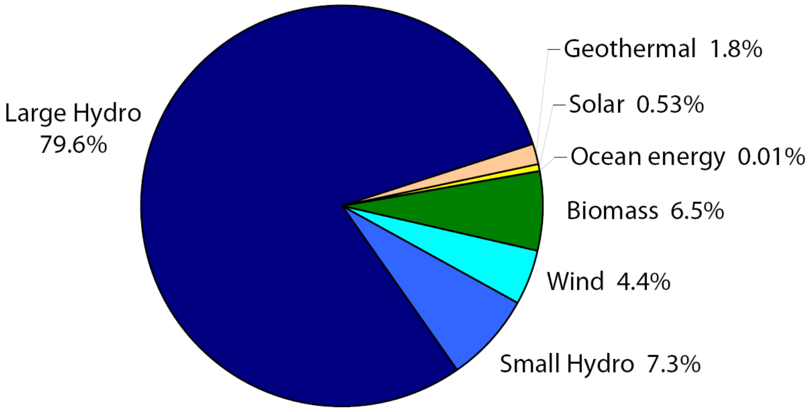

Figure 1.2-6: 2006 global shares of renewable electricity. Total primary energy: 35.5 EJ. Source: (REN21, 2008b).

Bioenergy for transport

With 2.2%, biofuels for transport hold a minor share of total bioenergy and are still insignificant compared to traditional biomass use (44.0 EJ). However, as a result of political support, they have developed dynamically in the past decade. Between 2000 and 2007, global bioethanol production tripled up to 1.2 EJ (55 million l) and global biodiesel production increased ten-fold up to 0.32 EJ (10 million l) (OECD, 2008).

The main producers of bioethanol are the USA (51%) and Brazil (36.5%). It is produced via fermentation and distillation from sugar cane (mainly Brazil), corn (mainly US) and sugar beet and wheat (mainly EU). Main producers of biodiesel are the EU (60%; Germany, France, Italy and others - mainly rape), the USA and Brazil (soya) plus Indonesia and Malaysia (90% of palm). It is produced via transesterification of plant oil, which has been extracted physically. Due to high feedstock prices and reduced state financing, some biodiesel plants have shut down their production. Both biodiesel and bioethanol can be used purely or blended with fossil fuels.

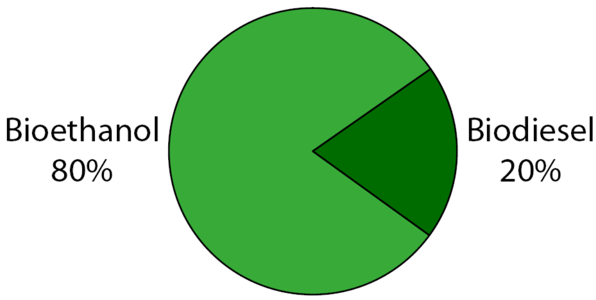

Figure 1.2-7: 2006 global shares of renewable fuels for transport. Total primary energy: 1.1 EJ. Source: (OECD, 2008).

So far, only bioethanol and biodiesel are counted in energy statistics, as straight vegetable oil use is minor in the transport sector. Renewable electromobility has not been registered yet, although there is wide spread utilization like electric bicycles in e.g.

China. Therefore, the global shares of renewables for transportation split 2007 in 1/5 biodiesel and 4/5 bioethanol energetically (Figure 1.2-7) (OECD, 2008).

2nd generation biofuels (mainly BTL - biomass-to-liquid) are in development stage. They promise better fuel properties, higher yields per hectare and higher GHG reduction potentials than 1st generation of biofuels (plant oil, bioethanol, biodiesel). It is doubtful whether these expectations can be met. Recent studies show that 2nd generation biofuels do not have better GHG balances than 1st generation biofuels and involve more complex and expensive plant technology (see chapter 2.2 to 2.4). Most of the fuels like Fischer-Tropsch Diesel and Kerosene, bio-hydrogen, Dimethylether (DME), Biomethane (Bio-SNG) or lignocellulose-ethanol are produced via thermo-chemical conversion of woody biomass (Sterner, 2007). 3rd generation biofuels like bio-hydrogen from algae are still in fundamental research. BTL fuels are expected to become market-relevant in the next decade. So far, the start of the first commercial Fischer-Tropsch-BTL-Diesel production of 340 barrels per day (bpd) was planned for 2008 but has not yet happened. For 2012, a plant with 200 tons per hour biomass input (10 trucks) and an output of 4.500 bpd is planned, which is equivalent to 0.12% of today's European diesel consumption (Choren, 2008).

1.2.1.4 Conclusions and vision

Fossil fuels are still the predominant energy source in the world's energy supply. However, the renewable energy sector notes the largest growth rates (see annex Table A3-1). Renewable power generation capacity has doubled within three years between 2004 and 2007 up to 240 GW worldwide (REN21, 2008b). The technical potential of renewables is sufficient to cover world primary energy demand several times without the threat of a climate collapse that could be caused by an uninhibited use of fossil fuels (UNDP) (Goldemberg, 2000; Nitsch, 2008). The price for fuel over the total lifetime of many renewable energy technologies like wind turbines or solar panels is zero. This is the fundamental difference to fossil, nuclear and biomass energy sources and therefore, renewables like wind or solar energy will continue to experience a strong development in the next decades as many potentials are yet untapped. The largest challenge is the integration of renewable energy, especially fluctuating wind and solar power. A new solution for this challenge is created in this thesis in chapter 4. The necessary transformation of the energy system into a 100% renewable energy system is technically possible and demonstrated in chapter 5 and 6.2.

1.2.2 Threats

The energy sector is facing three fundamental challenges (see also annex Table A3-1):

- Global warming: fossil energy use is the main cause for anthropogenic climate change which implies a transition of energy systems towards a low-carbon economy
- Security of supply: macro-economic supply security is at risk as fossil and nuclear sources are depleting leading to geopolitical tensions
- Security of operation: the use of nuclear energy has an unsolved disposal problem, causes proliferation of nuclear weapons and accommodates danger of operation in general; technical supply security is at risk since renewable power with unsteady nature like wind power is challenging the stability of electrical grid operation

1.2.2.1 Global warming by energy-related emissions

Global energy supply today consists of about 80% fossil fuels. Fossil energy use is the main driver of anthropogenic warming and responsible for approximately 85% of CO_2 emissions (IPCC, 2007d), p.265.

The use of coal - mainly for electricity - holds with 42% the largest share of energy-related emissions. Crude oil - used mainly for transport, but as well in heat and power sector - accounts for 39% and natural gas - used as well in all sectors, but mainly for heat and power - for 19%.

Coal is the main 'climate killer' in the energy sector, since it has (i) the highest emissions per energy unit among fossil fuels, (ii) the largest fossil energy growth rates in the past years and (iii) it is the longest lasting fossil resource with R/P-ratios of far over 100 years (see annex Table A3-1). Because of these reasons, research is conducted to find ways of a climate-neutral use of coal (chapter 1.2.3).

Besides fossil fuels, biomass can also be a threat to the climate. In theory, biomass is CO_2-neutral, as it is absorbing the same amount of CO_2 while growing as it is emitting during its combustion. In reality, biomass is not CO_2-neutral and in particular energy crops can even cause more GHG emissions for the same energy purpose than fossil fuels by e.g. accelerating deforestation (CO_2, CH_4) or an uncontrolled use of fertilizers (N_2O). The net effect of biomass on climate is examined in detail in chapter 2.4 and 3.3.

1.2.2.2 Security of supply and operation

Security of supply - resources

Economic welfare and development is highly depended on energy. The economic growth of the last century was based on inexpensive energy. Fossil fuels are finite and especially the dependency on oil is a threat to the global economy: The gap between supply and demand is growing and thus oil prices are rising, which is a heavy burden for all economies. After a peak at 144 US$ per barrel in mid 2008, the oil prices fell again and are currently below 100 US$ per barrel but still highly volatile (Tecson, 2009). Oil is also causing geopolitical conflicts (Worldwatch Institute, 2005). Although oil is currently not expensive, fossil resources can no longer be the backbone of the global economy as resources are ending and threatening climate stability. There is no clear fossil successor for oil as no other fossil or nuclear fuel can close the gap. Moreover, crude oil as basis for chemical products cannot be replaced as easily as in the energy sector. Hydrocarbons have the highest strategic value in material use.

Consequently, peak oil rings in a transformation of energy structures, which has to be shaped sustainably. A solution is given in energy savings and the development of renewable energy technologies like wind, solar and hydro which are geographically more distributed than fossil fuels and do neither cause fuel cost nor climate damage.

Security of operation – nuclear power

Besides renewables, another low-carbon technology is nuclear power. Unfortunately, this technology contains many risks and problems, which are yet to be solved (Schwarz, 2007):

(i) ‘supply security’ - like fossil fuels, uranium is running out in the next century and for uranium recycling or other nuclear fuels like thorium, technology does not yet exist.

(ii) ‘proliferation’ of nuclear weapons - international conflicts with Iran or North Korea reveal, how difficult a separation of civil and military use of nuclear power is.

(iii) ‚nuclear accident’ - despite highly developed safety engineering, a maximum credible accident cannot be excluded. This risk implies the destruction of large areas and death of thousands of people owing to radioactive contamination by a nuclear accident, a terror attack or an earthquake.

(iv) ‚disposal of waste’ - the question of nuclear waste disposal remains unsolved worldwide, even with most advanced future reactor technology. There is no serious final disposal of nuclear waste, since it is radioactive for millions of years and the risks of nuclear power are inherited to many future generations. Without solving the disposal question, it is irresponsible to use nuclear energy.

Security of operation – integration of renewable power grid stability at high fluctuating renewable power

Some renewable energy sources face challenges as well, but not as severe as nuclear or fossil fuels. One major challenge is the integration of fluctuating power sources like wind and PV without compromising electrical grid stability. Wind and solar power are meteorologically depended energy sources and are naturally not controllable by themselves. High penetration of wind and PV at times of low power demand can cause the destabilization of the power system. Modern technologies like wind power forecasting, wind park cluster management and the combination of different renewable power sources to balance fluctuation and meet exactly the load demand are in operation already or developed in demonstration scale (Mackensen et al., 2008). So far, pumped hydro power plants are the most important source for balancing power but capacities are limited nationally or power networks are not strong enough to transport power internationally. In this context, bioenergy can be used strategically as balancing power but maybe not sufficient. Nevertheless, a major challenge is the storage of large amounts of surplus renewable power. A new approach is developed in chapter 4 of this thesis to solve these problems of power storage, balancing power and supply security.

1.2.3 Potentials for a climate-friendly and energy efficient supply

Options for climate protection and a draft of a low-carbon energy system are discussed from a techno-ecological view in this subsection.

1.2.3.1 Options for climate protection: clean coal, nuclear power, natural gas, energy efficiency and renewables

Carbon capture and storage

Great hopes are being pinned on the carbon sequestration and storage (CCS) technology to separate CO_2 after combustion and store it underground. This is technically possible and demonstrated with the drawback of high efficiency losses. In addition, only about 70-80% of CO_2 from coal or other fossil fuels can be sequestrated. Storing CO_2 permanently underground is problematic and sites are limited and difficult to prepare for long-term CO_2 storage (IPCC, 2005). Further, underground site are in competition with geothermal energy use and storage capacities for natural gas and maintenance costs for storage sites are estimated at 1 US$ t CO_2^{-1} yr^{-1}, which cumulates to high amounts over time (SRU, 2009a). As long as these challenges are not solved, the use of coal remains the most climate-damaging form of energy supply. Therefore, the substitution of coal power by low-carbon power generation has the highest priority, resulting in the long run in a shift from fossil fuels to renewables (chapter 5).

Fuel switch to nuclear power

Although nuclear power has many drawbacks and risks like those discussed in the previous subchapter, the question remains, whether it can contribute substantially to climate change and is therefore indispensable. The following sample calculation indicates that this is not the case. Doubling the installed capacity of currently 440 nuclear power plants up to 880 by 2030 would require immense capital and all capacities of existing plant contractors and merely result in a reduction of global GHG emissions of 4% in an ideal case under the optimistic assumption of a GHG free nuclear power generation. At the same time, doubling nuclear capacity would lead to a faster depletion of nuclear fuel reserves.

Fossil energy use has a share of 78% in total global energy consumption and causes approximately 67% of total GHG emissions (chapter 1.1.1 and 1.2.1) (IPCC, 2007d).

Nuclear power covers currently 5.5% of global energy consumption (Figure 1.2-1). Thus, doubling worldwide nuclear capacities could substitute 5.5% fossil fuels and reduce global GHG emissions by 3.7%, assuming emission free nuclear power and neglecting energy-intensive uranium mining. Calculating with real CO_2 emissions of 10-140 g kWh_{el}^{-1} from nuclear power decreases this potential to 2.9-3.6% (Wagner et al., 2008).

This theoretical climate protection potential of 3-4% cannot compensate the risks and consequences of using nuclear energy. Therefore, nuclear power is excluded from further considerations in this work due to substantial operational risks, unsolved waste disposal challenges and a minor climate mitigation potential.

Fuel switch to natural gas

Natural gas emits about 189 g CO_2 kWh_{th}^{-1} and has therefore far lower GHG emissions per energy unit as crude oil (275 g CO_2 kWh_{th}^{-1}) or coal (331 g CO_2 kWh_{th}^{-1}) (IPCC, 2007d), p.264. The following theoretical climate mitigation potentials can be expected by fuel switching: Replacing oil with natural gas would therefore reduce energy related emissions by 12.2% and total GHG emission by 7.3% respectively. Switching from coal to natural gas could result in 16.8% less energy-related emissions (10.1% less total GHG) and the combination of both leads to a reduction of 29% energy-related and 17.4% total GHG emissions. This fuel switching would lead to a faster decline of natural gas resources.

Natural gas has also strategic functions in energy supply. On the one hand, it is flexible in use for all energy appliances (transport, heat, power). On the other hand, natural gas turbines can provide balancing power in few seconds, which is becoming essential for grid stability with high shares of wind and solar power penetration. In this way, natural gas can support the increase of renewable power and maintain supply security. Natural gas can be substituted by biomethane (chapter 3.2.1) or renewable power methane in combination with water and CO_2 from e.g. air (chapter 4.3). In this way, renewable methane makes use of the beneficial properties and functions of natural gas.

Energy efficiency and savings

One of the most feasible and potential instrument for climate protection is the rational use of energy by energy savings and energy efficiency measures in all sectors. Every energy unit saved equals avoided GHG emissions. Main elements like efficiency standards, the use of waste heat in CHP or electromobility are described in detail in chapter 5.2. In theory, a 100% use of waste heat from fossil power generation can save half of its CO_2 emissions (21% of total CO_2 emissions) and renewable electromobility up to 80-90% of GHG emissions in the transport sector.

Renewable energies

By replacing fossil fuels with renewables, in theory, all energy-related emissions can be cut down and thus 67% of the total GHG emissions can be avoided. Practically, even wind or PV systems are causing emissions as their production is still involving fossil energy and thus renewable technology is not totally emission-free. Among renewables, wind energy, solar energy and hydro power (including ocean energy) are emission-free in operation. This energy supply is called 'direct generation', as energy conversion does not contain thermal waste energy unlike thermal power generation. Some large hydro power plants have considerable CH_4 emissions from dams.

The climate effect of geothermal energy depends on the fuel source for the necessary auxiliary energy. If this additional energy is from direct generation, geothermal energy is emission-free. Bioenergy can be emission-neutral and can serve via CO_2 sequestration even as a CO_2-sink, but as well a major CO_2-source; this will be discussed further in chapter 2.4.

Pros and cons of the discussed five options are listed in Table 1.2-1. Energy efficiency and renewables in sustainable energy systems are discussed in detail in chapter 5.25.

Table 1.2-1: Assets and drawbacks of four options for climate protection in the energy sector

Options	Pros, Potentials	Cons, Obstacles
Carbon capture and storage	GHG reduction potential	Supply security Unsolved storage problems Limited storage capacities Competition with geothermal energy and methane storage capacities
Fuel switch - nuclear power	Minor GHG reduction potential	Supply security Proliferation (weapons) Operation security (nuclear accident) Disposal problem
Fuel switch - natural gas	GHG reduction potential Flexible use in all energy sectors Possible balancing power	Supply security Geopolitical conflicts GHG emissions
Energy efficiency	Major GHG reduction potential Applicable for all technologies (supply and consumption) regardless the fuel	
Renewable energy	Major GHG reduction potential Direct generation from wind, solar and hydro avoids thermal losses and has neither fuel cost nor GHG emissions	Need of balancing power Standards for bioenergy necessary

1.2.3.2 Conclusion on a low-carbon energy supply

Conclusion

It becomes clear, that neither carbon capture and storage nor fuel switching to natural gas or nuclear power can reduce energy-related emissions in the necessary way to limit global warming. The only way will be the transformation of energy systems using energy efficiency and renewable energy. The use of wind, solar and hydro energy is beneficial as fuel cost and CO_2 are avoided. The major problems of renewable energy like the integration of fluctuating energy sources can be met among measure like increased power transmission and storage capacities by the newly developed concept 'renewable power methane', described in chapter 4.

Elements of a low-carbon energy supply

The necessary transformation of global energy systems towards a low-carbon energy supply contains four major elements:

1) apply energy savings and energy efficiency measures
2) cover the energy demand primarily with ‚carbon-free' and 'fuel cost-free' energy sources like wind energy, solar energy, hydro power, geothermal energy and ocean energy
3) use 'carbon-neutral' energy sources like sustainable bioenergy or renewable power methane if required in a demand oriented, strategic way for balancing power, heat and special transport segments like long-distance traffic and heavy-duty task
4) cover the residual demand that cannot be met by the first three 'sources' with low-carbon fossil fuels in combination with CCS according to the order of their CO_2 emissions - first natural gas, then oil, and - if unavoidable - coal.

Bioenergy should be as well used according to its strategic properties (stored chemical energy and flexible to use in all energy sectors, widely and equally distributed) and where it can unfold its maximum climate mitigation potential (see chapter 3.2).

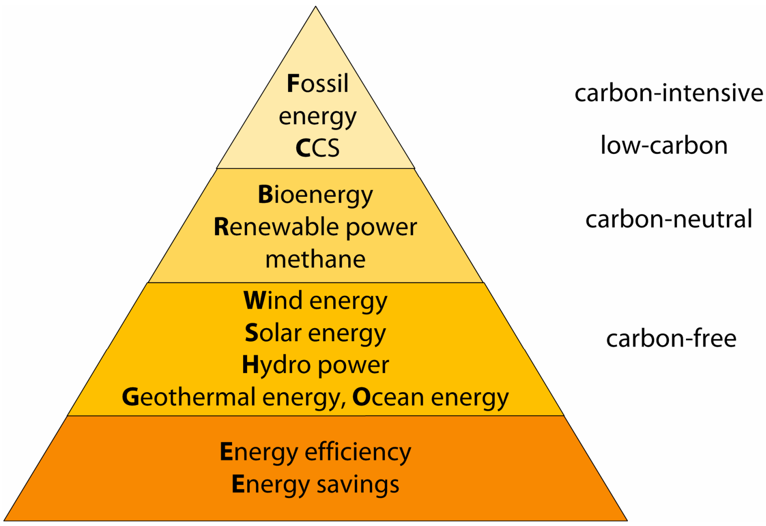

Figure 1.2-8: Pyramid of sustainable energy supply - four elements. CCS - Carbon Capture and Storage. Source: own compilation.

These four elements can build up a low-carbon energy supply, reducing energy-related emissions up to 95% while technical supply security is maintained (Figure 1.2-8). This draft energy system will be described more in detail in chapter 5.

1.3 Land use

Land use is linked to (bio)energy and climate in many complex ways. Fossil and nuclear fuels have been explored mostly underground and affect land use only locally in a small radius. Energy crops are like any cultivated plant, requiring fertile land. Bioenergy is thus the most 'area-intensive' energy source. Land-use and land-cover are mutually affecting the climate system including

(i) the exchange of GHG between atmosphere and land surface (water evaporation, combustion of biomass, soil respiration, carbon uptake, fertilizers, etc.)

(ii) the radiation balance of the land surface (solar and longwave - absorption, reflection (albedo), emission)

(iii) the exchange of sensible heat between atmosphere and land surface

Land use is decisive for the overall GHG balance and effect of bioenergy on the climate (chapter 2.4). Links of land use to climate and bioenergy are examined, looking at the main effects, threats and limitations to bioenergy use in chapter 1.3.1 and 1.3.2. This analysis is applied in chapter 1.3.3 to estimate the potential of bioenergy.

1.3.1 Status quo

1.3.1.1 Past and present land-cover and land-use

Both land-use and land-cover have an effect on the global biogeochemical cycle and thus on the earths productivity of storing energy in plants by photosynthesis. A common indicator for the net carbon uptake by biomass is the 'net primary production' (NPP) (Haberl et al., 2007). 'Land-cover' describes the physical cover of the earth, while 'land-use' refers to the purpose of human activities on land. Definitions of land-cover, land-use and NPP are listed in annex A2. Possible derivations in the following figures result in principle from different classification of land-cover and land-use forms in the course of time (Klein Goldewijk et al., 2004).

Land-cover and land-use changes observed from 1700-2005

In 2005, about 38% of global land area (130 million km²) is used by mankind for agricultural purposes. 12% are used as arable land for food and fodder production and 26% as natural grasslands (pastures). 30% forest area and 32% other land are left. There has been a dynamic development in the past 300 years: In 1700, the share of forest area and other land was about 85% and is today 62%. The growth of world population from approximately 0.75 billon in 1700 to 6.8 billion today increased the demand for food and for fodder, as the number of livestock increased as well (FAO, 2008a). This led to a large scale land conversion of forests and natural grasslands to arable land for crops and livestock (Figure 1.3-1) (Klein Goldewijk et al., 2004).

More than 75% of global land area has been apparently alternated as a result of human settlements or land use like agriculture and forestry (Ellis et al., 2008). 24% or 15.6 Gt C of global terrestrial net primary production (56.8 Gt C) is used by humankind in form of biomass. 58% of this biomass are used as fodder, only 12% as direct food, 20% as feedstock or raw material and 10% as firewood (traditional biomass) (Haberl et al., 2007; Krausmann et al., 2007).

About 0.14 million km² have been used for biofuels in 2004, corresponding to 1.0% of global arable land (IEA, 2006). Meanwhile, bioethanol production has doubled and biodiesel production even quadrupled between 2004 and 2007 (OECD, 2008). Therefore, about 0.20-0.28 million km² or 20-28 million hectare are used today for biofuels only, which is equal half the size of France (USDA, 2008a; Faaij, 2008). It is difficult to estimate the land used for other biomass, esp. for traditional biomass, since data availability is low.

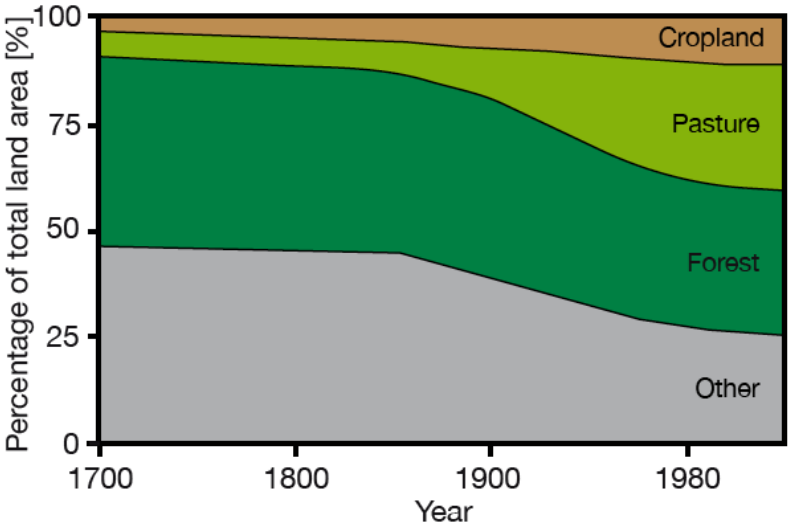

Figure 1.3-1: Estimated changes in land use between 1700 and 1995. Source: adopted from (Lambin et al., 2001), p.262

1.3.1.2 Causes and effects of land-cover and land-use changes

Changes of land-use and land-cover interfere with key aspects of earth system functioning. They contribute to local and global climate change; are responsible for soil degradation; have an impact on biodiversity and affect ecosystems in their functions to provide the basis for human life (Lambin et al., 2001).

Main drivers of land-use change

Main drivers of land-use change are of a demographic, technological, economic and political nature (MA, 2005a). Global population has doubled in the past four decades boosting food and water demand and land conversion. World population is prospected to grow to 8.3 billion in 2030 and to 9 billion in 2050 (UNPD, 2006). Today, about half the world's population live in urban areas that cover less than 3% of terrestrial surface. The urbanization trend is expected to continue so that in 2050 about two-third of global population live in urban areas. This trend goes along with a change in lifestyle and nutrition patterns towards a more resources and area-intensive way of living. The population growth implies an increased agricultural productivity and an exploitation of new agricultural land (Lambin et al., 2001).

Technology developments can decrease pressure on land-use by increasing agricultural yields. The first 'green revolution' from 1960 to 2000 doubled rice and maize yields and even tripled wheat yields in developing countries by improved technology like seed breeding, mechanization or improved fertilization and irrigation (MA, 2005a).

Economic factors usually determine the form of land use. Farmers make their choices according to the market demand. Since the agricultural sector is essential for every economy, it is protected and subsidized in many cases. Subsidies have a strong effect on prices of agricultural products and stimulate land exploitation and yield intensification (MA, 2005a). Other political decisions like trade barriers distort trade flows. Agricultural policy, energy policy, forest policy and climate policy are shaping land-use and are not always in line for the same targets. A positive example is India, where the 'green revolution' was boosted by a governmental program. Policy failure can have negative effects on land use: agroindustry and large landowners often have better lobbies than the poor rural population, ownerships are not clarified and corruption is widely spread. This is often resulting in an extensive use of land and resources, leading to land degradation (MA, 2005a; WBGU, 1999).

Effects of land-use and land-cover change

Land-cover changes and land-use changes have an influence on soil fertility, the carbon stock of the land surface and GHG emissions.

Both land-use and land-cover account for about 33% of GHG emissions. During the past four decades, there has been an increase in global fertilizer use of about 700%, causing a strong increase in N_2O emissions. Large areas of primary forests have been cleared, wetlands dried up and grasslands converted into arable land, releasing large amounts of global carbon stocks (chapter 1.3.2.1). As a result of these human economic activities, land-use change has caused approximately 35% of anthropogenic CO_2 emissions since 1850 (Foley et al., 2005). Intensively used agricultural land develops negative soil properties and leads to degradation. This has an amplifying effect on floods, since degraded land cannot absorb large amounts of rainfall (MA, 2005a).

The conversion of land is also affecting many ecosystems and causing a loss of biodiversity in flora and fauna. Natural habits are destroyed, nutrient cycles disrupted and therefore many species are in danger of extinction (MA, 2005a). Excessive fertilizer application causes eutrophication of waters. This decreases drinking water quality, causes algal blooms and the reduction of fish populations (MA, 2005a).

Land-use changes have a huge impact on global water resources too. Conversion of forest and grasslands to agricultural land decreased evapotranspiration. Today, 70% of global freshwater consumption is used for food production, led by irrigated agriculture that has expanded by 580% since 1900 (FAOSTAT, 2009a; Scanlon et al., 2007).

On one hand, these trends of agricultural expansion and land-use change would continue independently of modern energy crops plantation and bioenergy production. On the other hand, care needs to be taken that energy crops do not accelerate the competition on land for agricultural production (food) and negative environmental effects of global land-use trends and serve their main purpose: climate protection.

1.3.2 Threats

Global ecosystems are threatened by land-use changes decreasing their storage capacity for carbon (chapter 1.3.2.1). Bioenergy crops are amplifying the pressure on land and are thus in competition with food and fodder production, material and fiber use and freshwater resources (chapter 1.3.2.2).

1.3.2.1 Land conversion – impact on world's carbon stocks

Land conversion can have a negative or a positive effect on carbon stocks. The conversion of forests and peat lands to arable land is decreasing soil carbon stocks drastically, whereas the conversion vice versa by e.g. afforestation of cropland increases soil carbon stocks significantly (Figure 1.3-3) (Guo et al., 2002).

Total carbon stocks composite basically of 'aboveground biomass' (carbon in harvested biomass, dead wood or litter) and 'belowground biomass' (soil carbon) (FAO, 2005). The splitting of carbon stocks depends on the ecosystem. Forests are storing about 638 Gt C, corresponding to 40% of total global terrestrial carbon. Half of this is aboveground biomass and half soil carbon. This relation is important to understand CO_2 sequestration via biomass. Half or more of the CO_2 extracted from the atmosphere via photosynthesis is stored underground and not harvested (Figure 1.3-2).

Figure 1.3-2: 'Aboveground biomass' (grass) and 'belowground biomass' (soil carbon in roots) of a switchgrass plant. Source: (Loose, 19.11.2008).

Every year, an estimated 1.6 to 4 Gt C of this carbon stock of forests is lost mainly due to clearing of forests for agricultural land (IPCC, 2007d; FAO, 2006). In Brazil for example, large areas of rainforests are cleared for cultivating soya (Tollefson, 2008). The amount of carbon lost by energy cropping varies with the way and intensity of land-use change that goes along for the purpose of bioenergy. If firewood is extracted for traditional use, the impacts are far smaller than if a wide area or rainforest is removed for energy crop plantations.

Besides forests, peatlands are among the most productive ecosystems in general. Although they only cover 3-4% of land area, they store about 540 Gt C globally, which is 25-30% of total carbon stock (MA, 2005c). The conversion of peat land to arable land results in large amounts of GHG emissions (Figure 1.3-3). About 45% of peat lands in South-East Asia (Indonesia, Malaysia, Brunei, and Papua New Guinea) have been cleared and drained for agricultural use, mainly for oil palm plantations. Peatland conversion causes an estimated 632 million tones of GHG emissions annually (Hooijer et al., 2006). The conversions of forest and peatlands to energy crop plantations are therefore not beneficial for climate. Studies for the net effect of biofuels on climate change indicate that the 'pay-back time' of such land conversions e.g. for palm biodiesel ranges from 86 years on tropical rainforest to 423 years on peatlands (Fargione et al., 2008).

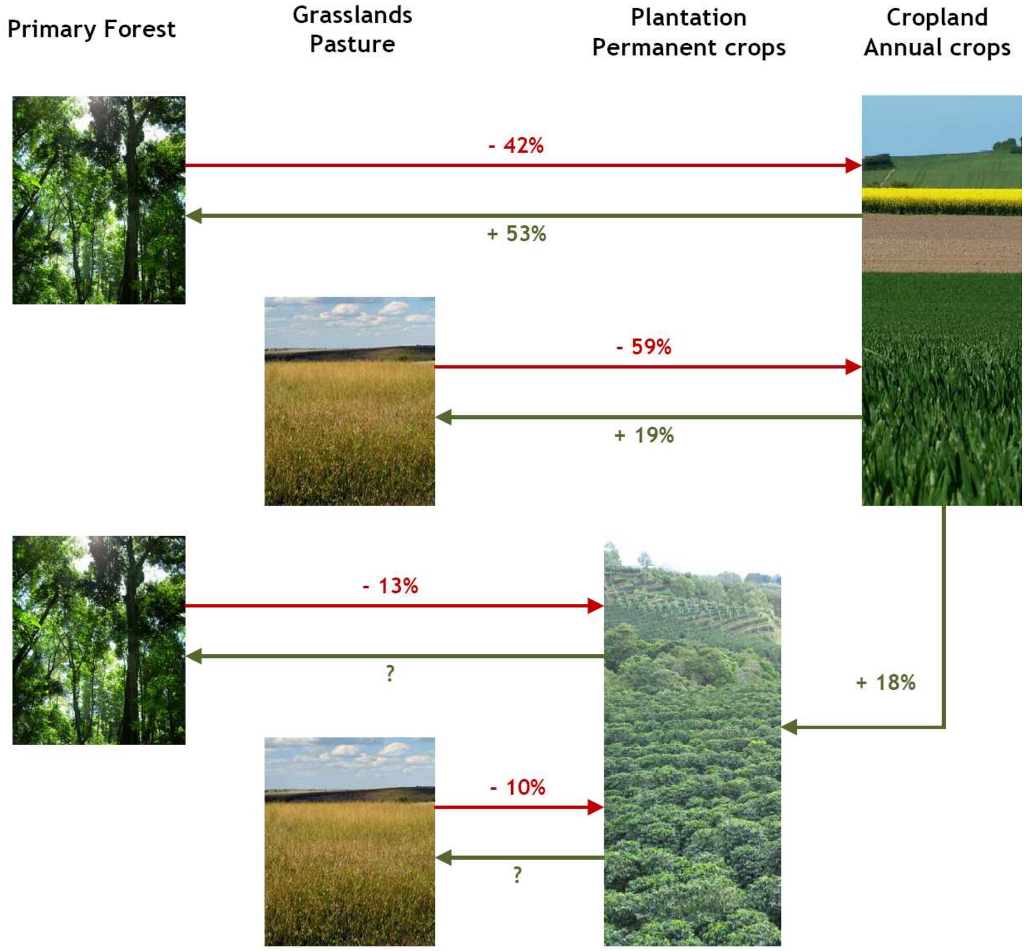

Figure 1.3-3: Effects of land-use change on soil carbon stocks. According to the land-use change applied, the soil carbon stocks increases (positive percentage) or decreases (negative percentage). Source: own compilation based on data from (Guo et al., 2002).

About 34% of total carbon stocks are stored in grasslands, which cover about 26-40% of land area (depending on the definition) and approximately 70% of agricultural land (White et al., 2000; FAOSTAT, 2009a). The main share of grasslands carbon is soil carbon stored in roots. Therefore, high intensive grassland cultivations like low-input high-diversity grassland ecosystems increase the stored carbon and are suitable for sustainable bioenergy production (Kägi et al., 2007; Tilman et al., 2006).

Afforestation of grasslands is another preferable option for climate mitigation. Cultivating energy crops or afforestation on marginal and degraded land has also benefits for soil carbon stocks. In contrast, the conversion of grasslands to croplands results in higher CO_2 emissions and a more vulnerable soil for erosion, since the soil respiration is amplified by opening the permanent vegetation cover (FAO, 2006).

GHG emissions do not only occur at land-use conversion. Every time the vegetation cover is changed e.g. by plowing; soil respiration is activated and the soil ‚looses' carbon i.e. emits CO_2 to the atmosphere. Therefore, those cultivations are favorable, which cover the soil permanently and are not ploughed up annually. Moreover, perennial crops are less fertilizer intensive and thus causing less damage to climate. Out of these reasons, perennial crops like 'short rotational crops' and 'sorghum' are more advantageous than annual crops like maize, wheat or rape.

Negative effects of soil respiration can be accepted for food production, since there are not other sources for food. This applies not for energy crops, since there are alternative ways for energy supply and bioenergy intends to mitigate climate change. Therefore, realistic GHG balances of bioenergy cover also emissions from land-use changes.

1.3.2.2 Land-use competition of bioenergy with food, materials, water and biodiversity

Land-use competition with food

Food is the most aboriginal form of land use. In history, there has been always enough land available to nourish people. Now, as world population increases drastically, the area available per person is shrinking. The per capita agricultural area for food depends much on eating habits and nutrition patterns.

In 2007, an estimated 923 million people or 17% of global population are chronically undernourished, most of them living in developing countries. This number increased by more than 80 million since the beginning of the 1990s and decreased at the beginning of this millennium. However, the positive trend reversed between 2003-05 and 2007. High food prices are the major cause for this misery, driving an estimated 75 million people more into food insecurity, especially in 'low-income food-deficit countries' in Sub-Saharan Africa and Asia. A main cause of malnutrition is not global food availability but the right and just distribution and accessibility, which is primary a matter of cost and security. On the other hand, high food prices are also an opportunity for those who own agricultural land and have access to markets. Crops can generate more income and in the long run more employment too (FAO, 2009).

Competition on land use is expected to increase with global population growth. A plus of 50% of food will be necessary to 'feed the world' of 8.1 billion people in 2030. As the expansion of agricultural land is limited by water resources, soil degradation and nature conservation, this plus has to be supplied 80% by improving agricultural productivity. But not only the mass of demanded food will increase but also the per capita food consumption, which is about 2,800 kcal person^{-1} day^{-1} and expected to increase to 3,050 kcal person^{-1} day^{-1} in 2030 (FAO, 2006, FAO, 2003).

To estimate the trend of nutrition patterns is difficult and depends on the global economic development. In general, countries with higher incomes have also a more resource-intensive way of life. Approximately 60% of global population will live in urban settlements by 2030. The nutrition pattern of urban population is very 'area-intensive', as more ready-made and livestock products (e.g. meat, milk, eggs) are consumed (FAO, 2006). Figure 1.3-4 illustrates the area in m² necessary to provide 1,000 kcal of different food products.

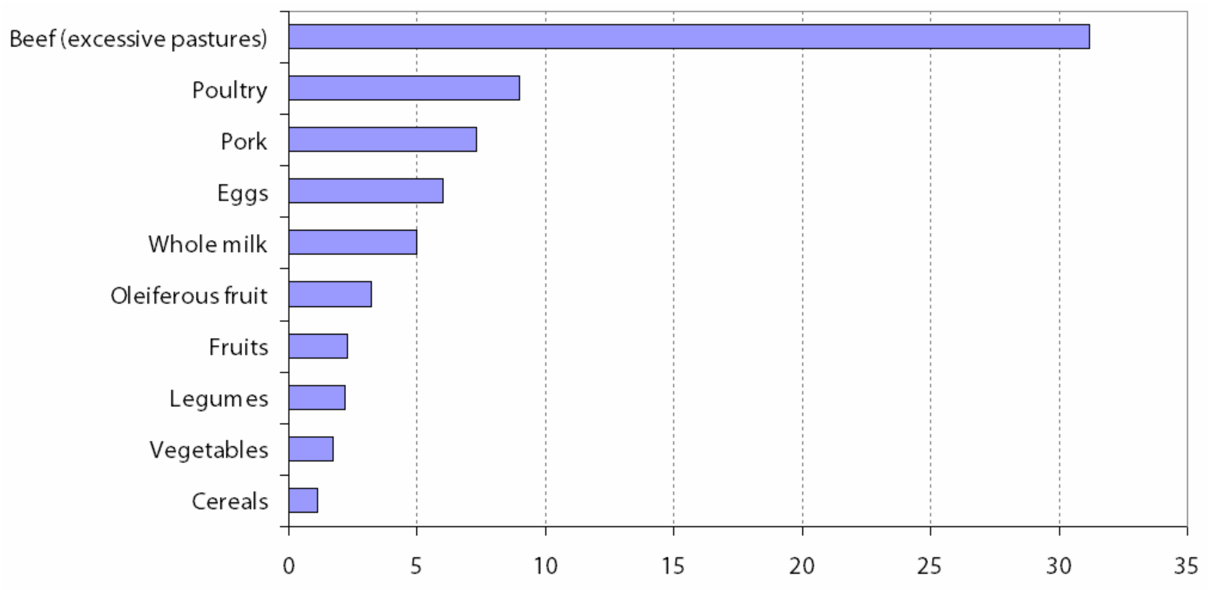

Figure 1.3-4: Land required and space needed for different food products per 1,000 kcal food energy content in the USA. Source: own compilation, based on data from (Peters et al., 2007).

There are clear trends towards more area-intensive food consumption. Globally, 83% of food is vegetable food like cereals that occupies 20% of total agricultural land. In contrast, 17% of food is provided by livestock products, which occupy 80% of agricultural land (FAO, 2006). Industrial countries use to some extent more agricultural land than they have. EU-15 countries increase their per capita agricultural land by 20% through imports, mainly animal fodder like soya for pig husbandry (Steger, 2005).

The so called 'welfare nutrition' composites of a high share of livestock products like meat, diary products, fruits and oils. Global agriculture is able to increase productivity and supply sufficient food, but it will not be able to nourish global population at the western welfare diet standards, which would increase the necessary agricultural land 2-3 times from today's 34% of land up to 100% and more (Gerbens-Leenes et al., 2002; Balmford et al., 2002). Even if this extreme case does not become reality, land available for other purposes like bioenergy will get rare. Brazil is one of the countries, where diets adopt to Western standards, large areas are used for bioethanol and simultaneously GHG emissions from deforestation are the 2nd highest worldwide (Schulze et al., 2007).

The FAO expects that beside the 80% increase in agricultural productivity, 11-13% additional land will be required to nourish world population in 2030. Mostly natural habits like forests and grasslands will be converted for this purpose to arable land, which has a negative impact on carbon stocks, biodiversity and ecoservices (chapter 1.3.1.2 and 1.3.2.1). This land-use change and productivity rise will - if not done sustainably - amplify climate change. An increase of global mean temperatures by 1-3 °C may still boost crop yields while an increase by 2-4°C and beyond depresses productivity and agricultural outputs at a global scale (Fischer et al., 2002; IPCC, 2007a). Extreme weather events like heat waves and higher growing season temperatures are very likely to have a dramatic effect on food security and agricultural productivity. Balancing food deficits in one part of the world with food surpluses in other parts will become a major challenge if agricultural production is not made tolerant to heat and water stress (Battisti, 2009).

Bioenergy can intensify future food crises. Already today, the food crisis of 2006-2008 is linked to the drastic growing demand for bioenergy feedstock. The exact contribution of biofuels in mid-2008 food prices is difficult to quantify. Depending on the method used, the results spread from 2-3% (USDA, 2008b) to 75% (Mitchell, 2008) of biofuels share. OECD estimates 5% for cereals, 7% for maize and 19% for vegetable oil (OECD, 2008); IFPRI approximates 30% for wheat (IFPRI, 2008). Bioenergy is just one driver of higher food prices along with e.g. higher production costs (energy, fertilizers) and harvest failures in key regions. Nevertheless, a further growing demand for bioenergy from energy crops will not release pressure on land use nor on agricultural prices (FAO, 2008b).

Rising fossil energy costs stimulate the production of biofuels as they become competitive. Today, biofuels would not be competitive without subsidies. This indicates the influence of policy. In contrast, provision cost of biomass feedstock accelerate as food prices increase and both food and feedstock come from the same market. (FAO, 2008b). Regardless, as land is getting rare, competition rises for the most productive areas and the fear cannot be dismissed, that customers pay a higher price for biofuels than for food and land is used for bioenergy while a large share of human population is suffering hunger.

Therefore, a clear priority for food is essential (WBGU, 2009) and bioenergy should be applied in a non-competitive way, e.g. by using the by-products of food production like residues (straw, shells) and waste (manure, fat) for energy purposes. Areas with high productivity will be required to ensure food security and therefore it is recommendable, to use marginal and degraded land for energy crops.

Land-use competition – material and fiber use

Biomass is not only used for food or energy, but increasingly as material and fiber for industry. The most popular use is probably timber and wood products from forestry for pulp and paper and for use in construction and furniture. These products are well documented and trade flows monitored (FAO, 2007).

Other products from biorefineries like organic oils, fertilizers, paints and lubricants as well as organic plastics (polymers, monomers) are still quite new and not directly registered in international trade. Main inputs to biorefineries are sugar, oil and fiber plants as well as carbon hydrate plants like wheat. Therefore, biorefineries are in direct competition with bioenergy and food. Today, all plastics, bitumen and lubricants account for about 10% of global crude oil consumption (IEA, 2006; IEA et al., 2008). Approximately 10% of global arable land would be necessary in theory, to replace all these products based on crude oil with biorefinery products (WBGU, 2009).

The situation of forestry is different to agriculture. Competition rises between material use of conventional forestry and bioenergy, food is excluded from this competition. Forests cover about 30% of global land area of which 34% are used for production of wood fuel or industrial purposes (Figure 1.3-6) (FAO, 2007).

Today, 3.6 billion m³ of timber are extracted every year of which 53% are used as wood fuel (firewood and charcoal, mostly as traditional biomass) and 47% as industrial roundwood for secondary products like wood pulp for paper and books (35%) or wood panels for furniture and construction (12%). This rate varies significantly by continent (Figure 1.3-5) (FAOSTAT, 2009c; MA, 2005d). Although the amount of wood removal appears huge, the annual growing stock usually far larger than quantities withdrawn. In Africa, the 90% woodfuel withdrawn accounts only for about 1% of growing stock (FAO, 2007).

A clear trend is notable: wood is increasingly used for energy as fossil fuel prices rise and environmental policies fix woody biomass as part of sustainable energy policy. This growing demand is competing with material use: primary and secondary paper products still dominate the international trade of forest products, which doubled between 1990 and 2004 and continues to grow, as the per capita paper consumption increases (FAO, 2007). This emerging competition will have a feedback to other functions of forests, which might be negative (deforestation, GHG emissions, biodiversity).

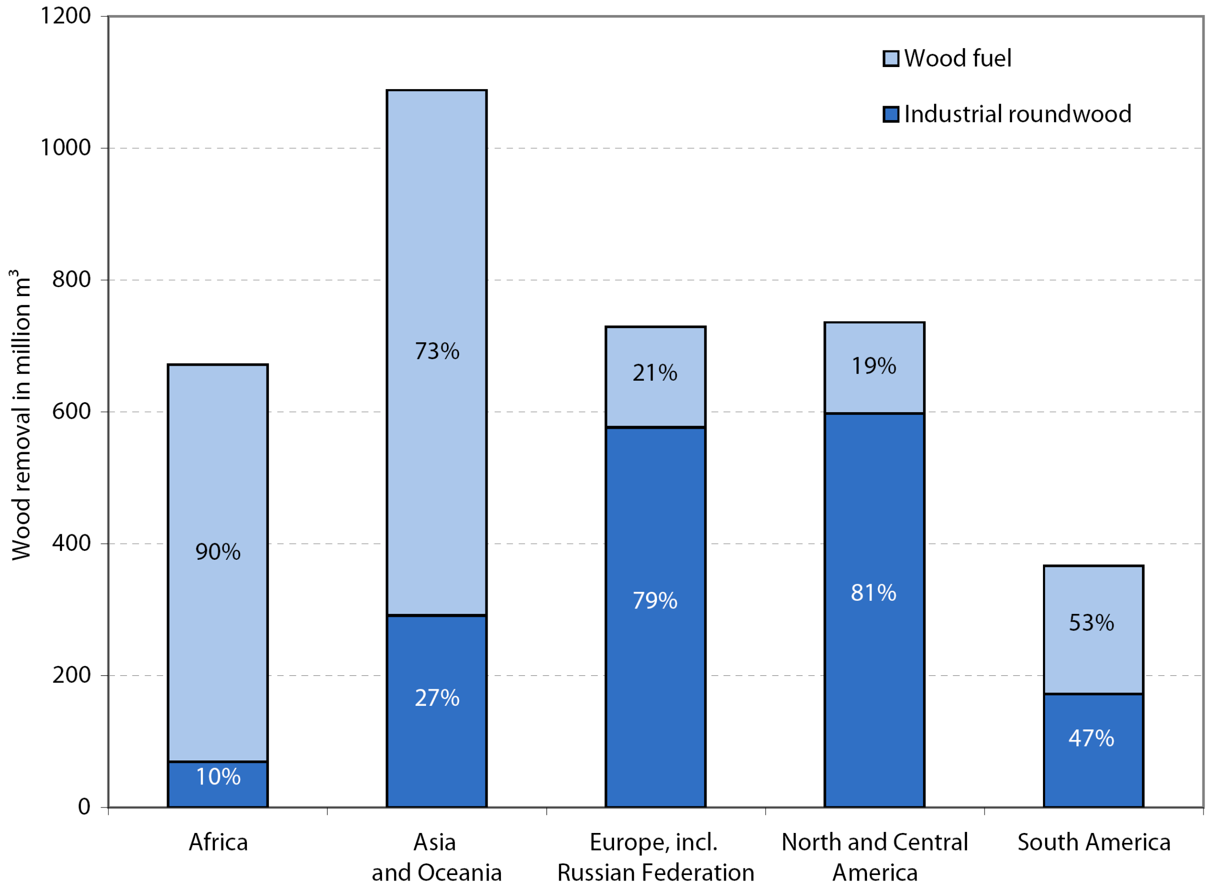

Figure 1.3-5: Wood removal 2007 for energy and material use in million m³; Total: 1705 million m³ industrial roundwood (47%) and 1,886 million m³ wood fuel (53%). Source: own compilation, based on data from (FAOSTAT, 2009c).

Tensions on forests and agricultural land can be relaxed by increasing efficiency and resource savings, similar to the energy sector. Efficiency in feedstock provision and product processing can be improved. Resource savings can be established by a more efficient consumption and by a multiple and cascade use of products (Figure 1.3-6).

Some examples for recycling and multiple uses of products are already established: Residues of timber industries like saw dust are used as pellets for heat and power generation. Black liquor from pulp mills can be used in the same way in CHPs and as well to produce transport fuel like dimethylether (Sterner, 2007). The food processing industry produces large amounts of organic waste that can be used energetically, for example by fermentation to biogas for heat and power supply.

Cascade use is as well as suitable solution for the increasing energy-material competition. First, forest and agricultural products are used as materials and later as bioenergy feedstock. Product design has to consider the attached energetic use and to be adopted accordingly. Examples are biorefinery products like plastics and lubricants or forest products like furniture and construction materials. Cascade use can also be applied for agricultural commodities, e.g. for rape: rape seeds are extracted; the oil is used for energy (CHPs or heavy-duty transport) and the rape seed extract substitute's maize as fodder. The rape straw is used for energy or as fertilizer left on the acre. In this way, one hectare serves two purposes and land-use competition is mitigated.

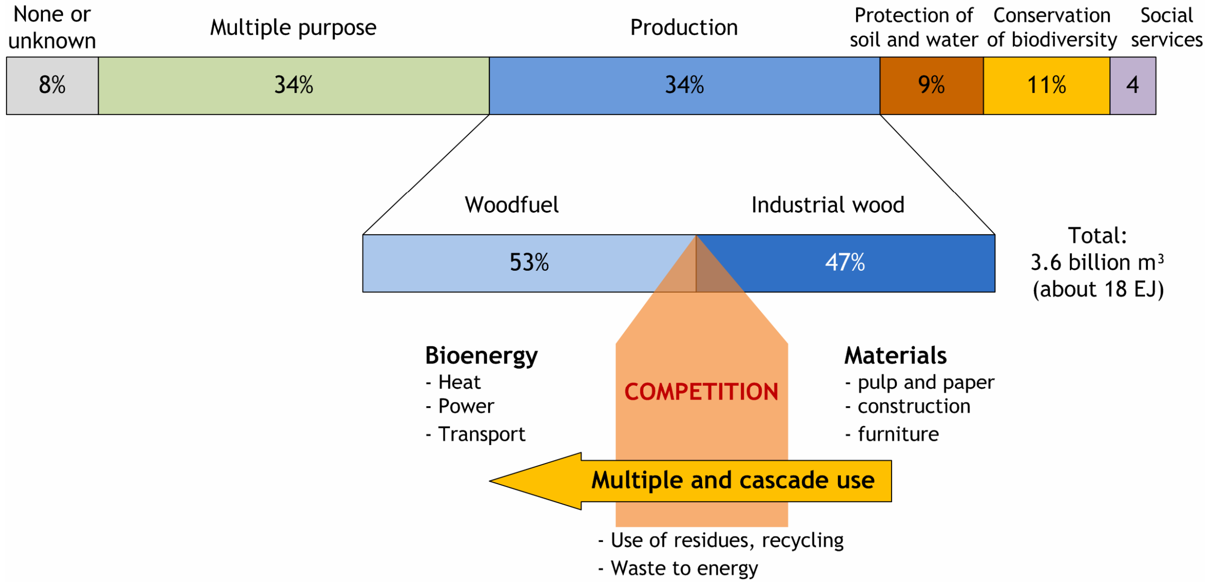

Figure 1.3-6: Primary functions of forests; 2007 shares of woodfuel and industrial wood - total: 3.6 billion m^3 or about 18 EJ; Multiple and cascade use - a possible solution for material-energy competition. Source: own compilation, based on data from (FAOSTAT, 2009c; FAO, 2007).

Agroforestry is another way to overcome land-use competition: one area is used for several purposes by combining trees with crops and/or livestock (silvopasture) in an intensive land-use management. Forestry can thus be combined with crop plantation for energy or other purposes like mitigation of soil erosion, habitat for biodiversity or improving water quality (CfA, 2008).

Land-use competition – water and soil resources

As global population grows and nutrition patterns become more resource-intensive, water is getting rare. Water scarcity may therefore limit energy crop cultivation.

70% of freshwater withdrawn is used in agriculture and is in competition with domestic, industrial and energetic uses like for cooling of thermal power plants (Figure 1.3-7) (FAOSTAT, 2009a). Water scarcity is already today a problem. About one billion people, mostly in developing countries, do not have access to drinking water and 2.6 billions do have neither a water supply nor a sewage system (Bauer et al., 2008). In contrast, 20% of arable land is artificially irrigated (FAOSTAT, 2009a).

An easy link between water shortage for people and available water for energy crops is not valid and depends on geographic, demographic and other parameters. Globally, there is sufficient water for agriculture and energy crops. However, the distribution of freshwater varies significantly from region to region. In countries like India and China, which are suffering from water stress and have high levels of food production and consumption, energy crop plantations can worsen water scarcity (de Fraiture et al., 2007). As diets change especially in emerging nations, not only more agricultural land is used because of a shift towards higher shares of livestock products but also the water demand increases. The production of meat requires 4,000 to 15,000 liters per kg, whereas grain productions manage on 1,000 to 2,000 l kg^{-1} (Scanlon et al., 2007).

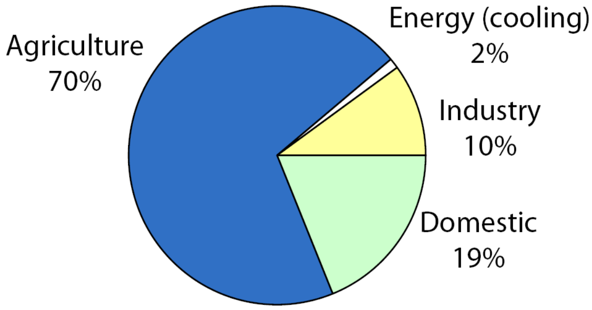

Figure 1.3-7: Global water use split in main demand sectors (UNESCO, 2009).

Currently, energy crops use an estimated 100 km^3 of freshwater per year, which represents 1% of all water transpired in agriculture. In addition, 2% or 44 km^3 of all irrigation water is used for bioenergy feedstocks. The amount of water necessary for bioenergy varies by region. In tropical Brazil under rain fed conditions, one liter of ethanol from sugarcane requires only 90 l irrigation water. In contrast, in rural India it takes 3,500 l of additional water to produce one liter ethanol, as sugarcane depends strongly on irrigation. The global average is at 820 liters per liter ethanol (de Fraiture et al., 2007). Also many other crops like oil palm and maize have high water demands to reach commercial yield levels. Rainwater harvesting can mitigate water stress and be very useful for energy crops as well (Berndes, 2008).

Again like in all ambivalent topics of bioenergy regarding climate change, carbon stocks, biodiversity or soil quality, the net effect of bioenergy can be both positive and negative, i.e. that water is stored or withdrawn from the soil. This depends on the plantation place, the water demand of the energy crop (C4 plants are more efficient than C3 plants) and which type of vegetation they replace. On one hand, deforestation of dense forests for planting energy crops like sugar cane or maize is reducing water availability. Plantations with little water demand like sorghum on marginal land and areas with sparse vegetation can improve water availability, as they reduce direct surface runoff and improve infiltration. In this way, water erosion is mitigated and soil quality improved. Perennials like fast growing woody biomass can also provide wind shelter and mitigate wind erosion (Berndes, 2008).

Impacts on soil resources

If land management and farming techniques are not sustainable, soil can loose its nutrients and thus its productivity and ability to filter water, nourish plants and host biological diversity. Just like any crops, energy crops can have a positive effect on soil quality and increase soil carbon stocks (chapter 1.3.2.1). They can have also a negative effect by reducing organic matter in soil and increase soil erosion, leading in the worst case to irreversible degradation. Basically, this effect depends on the cultivation practice. Soil quality will degrade if agricultural production is intensified by heavy-duty machines causing soil compaction, overdose of fertilizers and destructive irrigation. Already 38% of world's arable land, 21% of grasslands and 18% of forests and savannas are degraded, mainly caused by overgrazing and agricultural activities (WBGU, 1994). Newer studies number even half of global arable land as degraded (Bauer et al., 2008), p.14-15. Soil degradation amplifies desertification, especially in drylands, which cover 41% of global land area and host about 2 billion people. Water scarcity, intensive land use and climate change cause heavy stresses for the population (MA, 2005b).

On the other hand, energy crops can also reverse soil degradation. Crops like Jatropha or Pongamia can improve the vegetation cover and hence enrich soil with carbon and nutrients. Combined with soil friendly land management techniques like conservation- or no-tillage, terracing, reduced pesticide input, addition of alkaline lime fertilizer and drainage if necessary, degraded land can be recovered (Bauer et al., 2008; FAO, 2008b). A fundamental aspect is the conservation of the vegetation cover. Therefore, perennials like short-rotation coppice, switchgrass, palm or sugar cane are to favor compared to annual crops like wheat, sugar beets, rape or maize (FAO, 2008b). In the ideal case, degraded land can be recovered by sustainable energy crops for some period and later be used as arable land for food.

Land-use competition – biodiversity

The restoration of marginal and degraded lands by energy crop plantations can have a positive effect on biodiversity, but in most cases, plantations are a threat to biodiversity. Bioenergy is in competition with biodiversity, if protected areas are to be converted into plantation. Especially primary forests or peat lands host many special wildlife flora and fauna, which would be displace or even extinguished as their habitats are lost. The growing demand for biofuels is a driver for deforestation. Palm oil plantations are related to rain forest clearing in South-East Asia, especially in Malaysia and Indonesia (UNEP, 2008; Reinhardt et al., 2007). The correlation is obvious: both countries produce about 90% of global palm oil production and Indonesia has the highest deforestation GHG emissions, followed by Brazil and Malaysia (Schulze et al., 2007).

Conversion of agricultural land to energy crop plantations can also cause indirect effects, which can lead to land-use changes elsewhere. The displacement of food and fodder production by energy crops does not lower the demand for agricultural commodities. Therefore, food and fodder has to be produced somewhere else, causing land-use change with all negative consequences (WBA, 2007). Examples are the extension of sugarcane plantations in Brazil, displacing food production to areas with high biodiversity like Amazon rain forest or savannas, where natural ecosystems are converted into arable or grazing land (Sawyer, 2008). International trade globalizes this problem. Subsidies for ethanol production in the USA accelerate maize cultivation, displacing soya. Consequently, world prices for soya rise and soya production is taken up somewhere else (Searchinger et al., 2008), e.g. on arable land in Brazil, displacing agricultural cultivations to the Brazilian rainforests and so on (Morton et al., 2006).

Similar effects can be derived for Germany's rapeseed plantations, as fodder is demanded by animal husbandry and soya is increasingly imported as additional fodder.

In all discussion related to energy crop cultivation and its impact on ecosystems, it is necessary to distinguish between the type of energy crops and the land-use change previous to plantation. The palm oil tree itself is one of the most productive plant existing and does not need much fertilizer or pesticide and grows as well on poor soils. What is crucial is the annexed land-use change. If primary forests are converted into palm oil plantation, the overall effect on climate, biodiversity, water and carbon stocks is negative. If palm oil plantations are put on marginal and degraded land, the overall effects are positive (Soyka et al., 2007; CBD, 2008). A parallel and multiple use of land for protection, CO_2 sequestration, biodiversity and bioenergy can be very beneficial for ecosystems (Wiegmann et al., 2007). However, clear conclusions cannot be drawn yet, as data quantity is little and more analysis has to be carried out on the interaction between energy crops and land use (FAO, 2008b).

1.3.3 Potentials of land-use for climate protection and bioenergy supply

1.3.3.1 Options and estimated costs for climate protection in land-use

In principle, there are three fundamental ways for climate protection in land-use, land-use change and forestry (LULUCF) (IIASA, 2008):

(i) conservation, to prevent emissions from existing carbon stocks, e.g. avoided deforestation

(ii) sequestration, to increase carbon stocks, e.g. afforestation, reduced tillage, less fertilizers, longer rotations (perennials instead of annual crops)

(iii) substitution, to substitute fossil fuel (products) with renewables, e.g. sustainable bioenergy or solar energy; timber instead of concrete

The carbon mitigation potentials differ significantly by region, measure and time horizon chosen to compare options.

Conservation

Deforestation accounts for 17% of global GHG emissions (chapter 1.1.1), mainly due to the extension of agricultural land (Geist et al., 2002). Over 50% of these emissions are reported from Indonesia and Brazil, major palm oil and sugarcane producers (Houghton, 2003). The cost of avoiding these emissions from deforestation is estimated at 1-2 EUR ha^{-1} (Grieg-Gran, 2006) and therefore much more economic than most bioenergy options (chapter 2.4.4). Emissions in forestry can be as well avoided by a better timber management like longer rotation cycles or preventive measures from forest and bush fires. Improved crop and grazing land management or less fertilizer use can avoid GHG emissions in agriculture (IPCC, 2007g).

Sequestration

Sequestration can be done by afforestation and agricultural measures. Varying with tree species and land type, afforestation can accumulate about 1-35 t CO_2 ha^{-1} yr^{-1}. Reforesting arable land with pine is estimated to sequestrate roughly 15-29 t CO_2 ha^{-1} yr^{-1} in tropical regions (Righelato et al., 2007). The estimated costs are varying as well by site and land region and are influenced by the costs of available land, site preparation and labor (IPCC, 2007d), p.550-551. Costs range from 0.5 to 7 US$ per t CO_2 in developing countries, compared to 1.4 US$ to 22 US$/t CO_2 in industrialized countries (Righelato et al., 2007).

Agricultural soil carbon sequestration can be realized by reduced tillage and measures like reverting agricultural land to natural vegetation or black carbon sequestration. The latter is a mixture of sequestration and substitution. Biomass is decomposed to black carbon and a flue gas via low-temperature pyrolysis. The flue gas can be cleaned, upgraded and used as synthesis gas for biofuels and chemical products respectively and for heat and power generation. This is substituting fossil fuels. The separated black carbon can be stored by plowing into agricultural land, improving soil quality and acting as fertilizer. This technology is still at it's very beginning and GHG mitigation costs are estimated to about 40 US-$ t (Lehmann, 2007).

Substitution

Bioenergy can reduce GHG emissions by substituting fossil fuels. GHG reduction potential and mitigation costs of bioenergy are calculated in chapter 2.4. Land can be used for alternative substitution options like other renewables. In comparison with photovoltaics, the conversion efficiency of photosynthesis is rather small: on average, only 2% of annual input can be converted into chemical energy while solar cells harvest on average 15% (Schmidhuber, 2006). To substitute the same amount of fossil fuels, solar energy is 10 times more area-efficient than bioenergy in a rough estimation assuming average crop production. Nevertheless, bioenergy has specific characters which make bioenergy a strategic option in energy supply (chapter 3.2.1.2).

Besides fossil energy itself, also energy-intensive products can be replaced by biomass. Agricultural and forestry products like plastics or timber as construction material can substitute e.g. fossil plastics and chemicals, concrete, steal or aluminum. This substitution of materials can be combined with the substitution of energy carriers in the form of cascade use (chapter 1.3.2.2). Wood replacing concrete in building industry and later used as energy is maximizing the climate mitigation potential of woody biomass, as the CO_2 withdrawn from the atmosphere is fixed in biomass; stored in construction material replacing energy-intensive concrete and finally; emitted back to the atmosphere, avoiding fossil fuel emissions (IPCC, 2007a). Substituting basic substance of the chemical industry by biomass products can avoid as much GHG emissions per hectare as biofuels for transport (IFEU, 2007).

1.3.3.2 Potential for bioenergy

What is the technical, economic, or sustainable potential for bioenergy? This question is fundamental in classifying the role of bioenergy in future energy systems and climate mitigation. Studies on bioenergy potentials vary strongly with the assumptions made for agriculture and forestry. Three parameters are dominating the variation: availability of land (food demand, nutrition patterns and diets, industrial wood demand), irrigation (artificial or rain fed) and intensification (crop productivity, agricultural management).

Bandwidth of 15 selected bioenergy potential studies

To approximate a reasonable bandwidth, 15 selected recent studies have been reviewed and main figures extracted in Table 1.3-1. The comparison of these studies is difficult as they use different definitions and methodological assumptions on the above mentioned uncertainties. A rough classification in technical, economic and sustainable potential is done, whereby the definitions of 'sustainability' vary as well from study to study. Technical potentials are naturally larger than economic or sustainable potentials, as technically feasible is neither equal to economically feasible nor environmentally sustainable. The upper limit of bioenergy is given by the total energy collected by plants via photosynthesis. (Kapur, 2004) estimates this figure on 3,150 EJ yr^{-1}, which includes large amounts of biomass that (i) cannot be accessed or harvested or (ii) are used already as food, fodder or roundwood for energy and industry. For example, about 1,150 EJ yr^{-1} are produced as phytoplankton and other plants in the oceans and necessary for maritime food chains and at the same time very difficult to harvest (Kapur, 2004). Subtracting other similar inaccessible shares, roughly 1,000-1200 EJ yr^{-1} are available for all human needs: food, fodder, materials and energy. This rough estimate is an essential background in bioenergy potential discussions.

Most research has been done on energy crops potential, since it seems the largest item in future bioenergy supply. At the same time, it is the most controversial and inestimable. (Wolf et al., 2003) estimates this potential from 0-790 EJ yr^{-1}, whereby the value zero results from an estimation that all arable land is required for food production as the scenario contains a high population growth and extensive agriculture production. On the contrary, the upper value of 790 EJ yr^{-1} origins from a scenario assuming that agricultural productivity and intensification will rise to an extent where arable land is set free and can be used for energy crops. (Smeets et al., 2007) calculates a maximum crop potential at 1272 EJ yr^{-1}, assuming drastic improvements in land management, technology and irrigation and as well a vast increase of productivity combined with intensification. Assumptions and values above 800 EJ yr^{-1} seem unrealistic, as water resources may get scare in the future and all current arable land and even more will be required for food and fodder (as human diets are and will likely stay area-intense, see chapter 1.3.2.2).

Study	Potential, Year	Surplus forestry	Energy crops and plantations			Residues and waste			Sum
	TECHnical, SUSTainable, ECONomic		Arable land	Degraded, margin. land	Waste -, Barren land	Agriculture	Forestry	Organic waste	
Studies considering all elements of bioenergy potentials									
WBGU (2003) Kaltschmitt et al. (2003)	SUST	-	37			17	42	8	104
Berndes et al. (2003)	TECH, 2050	53-115	40-238			29-98	14-15	16-72	152-538
Smeets et al. (2007)	TECH, 2050	74	215-1272	-	-	76-96			365-1442
IFEU (2007)	ECON, 2050	0-45	200-390	15-30		15-70	5-30	5-55	240-620
OECD-FAO (2007)	SUST, 2050		109	-	-	35	91	10	245
Faaij (2008) Dornberg (2008)	SUST, 2050	60-100	120-190	70-140		40-170			430-740
Greenpeace (2008)	TE / SU, 2050	-	6-97			87			93-184
Behringer et al. (2008) WBGU (2008)	SUST, 2050	-	34-120			50			84-170
Studies on surplus forestry potentials									
Rokityanskiy et al. (2007)	TECH, 2050	145							145
Studies on energy crop potentials									
Wolf et al. (2003)	TECH, 2050		0-790						0-790
Hoogwijk et al. (2005)	TECH, 2050		-	43-268^{A}	129-409^{A}				172-777
Tilman et al. (2006)	SUST		45						45
Campbell et al. (2008)	SUST		32-41						32-41
Field et al. (2008)	SUST		-	-	27				27
Studies on residues potentials									
Vis, van den Berg (2006)	SUST					19	10	-	29
Estimated range used	SUST	30-70	5-140			30-90			65-300

Table 1.3-1: Review of recent bioenergy potential studies. ^{A} only one type of energy crops: woody biomass from short rotation crops. Source: own compilation, extended from (WBGU, 2009).

Recent studies, influenced by the global food shortage and increase of undernourished population, exclude arable land and limit the areas considered for energy crops to marginal, barren or degraded land. They therefore result in lower bioenergy potentials. (Field et al., 2008) estimates a sustainable energy crop potential "that does not reduce food security, remove forests, or endanger conservation lands" to harvestable bioenergy of approximately 27 EJ yr^{-1} by calculating the potential NPP on the available land of 386 million ha. In a similar range, (Campbell et al., 2008) estimates a potential of 32-41 EJ yr^{-1} for energy crops on degraded and abandoned agricultural land.

A very low estimate of 6 EJ yr^{-1} is found in (Teske et al., 2008), assuming reduced use of barren land for agriculture, no forest clearings, expanded ecological protection areas and reduced crop yields. (Beringer et al., 2008) uses a dynamic land-use vegetation model that integrates shifts of soil carbon and water due to climatic changes. The calculations exclude today's agricultural land, protected areas and land that cannot compensate emissions from land-use change by bioenergy within 10 years. The scenarios calculated result in energy crop potentials in the range of 35 EJ yr^{-1} (high food demand, high biodiversity conservation, rain-fed) up to 120 EJ yr^{-1} (low food demand, low biodiversity conservation, artificial irrigation). (Dornburg, 2008) integrates many aspects (food supply, water use, biodiversity, agro-economic and GHG effects, energy demand) which were missing or not bundled in previous studies and examines the impacts of large-scale biomass use for energy and materials. The outcome is a wide but still considerably high range of 430-740 EJ yr^{-1}. What is very interesting in this study is that energy crops are not the dominating source, but residues and surplus forestry show similar potentials.

As the potential of energy crops are contested rightly, the focus should be put on surplus forestry and residues in more detail. (Rokityanskiy, 2007) has modeled the surplus forestry bioenergy potential in context of GHG mitigation scenarios and expects 145 EJ yr^{-1} in 2050 and 230 EJ yr^{-1} in 2100 respectively.

(Vis et al., 2006) calculates residues potentials exclusively, split in agricultural and wood residues. Vegetable residues and animal dung are not included in the analysis. Alike, residues with a high feeding value used as fodder are excluded. However, the technical potential for agriculture residues is 45 EJ yr^{-1} and 19 EJ yr^{-1} for wood residues respectively. Parts of this available technical potential are subtracted for soil fertility and biodiversity, as it is necessary to leave some nutrients on the fields. For example, 25% of straw is assumed left outside for soil fertility and another 30-35% are used for e.g. animal bedding. The so obtained 'practical' and sustainable agricultural potential of residues is 19 EJ yr^{-1}.

Estimation of bioenergy potential used for this study

Figure 1.3-8 shows the range of global bioenergy potentials of 13 selected studies from Table 1.3-1, excluding economic potentials of (IFEU, 2007) and unrealistic high bioenergy potential assumptions of about 1,500 EJ yr^{-1} in (Smeets et al., 2007) as the maximum harvestable biomass for all purposes is estimated at 2,000 EJ yr^{-1}.

Surplus forestry is an unattended potential so far. The global average growing stock available for wood supply ranges from 105 to 145 m^3 ha^{-1} of which only half is used. The global removal rate is estimated to 53% for temperate and boreal regions. Today, 3.6 billion cubic meters of wood are harvested annually for energy (1.9 billion m^3) and material use (1.7 billion m^3).

Studies for annual available fuelwood range from 1.9 to 4.2 billion cubic meters, which corresponds to about 12 to 30 EJ. These figures do not contain trees outside forests and recycled or reused woody residues. Additionally, it has to be considered that the global forest area of about 4,000 million ha is decreasing annually by about 12 million ha and that only half of global forest area is suitable for wood harvesting (MA, 2005d). The surplus forestry potential will be in one way also limited by competition with material use but in another way just shifted to the residues potential, as product design improves and cascade use is applied or agroforestry becomes more popular (chapter 1.3.2.2).

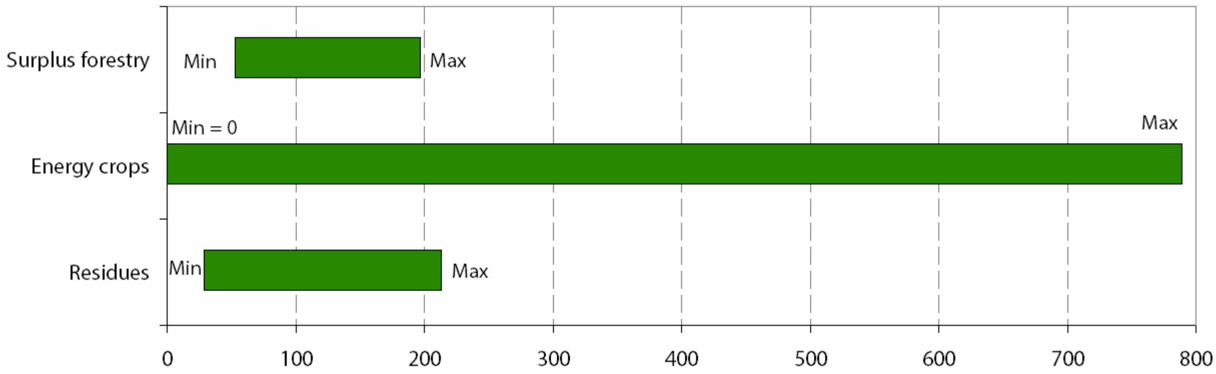

Figure 1.3-8: Range of global bioenergy potential estimations for 2050 in EJ per year. Technical and sustainable potentials of selected studies, excluding Smeets et al. (2003) and economic potential estimations from IFEU (2007). Source: data from studies in Table 1.3-1.

In general, surplus forestry and residues bioenergy potentials seem to be more reliable than energy crop potentials; land-use competition can be avoided easier and less soil and water stress is implied. These advantages make surplus forestry and residues potentials favorable.

Figure 1.3-9 illustrates the scope of estimated global sustainable bioenergy potential in 2050 used in this study. The cumulated value ranges from 65 to 300 EJ yr^{-1} and is rated using a rough and simple methodology. The upper limit cannot be higher than ½ of studies highest technical potential and may not exceed the highest value of sustainable potential listed in Table 1.3-1. The value for energy crops is lowered due to foreseeable land-use competition.

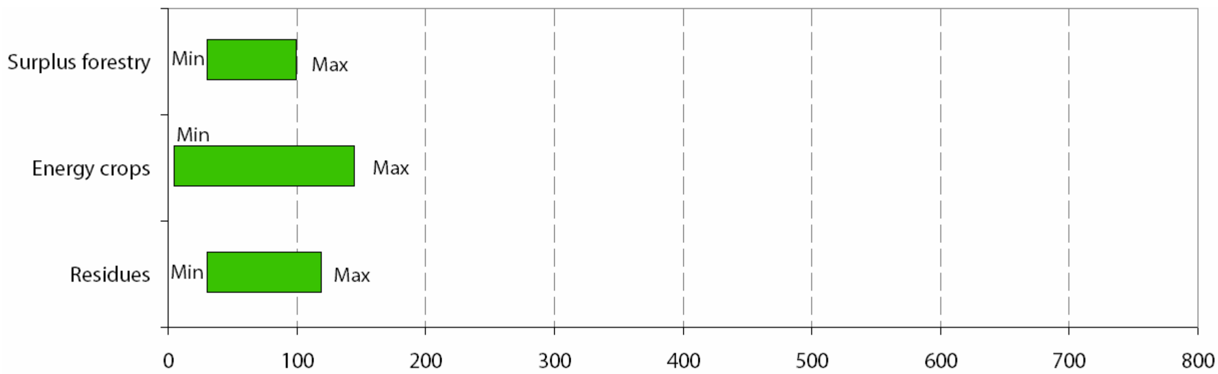

Figure 1.3-9: Range of estimated global sustainable bioenergy potential in this study for 2050 in EJ per year. Source: data base from all selected studies in Table 1.3-1.

Not all technical potential can be explored due to reasons like political stability and missing frameworks. Therefore, it is assumed that half of the bioenergy potential (30-150 EJ yr^{-1}) will be mobilized as economic potential by 2050.

Conclusions on bioenergy potentials

Bioenergy potential estimations differ widely depending on assumptions and methodologies, especially on availability of land, irrigation and agricultural intensification. Further, it is not clear, whether there is an overlap of potential estimation with current traditional biomass use. Another factor that could probably narrow bioenergy potential is the increasing demand of biomass for material use as fossil resources deplete and need to be replaced. The sum of these factors indicate the high degree of uncertainty about the potential contribution of bioenergy to future global energy supply.

Considering these uncertainties as best as possible, the estimated technical sustainable bioenergy potential used in this study complies with a significant share of 9 to 40% of total primary energy supply (752 EJ yr^{-1}) in 2050 in the alternative energy scenario of Greenpeace (Teske et al., 2008). Bioenergy potential analyses are mostly coming from the supply side. On the demand side, figures for bioenergy in energy system models are usually lower than most supply estimates, as bioenergy is competing with other energy sources that show lower production and GHG mitigation costs. According to (Faaij, 2008), the estimated demand range of biomass ranges from 50 to 250 EJ. This means that probably less biomass is needed on the demand side than can be produced in theory from the supply side. This would be in favor of other forms of land use and compensate uncertainties in bioenergy potentials.

Concluding, the potential of bioenergy could play a significant role in future energy systems. However, it may not be required as other renewable technologies with less risk, resource competition and potential uncertainties cover the energy demand.

2. Analysis of 78 biomass pathways

A certain given potential of sustainable bioenergy does not indicate or itemize its climate mitigation potential yet. The net emissions avoided can only be calculated after biomass was combusted and has fulfilled a certain energy service. In general, the more fossil fuel is replaced, the higher the climate protection effect of bioenergy gets. In most cases, biomass does not replace fossil fuel at the energy carrier level but the energy service in terms of electricity (kWh_{el}), heat (kWh_{th}) and transport (km per kWh_{input}). Harvested biomass has to be converted into final and target (bio)energy via pathways to provide these energy services. Comparing GHG emissions of (bio)energy pathways with conventional fossil fuel pathways gives the net emissions avoided. Using these avoided emissions, different scenarios for the emission reduction potential of biomass can be drawn by combining the sustainable bioenergy potential with the most promising pathways. In this way, the overall climate mitigation potential of bioenergy can be estimated, which is done in chapter 3.3.

The principle pathways are described in chapter 2.1. 70 current and future pathways have been selected and examined on technical conversion efficiency (chapter 2.2), production costs (chapter 2.3) and GHG emission reductions per energy service and costs per ton $CO_{2\text{-eq.}}$ avoided (chapter 2.4). In addition, 8 pathways in traditional biomass and bioenergy in rural application were examined in parallel. Finally, the technical, economic and ecologic parameters are plotted against each other and conclusions are drawn in the synthesis chapter 2.5.

2.1 Principle and selected pathways

2.1.1 Principle pathways

Biomass can be converted in many ways to bioenergy. Several hundreds if not thousand different kinds of combinations of conversion elements are possible and existing. The fundamental conversion is chemical energy to thermal energy by combustion of the chemical elements in biomass, mainly carbon and hydrogen. Besides combustion, other core conversions are thermo-chemical conversion (e.g. gasification), physical-chemical conversion (e.g. extraction) and bio-chemical conversion (e.g. fermentation). These basic technologies are described in detail in annex A4.

A pathway is a combination of all processes in providing energy services with bioenergy. This includes biomass production (e.g. energy plantations), biomass collection (e.g. harvesting, transport) and the conversion to final energy itself or to secondary energy carriers (e.g. liquid biofuels), transportation of these energy carriers (e.g. distribution) and the conversion to final energy (e.g. internal combustion engine to propulsion). The target (final) energy is mechanical, electrical or thermal energy. Along the pathway, waste energy and materials can be integrated into the process or can be recycled (Kaltschmitt et al., 2003; FNR, 2005).

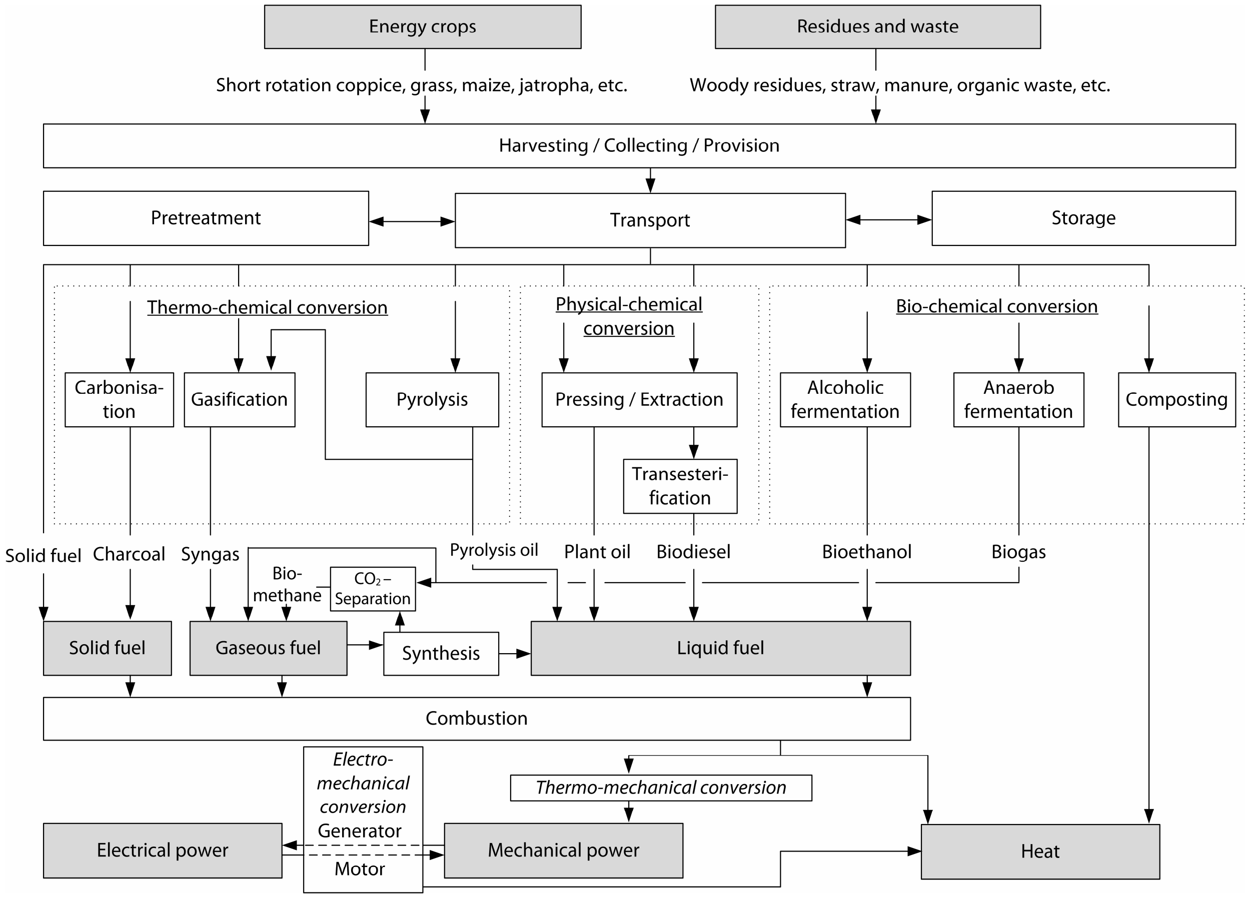

Figure 2.1-1: Simplified description of bioenergy pathways for final and target energy services (grey boxes and free text: energy carriers – other boxes: conversion processes and devices). Source: extended compilation; adopted from (Kaltschmitt et al., 2003).

2.1.2 *Selected modern bioenergy pathways, cropping systems and residues*

In this thesis, today's most relevant pathways for modern bioenergy have been selected for analysis and promising future pathways added to this list. Selection criteria were data availability, market relevance and techno-ecologic features. All investigated pathways are related to Germany as point of end energy use, as the methodology of GHG balances requires a certain energy profile and thus country setting. As origin countries of tropical energy crops, Brazil (sugar cane), India (jatropha) and Indonesia (palm) were chosen (Table 2.1-1). Out of thousands of possible pathways, 70 have been chosen and analyzed: 25 in mobility, six heat supply and 39 for power and heat supply (CHPs). Rather new pathways like algae or biorefinery concepts are not included in the analysis. Reliable data on the energy balance of algae production is not available yet (Kröger et al., 2009).

Selected biomass feedstocks and cropping systems

The selected biomass feedstocks and cropping system are listed in Table 2.1-1. They range from popular crops like maize, rape, sugar cane and palm to plants on degraded land (jatropha) and perennial crops like switchgrass or short rotation coppice.

Table 2.1-1: Selected biomass feedstocks and cropping systems, [A] only palm fruit oil considered, the high palmoil yields used include all products of the entire plant [B] only seeds considered, [C] literature reviewed: (FAOSTAT, 2009b; KTBL, 2006; Lieberei et al., 2007; El Bassam, 1998; TFZ, 2008; Sterner et al., 2008b). Source: Source: own compilation, based on (WBGU, 2009) and data from (Fritsche et al., 2008c).

Name in settings	**Previous land use** (Origin of crop / feedstock)	**Cropping system, Crop / feedstock**	**Productivity** (Raw-biomass yields in tons dry mass or raw biomass / (ha*a))		
			2005	2030	Literature review[C]
Tropical monocultures					
palm oil (rain forest)	Tropical rainforest (Indonesia)	Palm oil	-	66	14 - 30[A]
palm oil (degraded)	Degraded land (Indonesia)		55	-	
Jatropha	Cropland (India)	Jatropha	-	2.1	0,2 - 8[B]
Jatropha (marginal)	Marginal land (India)		-	4.4	
Sugar cane	Cropland (Brazil)	Sugar cane	44	-	10 - 120
Sugar cane (degraded)	Degraded land (Brazil)		-	31	-
Temperate monocultures					
Rape seed	Cropland (Germany)	Rape	3.3	-	3.4 - 4.1[B]
Wheat	Cropland (Germany)	Wheat, cereals	6.2	-	3.5 - 9[B]
Maize grain, Maize silage	Cropland (Germany)	Maize	7.6 / 14.5	-	9[B] / 8 - 14
Switchgrass	Cropland (Germany)	Panicum virgatum L. – Sorghum	-	11.5	5.2 - 17
Perennials					
SRC	Cropland (Germany)	Willow - Short rotation coppice	6.6	7.3	2 - 20
Grass, Grass silage	Pasture (Germany)	Grass	7.3	-	7 - 15
Mix of crops and residues					
Grass silage / manure	Pasture (Germany)	Grass silage (70%), manure (30%)	5.3	-	5 - 10.5
Residues and waste					
Manure / crop residues	-	Crop residues and animal manure	-	-	-
Woody residues	-	Wood chips, sawdust, woody waste	-	-	-
Straw	-	Wheat straw	-	-	-
Waste grease	-	Cooking fat, used grease	-	-	-
Organic waste	-	Biowaste, organic waste	-	-	-

The ecologic analysis of cropping systems also includes land-use changes from grassland to arable land. The effects on GHG emissions are discussed in chapter 2.4. The most common biomass residues and waste feedstocks complete the selection of biomass feedstocks.

Selected technical pathways

All examined modern pathways are listed in Table 2.1-2 and Table 2.1-3. The grass silage / manure settings consist of a 70/30% mix of grass silage and manure.

Table 2.1-2: Selection of 70 biomass pathways – mobility and heat. Source: own compilation, based on (WBGU, 2009) and data from (Müller-Langer, 2008; Sterner, 2007; WBA, 2007).

Name in settings	**First conversion steps** Raw biomass to energy carrier (product)	**Product / Second conversion step** Energy carrier to final energy	**Capacity of conversion plant** (Biomass-Input in MW; thermal combustion capacity)		**Year considered** 2005 / 2030	
Mobility						
Biodiesel-car	Extraction Ethyl trans-estherification	Biodiesel (1. Gen.) Diesel engine	Rape seed	175	X	
			Palm oil	300	X	x
			Jatropha	290		x
			Waste grease	60		x
Plant-oil-car	Extraction	Plant oil (1. Gen.) Adopted diesel engine	Rape seed	2.9	X	
Ethanol-car	(Saccharification) Fermentation Distillation Dehydration	Bioethanol (1. Gen. - except staw: 2. Gen.) Otto engine	Maize	190	X	
			Sugar cane	320	X	x
			Wheat	230	X	
			Straw	380		x
Biomethane-car	Anaerobic fermentation Biogas upgrading	Biomethane (2. Gen.) Gas-otto engine	Maize	3.2	X	
			Manure / crop residues	5.0	X	
			Grass silage / manure	3.8		x
			Organic waste	3.9		x
Biomethane-car	CFB Gasification, Gas cleaning and conditioning, methanation	Biomethane (2. Gen.) Gas-otto engine	Willow (SRC)	40		x
			Woody residues	40		x
Fischer-Tropsch-BTL-Diesel	Entrained flow gasification, Gas cleaning and conditioning, Fischer-Tropsch-Synthesis, Raw product upgrading	BTL-Diesel (2. Gen.) (Biomass-to-Liquid) Diesel engine	Willow (SRC)	520		x
			Woody residues	520		x
			Straw	535		x
Hydrogen-FuelCell-car	Gasification, Gas cleaning and conditioning	Bio-hydrogen (2. Gen.) Fuel Cell Electric engine	Woody residues	250		x
Biogas-CHP-electric car	Anaerobic fermentation Combustion in CHP for bioheat and biopower	Biopower Electric engine	Switchgrass	1.6		x
			Woody residues	22		x
			Manure / crop residues	2.5	X	
Heat						
Pellet-heating system	Pelletizing Combustion	Pellets Small heating system	Switchgrass	0.017		x
			Willow (SRC)	0.015		x
			Woody residues	0.016	X	
			Straw	0.019	X	
WoodChips-heating system	Combustion	Wood chips Medium heating system	Willow (SRC)	0.48		x
			Woody residues	0.48	X	

Table 2.1-3: Selection of 70 biomass pathways – combined power and heat. Source: own compilation, based on (WBGU, 2009) and data from (Müller-Langer, 2008).

Name in settings	**First conversion steps** Raw biomass to energy carrier (product)	**Product / Second conversion step** Energy carrier to final energy	**Capacity of conversion plant** (Biomass-Input in MW; thermal combustion capacity)		**Year considered** 2005	2030
Power and heat – cogeneration						
Plant oil-CHP	Extraction, (trans-estherification)	Plant oil Decentral CHP Diesel engine	Rape seeds	2.9	X	
			Palm oil	3.9	X	X
			Jatropha	3.7		X
Ethanol-CHP	(Saccharification), Fermentation Distillation, Dehydration	Ethanol Decentral CHP Otto engine	Sugar cane	3.9	X	X
Biogas-CHP	Anaerobic fermentation	Biogas Decentral CHP Gas-otto engine	Maize	1.6	X	
			Switchgrass	1.6		X
			Manure / crop residues	2.5	X	
			Grass silage / manure	1.9		X
			Organic waste	3.9	X	
Biogas-FuelCell	Anaerobic fermentation	Biogas Solid oxide fuel cell (SOFC)	Maize	1.6	X	
			Switchgrass	1.6		X
			Manure / crop residues	2.5	X	
			Grass silage / manure	1.9		X
			Organic waste	3.9	X	
Biomethane-CHP	Anaerobic fermentation Biogas upgrading	Biomethane Decentral CHP Gas-otto engine	Maize	3.2	X	
			Switchgrass	3.1		X
			Manure / crop residues	5.0	X	
			Grass silage / manure	3.8		X
			Organic waste	3.9	X	
Biomethane-CombinedCycle	Anaerobic fermentation Biogas upgrading	Biomethane Central combined-cycle plant	Maize	3.2	X	
			Switchgrass	3.1		X
			Willow (SRC)	40		X
			Woody residues	40		X
			Manure / crop residues	5.0		X
			Grass silage / manure	3.8		X
			Organic waste	3.9	X	
Rawgas-Gasturbine	CFB gasification, Gas cleaning	Raw gas Central CHP - Gas turbine	Willow (SRC)	90		X
			Woody residues	90		X
Rawgas-FuelCell	CFB gasification Gas cleaning	Raw gas Solid oxide fuel cell (SOFC)	Willow (SRC)	18		X
			Woody residues	18		X
WoodChips-CHP	Combustion	Wood chips Central cogeneration plant Steam turbine	Willow (SRC)	22		X
			Woody residues	22	X	
			Straw	22	X	
Pellets-CoalPowerPlant	Pelletizing Co-firing	Pellets Central hard coal power plant	Willow (SRC)	100		X
			Woody residues	103	X	
			Straw	144	X	

The system boundaries have been set from well-to-wheel for a holistic analysis. Among the intermediate steps considered are biomass provision and transport, biomass conversion, product transport and conversion to final energy power, heat and mechanical power at the wheel (motive or mechanical power), i.e. transport including the vehicle technology.

The most common technologies have been selected in the first conversion step (biomass to bioenergy carrier - product). Moreover, promising future fermentation and gasification pathways have been added. In the second conversion step (product to energy service), mobility covers biofuels in internal combustion engines, fuel cell cars and pure electric cars. To be able to compare these options, the system boundary 'mechanical shaft power at the wheel' was chosen, which is almost 100% proportional to the range of the car. Biopower pathways are focused on CHP applications, as exergetic efficiency and biomass conversion rates are higher than in pure power generation. Part of the analyzed technologies are state-of-the-art (2005), others include assumptions about technology and price developments (2030).

Assumptions on technology specific parameters like full-load hours or efficiencies of vehicles and CHPs can be found in annex A5 and A7.

In addition, several main traditional biomass conversion technologies have been selected and investigated in chapter 2.2.3.

Effect of economies of scale on technical, economic and ecologic parameters

The size of the bioenergy plant, which is given as thermal combustion capacity in Table 2.1-2 and Table 2.1-3, has a crucial impact on conversion efficiency. Generally, the larger the plant and the more processes that are internally integrated, the more efficient it is. Higher efficiencies result usually in lower energy supply costs, less GHG emissions and thus smaller GHG mitigation costs (chapter 2.2 to 2.4). This sensitivity comes especially into effect in the selected mobility pathways. Biogas for electromobility is the smallest conversion plant with 1.6 MW and 0.4 t biomass feedstock input per hour. The largest plant is 300 times bigger: the Fischer-Tropsch-Diesel gasification plant with 535 MW thermal power capacity and 140 t biomass input per hour.

2.2 *Technical analysis*

Several parameters are analyzed in the technical analysis. The main technical parameter of a biomass pathway is its conversion efficiency, which is analyzed in detail for the selected modern pathways (chapter 2.2.1) and the main traditional pathways (chapter 2.2.3). In addition, energy yields per hectare are determined as techno-agricultural parameter in chapter 2.2.2. The energy balance includes main energy fluxes (biomass input, final energy output), by-products (heat, materials) and auxiliary energies (power, heat) and a distinction in energy and exergy.

2.2.1 Conversion efficiency

The technical efficiency of biomass pathways in the system boundary of raw-biomass to target energy electrical, mechanical and thermal power is given in Figure 2.2-1. The VDI guideline 4461 is applied for efficiency calculation (see also annex A5). In many publications, the efficiency of thermal, electrical and chemical energy (biofuels) are compared without integrating the second law of thermodynamics. This integration is done in this work by evaluating the exergy of heat as mechanical- and electrical power-equivalent. This enables a cross-sectoral comparison of bioenergy pathways. The energy of heat is useful for inner-sectoral comparison of heat supply chains. In all efficiency calculation figures, heat energy is split in exergy and anergy. The definitions of efficiency calculations, exergy of heat, system boundaries, technology characteristics and applied methodologies are described in detail in annex A5. A further in-depth discussion on energy efficiency calculation can be found as well in (Sterner, 2007).

2.2.1.1 Comparative assessment of efficiencies in mobility, heat and CHP applications

Considering *energetic* efficiency (9% to 80%), the following conclusions from Figure 2.2-1 can be drawn:

- the heat supply concepts achieve the highest efficiencies (53%–80%) along with some very effective direct combustion steam turbine CHP concepts (70%–77%)
- other CHP concepts are in the mid-range of 29% to 63% with gasification of woody biomass and fermentation of switchgrass on the upper range
- conventional mobility concepts show the lowest efficiencies (9%–28%)

Considering *exergetic* efficiency of CHP and mobility (9% to 39%), which enables a cross-sectoral comparison, the following conclusion can be drawn:

- the CHP concepts show the highest efficiency (17%–39%), followed by conventional mobility (9%–26%) and e-mobility (22%–32%)
- on average, CHP concepts are twice as efficient as mobility concepts; therefore, biofuels like ethanol, biodiesel, plant-oil or biomethane are used more efficiently in CHP applications than in transport
- cofiring of pellets in a coal power plant shows the highest exergetic efficiency (max. 39%) followed by fuel cell CHPs and fermentation concepts (max. 37%)
- the lowest exergetic efficiencies are obtained by sugar cane-bioethanol or fermentation-biomethane in conventional cars (9-10%)

The limited resource biomass is used most efficiently in CHPs. However, the final utilization depends on the sectoral energy demand and the energy system itself. Both parameters differ on a country basis. For example, if the power demand is already covered by other renewables, biomass can be used also very efficiently in heat applications or strategically as biofuels for heavy-duty transport, navigation or aviation.

Comparing efficiencies in mobility

The supply task of biomass in transport is to provide mobility in form of 'vehicle miles traveled' (mileage). The examined 25 mobility pathways differ in fuel supply and vehicle technology (see also annex Table A5-1). The well-to-wheel analysis enables a comparison of first and second generation biofuels with electromobility concepts. The following conclusions can be drawn from efficiency calculation results:

- mobility with bioenergy can be provided most efficiently via biopower in electric cars (22%-32%), as the stationary combustion process is more efficient and surplus heat can be used. This is not the case for biofuels in conventional cars, whereby first (10-26%) and second (9-21%) generation concepts are in the same range. The electromobility concepts are rather small in scale (1.6 MW_{th}) and yet the most efficient.
- production and use of bioethanol in conventional cars has a low efficiency (9-11%)
- biodiesel pathways are more efficient than ethanol concepts, which is partly due to a different feedstock (parts of the plant like seeds vs. the entire plant) and a more efficient combustion process of the diesel internal combustion engine
- an efficient exception is biodiesel from waste grease (26%), whereby the feedstock is not raw biomass but an already harvested and used biomass oil plant
- the production of Fischer-Tropsch diesel (BTL) via entrained flow gasification and its use in conventional cars is not very efficient (13-16%), although the 500 MW_{th} concepts scale is the largest among the examined pathways
- it is more efficient to produce biomethane for mobility via gasification (about 21% with woody biomass) than via fermentation (9-16%), which depends strongly on the feedstock used here and whether polygeneration is applied or not
- gasification of woody biomass to hydrogen and its use in fuel cell cars shows merely an efficiency of 16%, although the scale of the concept is quite large (250 MW_{th})

The main reason for the low overall efficiency of mobility concepts is found in the poor efficiency of the internal combustion engine, i.e. the conventional car technology itself and the fact, that waste heat is not utilized in mobile application (see also annex Table A5-1). The only exception is electromobility, which is nevertheless still at its beginning, and practical heat utilization concepts, which have to be established to use the full efficiency potential of combined heat and power generation.

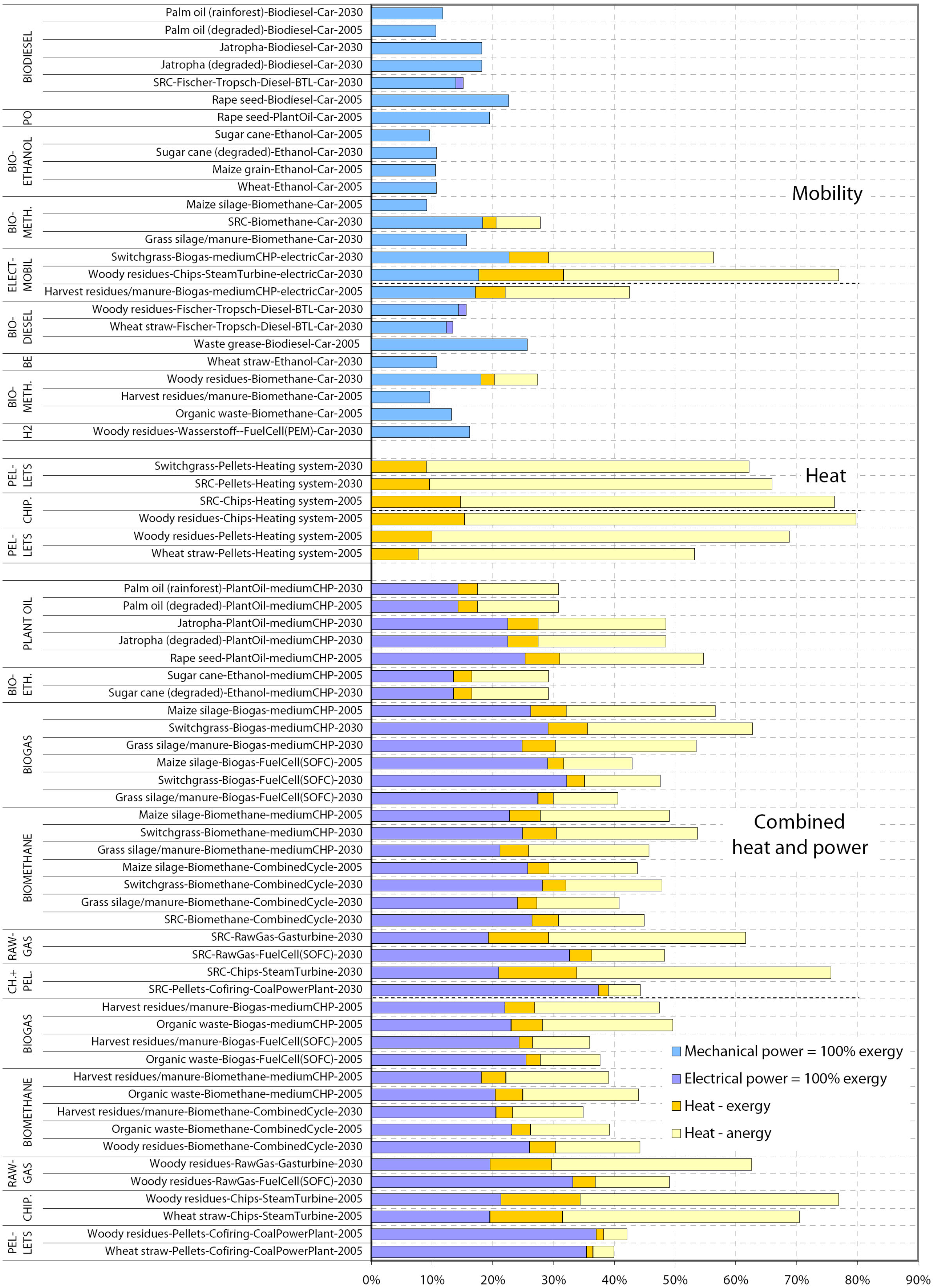

Figure 2.2-1: Energetic and exergetic efficiency (with or without bright yellow bars) of the analyzed 70 pathways in %. The resolutions of the pathway naming are listed in Table 2.1-1, Table 2.1-2 and Table 2.1-3. Within an energy sector, energy crops and residues are separated by a dashed line. Source: own calculations, based on (WBGU, 2009) and data from (Müller-Langer, 2008; Sterner, 2007; WBA, 2007; Fritsche et al., 2008b).

Comparing efficiencies in heat supply

Six solid biomass-to-heat conversion chains have been examined. Moreover, heat can serve as supply in many other ways, like via biomethane as well. The following conclusions can be drawn from the results in Figure 2.2-1:

- The 400 kW_{th} wood-chips heating system is the most efficient heat supply system (76-80%) followed by the 15 kW_{th} small pellet heating system (53-69%), which is less efficient due to its scale and additional energy efforts of pelletizing raw biomass
- Feedstock with high energy density like SRC, woody residues or switchgrass require less energy for feedstock provision than wheat straw
- for pure heat supply tasks, heating systems are energetically the most efficient

Comparing efficiencies in combined heat and power generation

36 different CHP pathways with pure biomass input and three biomass with coal co-firing CHP concepts have been analyzed. The following results can be derived:

- the energetic efficiency ranges from 29 to 77%, whereby direct combustion of biomass in steam turbine CHP are the most efficient (70-77%), followed by gasification CHP (62-63%) and fermentation CHP, especially direct power generation from biogas (47-63%)
- using jatropha or rape seeds as plant oils in biofuel CHP is very efficient (49-55%), while bioethanol or palm oil are at the lower end (29-31%) as more processing is required than just the extraction of oil from seeds like for jatropha or rape; nevertheless, the use of all biofuels in CHP is more efficient than in mobility
- regarding exergetic efficiency, co-firing of SRC, woody residues and wheat straw with coal are the most efficient pathways examined (36-39%), followed by the use of raw gas in fuel cells from gasification of woody biomass (37%) and the fermentation of switchgrass and its use as biogas in medium scale CHP (36%)
- the comparison of different feedstocks with one technology (e.g. mediumCHP) shows that the direct use of plant oil is favorable against sugar cane ethanol or palm oil and that woody biomass via gasification as well as maize and grasses can be converted more efficiently than organic waste or harvest residues

2.2.1.2 Comparing technologies using the same biomass feedstock

Figure 2.2-2 displays different technologies which use one common feedstock: woody residues.

From an energetic point of view, the most efficient conversion for heat supply is the wood chips heating system. From an exergetic view, combined power and heat generation are the most efficient pathways, led by co-firing and gasification processes (biomethane in combined cycle and raw gas in SOFC fuel cells).

In both cases, energetically and exergetically, much more of the limited biomass resource is used when directly combusted for heat and power generation than when changing the state of the fuel twice (solid-to-gaseous, gaseous-to-liquid) and finally combusting the liquid in a conventional inefficient car; like it is done in the BTL pathway. The most efficient application of biomass in mobility is its conversion into power in a CHP and the use of bioelectricity in an electric car.

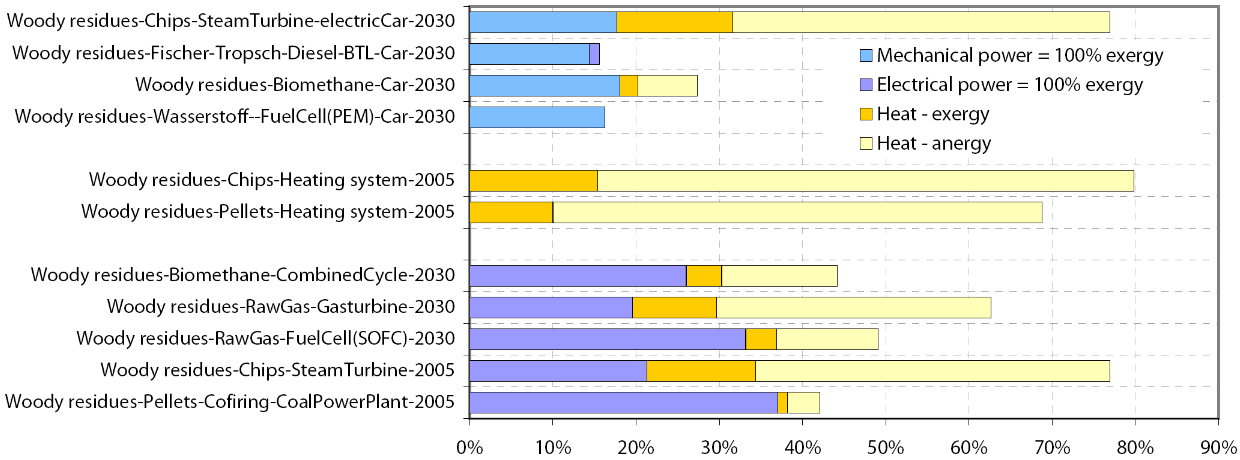

Figure 2.2-2: Efficiencies of different technologies using woody residues as common feedstock. own calculations, based on data from (Müller-Langer, 2008; Sterner, 2007; WBA, 2007; Fritsche et al., 2008b).

2.2.2 *Yields per hectare for raw-biomass and target energy*

The area available for biomass is limited due to land-use competition (chapter 1.3.2.2). Therefore, area-specific raw-biomass and energy yields of energy crops are important for the estimation of their overall energy supply and climate mitigation potential, which are listed in Figure 2.2-3. The raw-biomass yields applied in this work are as well given in Table 2.1-1.

Tropical energy crops like palm oil or sugar cane are the most productive and therefore also gain the highest energy yields. Again, their application in CHPs is more efficient in terms of energy and exergy than their use in mobility. Besides tropical crops, switchgrass is the most energy yielding temperate crop, along with maize and SRC in certain applications. The values of grass/manure fermentation are rather low, since a 70/30% mix is assumed. Among conventional mobility pathways with temperate crops, second generation biofuels reach higher energy yields due to the use of the entire plant for energetic purposes. However, applying electromobility on temperate crops is gaining the highest yields in mobility pathways. The yield is even higher if tropical plants like sugar cane or palm oil are used for (heat and) power generation and electromobility.

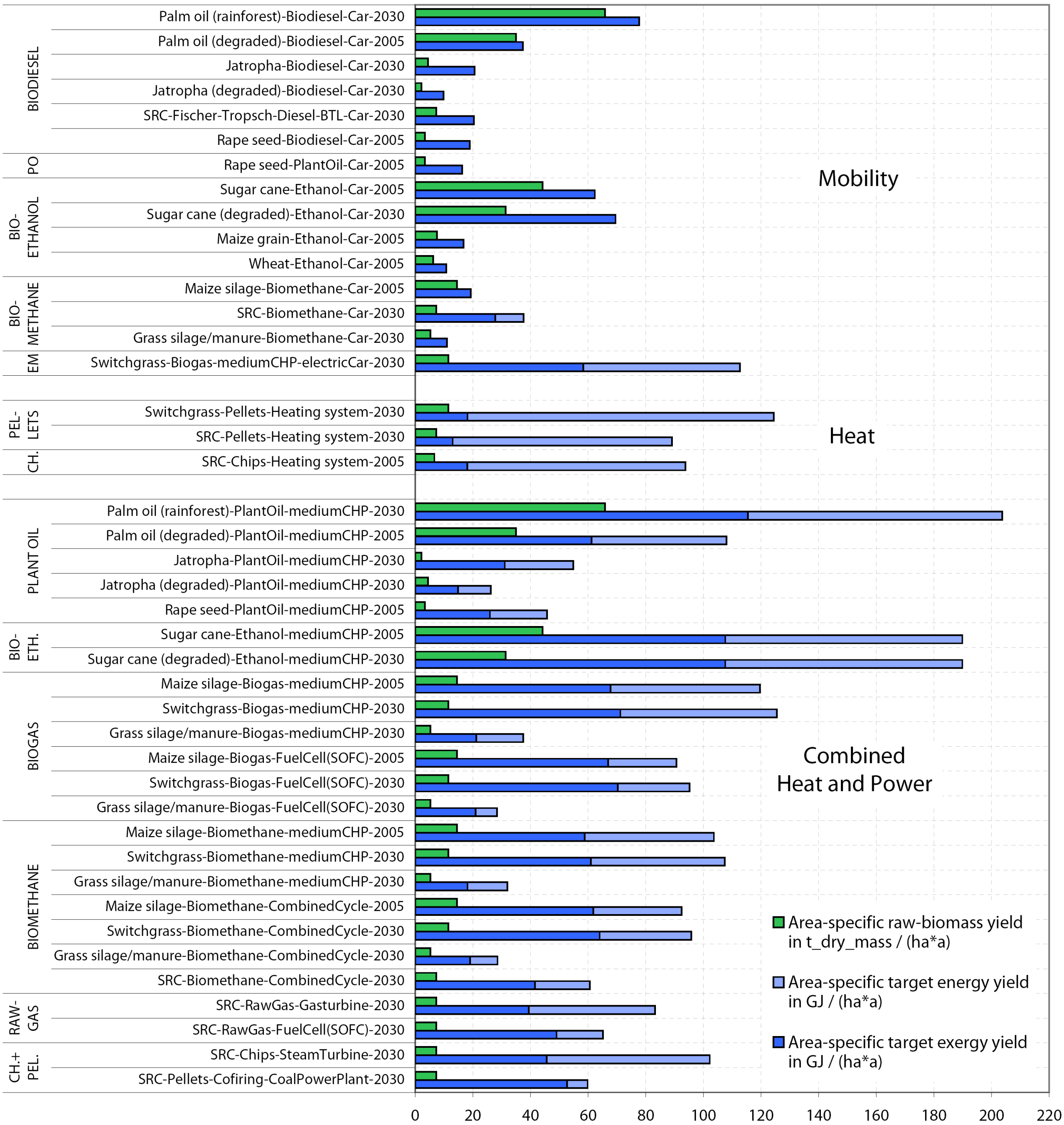

Figure 2.2-3: Area-specific raw-biomass yields in ton dry mass per hectare and year (green bars) and area-specific target exergy/energy yields in GJ per hectare and year (dark/light blue bars) of selected bioenergy pathways. Source: own calculations, based on data from (Müller-Langer, 2008; Sterner, 2007; WBA, 2007; Fritsche et al., 2008b; Fritsche et al., 2008c).

2.2.3 *Conversion efficiency of traditional biomass and bioenergy in rural applications*

Eight typical (traditional) biomass pathways in rural applications are examined.

Cooking stoves

Cooking stoves are the main conversion technology for biomass in developing countries. The efficiency of fuel wood in traditional biomass fired-stoves ranges from 5 to 15% (exergetic efficiency 1-2%) due to low combustion and heat transfer efficiency (Mande et al., 2007; Bhattacharya et al., 2002). Charcoal use and combustion is as well very common and increasingly used in urban regions. 18% of fuel wood can be converted into charcoal, which can be used in charcoal stoves with an efficiency of 23%, resulting in an overall efficiency of about 4% (FAO-RWEDP, 2008).

Efficiency can be increased drastically and at low cost by replacing traditional stoves with improved cooking stoves. For example, simple clay stoves have been developed in South India, which improve efficiency from initial 5-15% up to 20-41% or even 50% with gasifier stoves (factor 3-8) (exergetic efficiency 3-7%) (Bhattacharya et al., 2002; GTZ-EAP, 2007; Dasappa, 2009). They enable a better combustion of the fuel and an efficient heat transfer by using two hot plates and a flue gas heat recovery system, using a chimney and a vessel for heating water. If the stove does not include this heat recovery, the efficiency is still at 25-30%. Charcoal and metal stoves can be as well improved by a different design, lifting overall charcoal application efficiency to 8%. Applying improved cooking stoves can reduce fuel consumption roughly by factor 4 and thus also the linked deforestation (Jagadish, 2004; Kumar et al., 1990).

Small biogas digesters

House-hold scale biogas digesters can provide basic energy services like lighting and cooking and replace fuel wood and traditional stoves. Unlike industrial biogas plants, small biogas digesters use almost exclusively residues from livestock (manure). The efficiency of this simple technology is about 80% for manure to methane. Used in a biogas stove, the overall biogas utilization efficiency ranges from 40 to 60% (exergetic efficiency 7-9%) and from 15 to 25% for power generation via a genset (combined combustion engine with a generator) (FAO-RWEDP, 2008).

Small gasifiers

Small-scale biomass gasifiers are standard technology and very popular for rural (off-grid) power supply in India and China. Residues like coconut shells or rise husk can be converted into rawgas with an efficiency of 70 to 80%. The raw gas can be used in conventional diesel generators or gas engines. Diesel generators in dual-fuel mode use 80% rawgas and 20% diesel with a conversion efficiency of 20-25%, resulting in an overall biomass-to-electricity efficiency of 14-20%. Using rawgas directly in gas engines can raise efficiency (Dasappa, 2009; Sterner, 2006). Gasifiers are also used for industry heat applications like drying of rubber and silk or baking. About 20 gasifiers are in commercial operation in Indian rubber industry. Depending on the biomass feedstock, the overall thermal efficiency for heat applications ranges from 30 to 50%. The cleaning of waste water and offgases is a remaining technical challenge (Bhattacharya et al., 2002; Mande et al., 2007; Dasappa, 2009).

Biofuel combustion engines, gensets and CHPs

Combustion engines are applied in rural energy supply for process motive power like milling and water pumping. These combustion engines can also run on biofuels like plant oil from jatropha, sunflower or palm trees. They are also used in combination with a genset or a CHP for local power supply (hospitals, schools, mini-grids). The biofuel combustion engines show an efficiency of 20-25%, are easy to use and have low maintenance costs (FAO-RWEDP, 2008). The off-heat of the engine can be used in CHP mode as process heat applications like drying.

Comparative assessment

Largest efficiency improvements can be achieved by replacing traditional biomass use for heating and cooking by modern biomass use via small biogas digester, biofuels in liquid fuel stoves or fuelwood in improved cooking stoves. The average five person household in India or Uganda consumes 10 kg (160 MJ) of firewood per day on traditional-fired stoves (12 GJ yr^{-1} $person^{-1}$) (Subbarao, 20.05.2009; MEMD, 2007). About 30 EJ yr^{-1} are used by 2.5 billon people in this traditional way globally. This figure matches roughly with the reviewed literature in chapter 1.2.1. This demand can be reduced by factor 2-4, as efficiency can be increased 2-4 times depending on the applied technology. Therefore, overcoming traditional biomass completely would save 20 EJ yr^{-1} primary energy and the GHG emissions respectively, assuming efficiency improvements from 10-30% by economical modern technologies.

2.3 Economic analysis

2.3.1 Production cost

The production cost of bioenergy for mobility, heat or electricity is an important figure in the market integration of bioenergy technology. They are calculated for all selected pathways (Table 2.1-2 and Table 2.1-3), using a dynamic annuity method according to VDI 2067 and VDI 6025 (VDI, 2000a, VDI, 1996) and based on (Müller-Langer, 2008) and (WBA, 2007).

All relevant costs like capital-related costs, operation-related costs and consumption-related costs (mainly biomass provision costs) and revenues from by-products are included in production cost determination. The target energy is the same as in efficiency calculations (chapter 2.2.1). The cost analysis covers all parts of the pathway for heat and power including the combustion device. The mobility pathways are an exception: production costs do not include the combustion engine, i.e. the car itself. Assuming an existing internal combustion engine car, only additional costs for a hydrogen, natural gas or electric vehicle are added. The cost calculations do not include revenues for the bioenergy product and are therefore merely comparing the cost efforts of providing energy services. The reverence period for costs is set to 2005 for all pathways, even for settings with an 2030 time reference, since future costs involve economic developments that are hardly assessable and predictable. The assumption of a price bandwidth for both fossil fuels and biomass feedstocks for 2030 spreads results on production costs to an extent that they are beyond recognition. Therefore, all costs are referred to the year 2005.

Further details about finance and cost assumptions are given in annex A6 and in (Müller-Langer, 2008) and (WBA, 2007).

Production cost of pathways

The production cost of combined heat and power pathways ranges from four to 43 EURcents per kWh_{el} (Figure 2.3-1). Co-firing of biomass is very cost effective (4-5 EURcents / kWh_{el}) since capital and technology costs are very small as an available plant can be utilized. Fermentation of harvest residues or grass with manure to biogas is as well uncostly as the feedstock is inexpensive (6-7 EURcents / kWh_{el}). Fermentation pathways using medium CHP or combined cycle power plants are in general at the lower end of production costs. Technologies applying fuel cells hold rather high production costs (22-43 EURcents / kWh_{el}) and are similar to pathways with gasification (sophisticated technology) or use of organic waste (feedstock preparation).

Heat supply costs vary between 7 to 16 EURcents per kWh_{th} (Figure 2.3-2). Heat from wood chips heating systems is inexpensive (7-8 EURcents / kWh_{th}) and already competitive with fossil fuel heating systems. The medium 400 kW_{th} scale allows the heat supply of up to 20 households. Small scale household pellet heating systems are rather expensive (16 EURcents / kWh_{th}) due to high investment costs of about 14,000 EUR for a 15 kW_{th} system, whereby costs do not differ much by feedstock.

Costs for bio-mobility vary between two and 20 EURcents per driven kilometer (Figure 2.3-3). The most competitive pathways are first generation biofuels from jatropha, rape seed oil, sugar cane ethanol, palm oil biodiesel and waste grease biodiesel (2-3 EURcents / km). Second generation biofuels like Fischer-Tropsch diesel or biomethane are still twice as expensive (5-8 EURcents / km) as first generation biofuels, because capital costs are still very high. Today, using biofuels in conventional cars is much more economical than the use of bioenergy in new car technologies like fuel cells or electromobility (14-20 EURcents / km), which have high investment costs and still a low lifetime of the fuel cell and battery respectively.

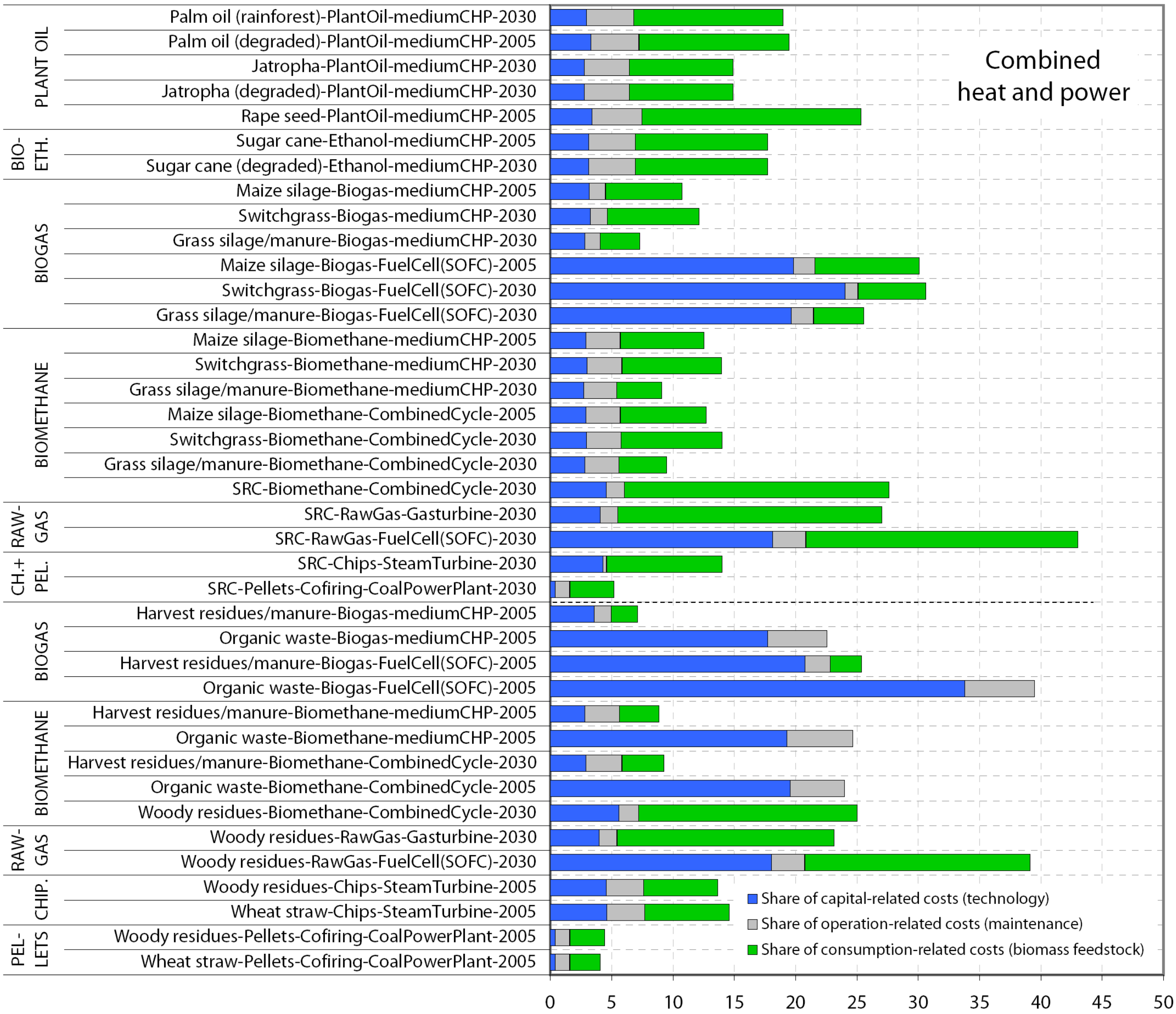

Figure 2.3-1: Production cost of combined heat and power generation in EUR cent / kWh_{el}. The share of capital-, operation-, and consumption-related costs are indicated in blue, grey and green bars. Within an energy sector, energy crops and residues are separated by a dashed line. Source: own calculations, based on (WBGU, 2009) and data from (Müller-Langer, 2008).

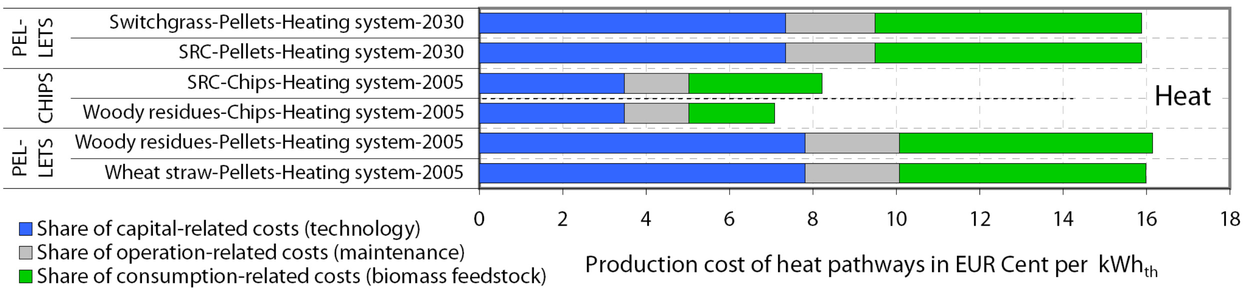

Figure 2.3-2: Production cost of heat supply pathways in EUR cent / kWh_{th}. The share of capital-, operation-, and consumption-related costs are indicated in blue, grey and green bars. Residues and energy crops are separated by the dashed line. Source: own calculations, based on (WBGU, 2009) and data (Müller-Langer, 2008; WBA, 2007).

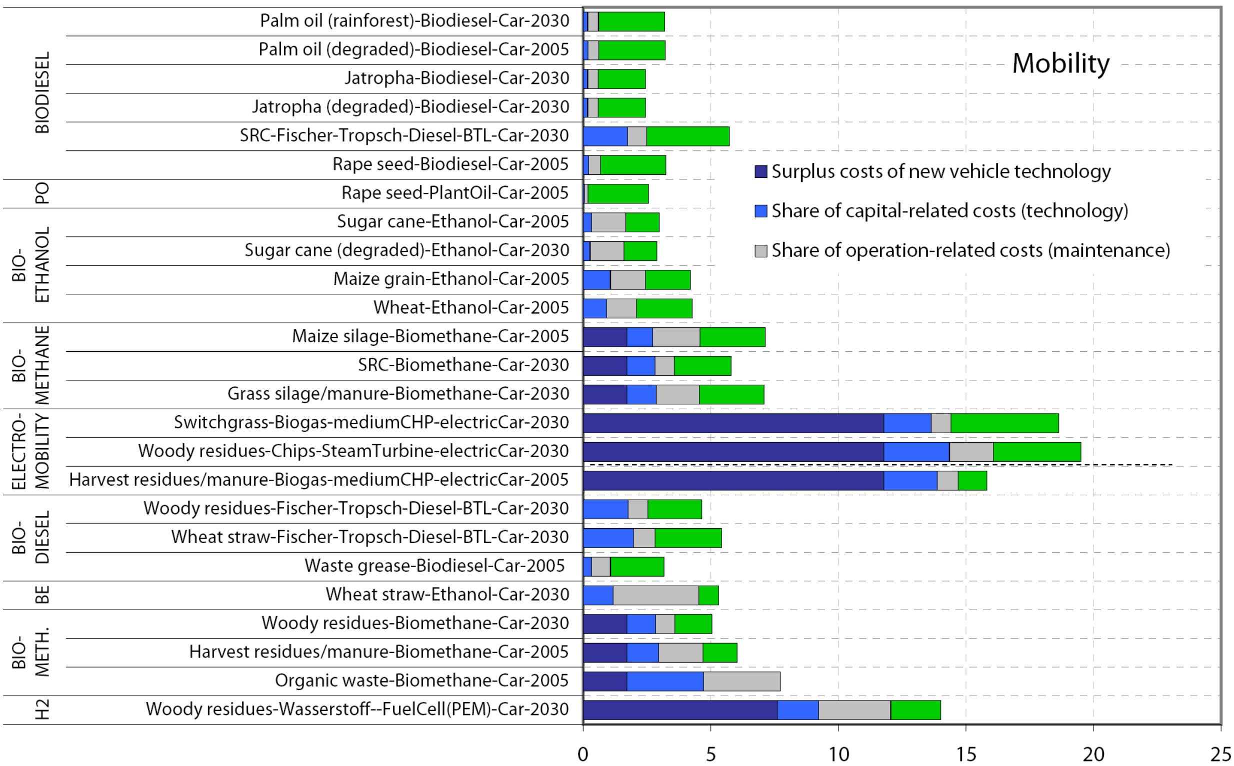

Figure 2.3-3: Production cost of mobility pathways in EUR cent / km. The share of capital-, operation-, and consumption-related costs are indicated in blue, grey and green bars. In addition, the surplus vehicle technology costs are given as purple bars. Within an energy sector, energy crops and residues are separated by a dashed line. Source: own calculations, based on (WBGU, 2009) and data from (Müller-Langer, 2008).

Conclusions on production costs

Some bioenergy pathways like co-firing or fermentation processes for heat and power, wood chips heating systems for heat and some first generation biofuels for mobility are already competitive today. Apart from capital intensive pathways (fuel cells, gasification, electromobility, use of organic waste), the main share of production costs holds the supply and provision of biomass feedstock. Therefore, bioenergy production costs are very sensitive to feedstock price changes, which make it difficult to predict future price developments as land-use competition increases (chapter 1.3.2.2). The competitiveness of bioenergy depends strongly on fossil fuel prices, which are fluctuating significantly. Both cost parameters, biomass feedstock costs and fossil fuel costs, have changed strongly between today (2009) and the reference year 2005. In the long run, both cost parameters are likely to increase due to increased land use and energy competition. Only the technology / capital costs are likely to decrease by time, as rather new technologies like gasification, biomethane production or electromobility are developed and costs decline with economy-of-scale effects.

2.3.2 *Production cost of traditional biomass and improved cooking stoves*

The production costs of traditional biomass pathways are difficult to estimate. Neither the investment cost nor the fuel cost can be determined clearly. This becomes apparent in case of the traditional biomass fired-stove. Its investment cost is not relevant because stones, mud and clay are usually used and the fuel costs are only linked to the working effort of collecting fuel wood. Improved cooking stoves for a 5-persons household in India cost at around 20 EUR and in Uganda around 10-20 EUR per stove (Subbarao, 20.05.2009; Mubbala, 18.05.2009). The cost of small biogas digesters including biogas stoves are about 140 EUR (200 US$) (ter Heegde, 2005; Smith, 2000).

Around 58 GJ yr^{-1} $household^{-1}$ are consumed in traditional biomass fired-stoves with an efficiency of roughly 10%, resulting in a thermal energy demand of 6 GJ (1.7 MWh_{th}) yr^{-1} $household^{-1}$. Improved cooking stoves meet this demand with 19 GJ (5.3 MWh_{th}) yr^{-1} $household^{-1}$ and biogas digesters with 9 GJ (2.5 MWh_{th}) yr^{-1} $household^{-1}$. Assuming an average lifetime of 10 years for improved cooking stoves and 15 years for the biogas digester, the stoves cost 2 EUR and the biogas digester 9 EUR yr^{-1} $household^{-1}$. Thus, given free biomass feedstock (residues), the surplus production costs for bioheat are estimated at 0.12 EUR cent kWh_{th}^{-1} for improved cooking stoves and at 0.53 EUR cent kWh_{th}^{-1} for biogas digesters plus biogas stoves; therefore they are more economical than modern bioheat supply concepts in industrialized countries.

2.4 *Ecological analysis – greenhouse gas balances and mitigation costs*

GHG balances of the investigated bioenergy pathways are calculated in this chapter using the GEMIS 4.5 model and data (Fritsche et al., 2008c; Fritsche et al., 2008b). Emissions from direct and indirect land-use change caused by energy crop plantations are integrated into the GHG balances (chapter 2.4.1). The GHG reduction of the conversion pathways are calculated by comparing the total emissions of bioenergy with emissions of fossil reference systems (chapter 2.4.2 and 2.4.3). Finally, GHG mitigation costs are determined by comparing surplus bioenergy costs (production costs of bioenergy minus production costs of fossil reference systems) with GHG reductions in chapter 2.4.4. The methodology used for these calculations is described in chapter A7. Like bioenergy potential estimations, GHG balances of bioenergy have a wide range of uncertainties. The two most important factors on GHG reduction potentials are the effect of land-use changes and the choice of reference systems. Therefore, these two parameters are listed explicitly.

2.4.1 *Effect of direct and indirect land-use change caused by bioenergy*

In general, the expansion of energy crop plantations is going along with land-use change and land-use competition. Direct land-use change (dLUC) occurs by changing the purpose of land-use and can have positive and negative effects on carbon stocks and the environment (see chapter 1.3.2.1 and 1.3.1.2). The land taken for bioenergy may have been idle land, pasture or forest or used as arable land for other crops. Emissions caused by direct land-use change are well-documented and default-values for a 20-year framework based on IPCC carbon content data are applied in GHG balancing of bioenergy pathways (Gnansounou et al., 2008; Fehrenbach et al., 2008). Energy crops on arable land do not cause dLUC emissions. However, if pasture is converted into arable land for energy crops, dLUC emissions contribute about 20% of total GHG emissions.

Indirect land-use change (iLUC) happens, if bioenergy displaces a form of land-use (e.g. crop production for food and fodder) to another area where a land-use change happens to meet the need for the displaced crop and maintain crop production. In this way, bioenergy crop plantations cause land-use change 'indirectly'. In previous literature, this effect has been called 'displacement' or 'leakage' (Fehrenbach et al., 2008).

To replace the crop production formerly done on ‚bioenergy land', either production can be intensified on other cropland or additional land is converted for crop production. If this additional land converted ‚indirectly' by bioenergy for food or fodder has a high carbon stock (forests, peatlands), the land-use change causes high amounts of GHG emissions (see chapter 1.3.2.1). Although these emissions occur on a different place (sometimes at another continent), they have to be accounted (Fehrenbach et al., 2008). A simple example may illustrate the indirect land-use changes: A farmer in Germany is growing maize as fodder for his cattle for milk and meat production. He decides to use the maize to produce biogas in a new biogas plant. Fodder is still required for his cattle but no arable land is left at his farm land and thus he buys soya from an importer. This additional soya comes from Brazil and has to be planted on arable land, which might have been used for food or has been a primary forest. Food production is displaced again in Brazil and people shift into the rainforest for food production and so on. As agroindustry markets are global, production will shift to the easiest and cheapest areas where land conversion is possible, regardless of the present carbon stocks.

Emissions from indirect land-use changes cannot be quantified directly like emissions from direct land-use change, they have to be modeled. As the displacement effect is of an international dimension, it is difficult to register exactly which areas are converted indirectly by energy crops and which areas are not. The modeling of iLUC effects would be needless if the system boundaries of GHG balancing are set to a global scale and all emissions are registered and regulated by an international 'GHG regime'. As long as such a regime is not established, the iLUC modeling is necessary.

The iLUC-factor modeling is done in this study according to (Fritsche et al., 2008c). In theory, the iLUC emissions of bioenergy are derived from the displaced agricultural products (palm oil, soya, maize, wheat and rape seed) by calculating the land required by these products for agro-export (2005 figures) and the land-use change effects caused by their production in the corresponding main regions (USA and EU: pasture to cropland, Brazil: savannah to cropland, Indonesia: rainforest to cropland). The theoretical iLUC emissions are calculated using these land-use change assumptions and cropland expansions, resulting in an global weighted average value of 400 t $CO_{2\text{-eq.}}$ per hectare. Discounting this value on a 20-years timeframe gives an area-specific iLUC emission of 20 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1}.

These iLUC emissions are not necessarily becoming real, as displaced crop production can also be covered by intensification of production on the same land or by the recovery of idle, abundant and set-aside land. Therefore, only a certain percentage of the iLUC factor is assumed. In literature, the maximum iLUC factor is set to 75%, medium to 50% and low to 25% (Fehrenbach et al., 2008; Fritsche et al., 2008c). In the next decade, the low value of 25% may match the development. As energy crop production and food and fodder demand increase, higher iLUC factors (50% and more) have to be applied. These relations are not linear, as not every increase of energy crop production is leading automatically to indirect land-use change. Yet, some studies assume already today a 100% displacement (thus an iLUC factor of 100%), resulting in very high (theoretical) emissions from bioenergy pathways (Searchinger et al., 2008).

In this study, the iLUC factor is set to a typical literature value of 25%, which corresponds to iLUC emission of 5 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1}, as the bioenergy pathway settings refer to Germany as final bioenergy consumption place (Fehrenbach et al., 2008). Based on expert interviews, this seems a realistic assumption (Fritsche, 26.04.2009). The iLUC emissions are thus a function of the land used for bioenergy. The iLUC-factor for degraded land, set-aside land, idle land, marginal land and all forms of residues and waste is set to zero in the reviewed literature and in this study.

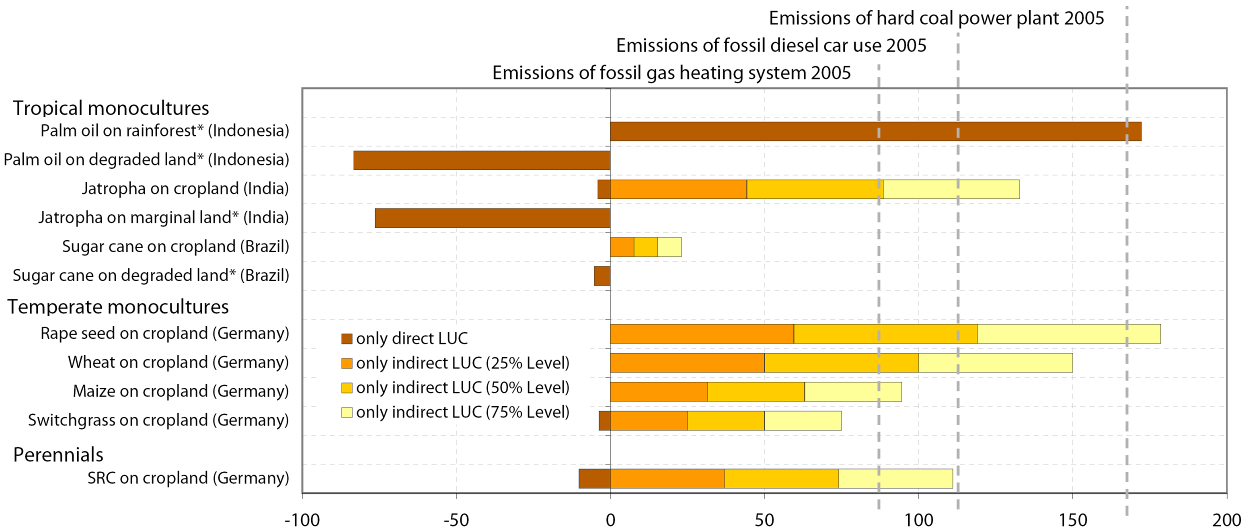

Figure 2.4-1: GHG emissions from direct (dLUC) and indirect (iLUC) land-use change for selected energy crops and different iLUC levels in t_CO2_eq per TJ raw biomass. * assumption of no indirect land-use change effects as no cultivation on this area has happened yet. Conventional grass from pasture in Germany is assumed to cause no indirect land-use change, as many pastures are idle due to a shrinking agricultural sector. This assumption cannot be applied on a global scale. Energy crop characteristics are listed in Table 2.1-1. Source: own compilation, based on (WBGU, 2009) and data (Fritsche et al., 2008c).

Figure 2.4-1 illustrates the effect of dLUC emissions and iLUC emissions for a 25%, 50% and 75% level in comparison with emissions from fossil reference systems. It is obvious that land-use change emissions are substantial in GHG balances of bioenergy.

These LUC emissions are related to the energy content of harvested raw biomass. That is why the emissions are higher, the lower the area-specific energy yields of the energy crop (see also energy yields in Table 2.1-1). This is especially the case for rape seed, wheat and jatropha.

The highest LUC emissions are resulting from rainforest clearance. The linked $CO_{2\text{-eq.}}$ emissions cannot be recovered by palm oil in the assumed timeframe of 20 years. In contrast, energy crops on marginal and degraded land or short-rotation coppice on arable land can sequestrate carbon to the soil (see also chapter 1.3.2.1) and improve the overall GHG balance drastically. The GHG balance of palm oil and jatropha on degraded land is positive, even without accounting fossil fuel replacement.

Apart from LUC emissions, land-use causes continuous GHG fluxes: arable land is usually a carbon source, pastures a carbon sink. These continuous fluxes are not accounted in the present GHG balances; neither have other GHG emissions from harvesting specific technologies like sugar cane leave burning.

2.4.2 Fossil reference systems

The GHG emissions of bioenergy pathways are compared with emissions of fossil reference systems to obtain the GHG reduction potential of bioenergy. The selection of fossil reference systems is as sensitive and crucial as emissions of land- use change. The effect is substantial. If natural gas is chosen as reference, the avoided emissions are much lower than if brown coal is substituted. In reality, many factors like the energy mix, economic framework conditions and policies like subsidies for fossil, nuclear and renewable energy sources determine the replaces fuel mix.

Bioenergy can only unfold its climate protection potential if it is substituting fossil fuels and not renewables like wind, hydro or solar energy. The most favorable solution in GHG balancing would be the exact knowledge of the fuel to be replaced (fuel switching). In reality, this can be done for single bioenergy pathways like biodiesel replacing fossil diesel or pellets replacing hard coal but for most of the pathway, this is not possible. Therefore, a fossil fuel mix for each energy sector is assumed for the reference years 2005, as production costs and thus mitigation costs are only available for this year and hardly to tell for 2030. However, the 2030 emission values are used in a sensitivity analysis to point out the probable spectrum of GHG reductions.

Fossil reference emissions and production costs

All settings refer to Germany, and thus German emission values are used (Table 2.4-1). The energy mix in transport and heat supply is almost purely of fossil nature, facilitating emission benchmarking. In the power sector, the mean emissions in 2005 amounted to 648 g $CO_{2\text{-eq.}}$ kWh_{el}^{-1}, corresponding to the energy mix of fossil, nuclear and renewable sources (Fritsche et al., 2008c). However, the fossil share was 60% and dominated power generation. This fossil share splits roughly in 80% hard and lignite coal and 20%

natural gas. This fossil mix is applied as fossil power reference system and for sensitivity analysis on one side for optimistic GHG reduction potentials the high emission value of lignite in a coal power plant in 2005 (1,248 g $CO_{2\text{-eq.}}$ kWh_{el}^{-1}) and on the other side for pessimistic GHG reduction estimations the low emission value of natural gas in a very efficient combined cycle plant in 2030 (398 g $CO_{2\text{-eq.}}$ kWh_{el}^{-1}) (Fritsche et al., 2008c; Müller-Langer, 2008). This bandwidth covers German mean emissions in the power mix for the period examined.

Similar fossil reference systems are used for heat and transport. The 2030 fossil reference system for transport fuels contains assumptions on a lower oil production efficiency due to depleting wells and GHG emission reductions by an improved utilization of carrier gas (Fritsche, 01.07.2009). As peak oil is taking place (chapter 1.2.1), more unconventional oil (shale oil, oil sand) is likely to be produced in different places around the world. However, it is unlikely that this sort of oil reaches high-quality oil markets like Germany, as unconventional oil contains large quantities of sulfur that hinders the refinement of crude oil to pure fossil diesel. The operation of refineries would have to be adopted and the use of hydrogen for desulphurization would be necessary (Ullmann, 2003). Assuming a 20% share of Canadian oil sand in the German diesel mix 2030 would increase the reference value of the diesel car by approximately 10% (Fritsche, 01.07.2009). This neither changes results greatly nor does it alter main conclusions.

Table 2.4-1: GHG emissions of fossil reference systems for power, heat and transport – mean values and extreme values for sensitivity analysis. [A] brown coal (lignite) power plant [B] Compressed natural gas car. Source: own compilation, based on (WBGU, 2009; Fritsche et al., 2008c; Fritsche et al., 2008b).

Energy sector	**Fossil reference system**	**Emissions for reference values**	**Emissions for sensitivity**		**Share in mix**	**Emission reference values**	**Production costs** (also for sensitivity)	**Prod. costs reverence values**
		g $CO_{2\_eq.}$ per kWh_{th}	g $CO_{2\text{-eq.}}$ per kWh_{el}; per kWh_{th}; per Person-km (mileage)		%	g $CO_{2\text{-eq.}}$ per kWh_{el} per kWh_{th} per Person-km	EUR Cent per kWh_{el} per kWh_{th} per Person-km	
		2005	2005	2005/2030	2005	2005	2005	2005
Power	Hard coal power plant	411	1,085	1,248 (2005)[A]	80	953	5.2	6.2
	Natural gas comb. cycle plant	234	425	398 (2030)	20		10.0	
Heat	Fuel oil heating system	321	376	376 (2005)	40	327	10.8	11.3
	Natural gas heating system	252	295	278 (2030)	60		11.6	
Mobility	Gasoline car	328	250	250 (2005)	60	230	2.68	2.6
	Diesel car	316	201	144 (2030)[B]	40		2.58	

The highest GHG reduction values will be obtained by replacing coal, regardless of the energy mix and its future development. The GHG balances only apply for Germany. Other countries hold different energy mixes and thus reference systems need to be adopted. Norway or Brazil for example has a high share of hydropower and hence a low-carbon reference system for power whereas China's energy mix is dominated by coal and the applied German values are below the emissions of the Chinese reference system.

In general, the most emission-intensive fossil energy carrier should be substituted by bioenergy. This is different for each country and at the same time not constant over time as the energy mix changes. Although unconventional oil is likely to be produced at very high emissions, lignite and coal are expected to remain the most emission-intensive fossil fuel in the majority of countries.

Uncertainties about future fossil energy and biomass feedstock costs – 2005 data

The fossil reference production costs are built by using the production costs of the same mix of fossil energy carriers. The reference costs are taken from the year 2005 and not extrapolated to the future. Technology developments can be predicted in a certain range but this is very difficult for production costs out of several reasons: there is a high uncertainty about the future energy mix in Germany, fossil energy costs vary significantly and market demand and supply is difficult to tell (see chapter 1.2.1.2).

There is the possibility of assuming ranges for 2030 fossil fuel and biomass feedstock prices, based on literature assumptions. The result is a bandwidth from very economical bioenergy (low biomass feedstock and high fossil fuel prices) to very expensive bioenergy production costs (high biomass feedstock and low fossil fuel prices). Using these assumptions in GHG mitigation costs results in a range that allows only one conclusion, namely that it is impossible to predict GHG mitigation costs of bioenergy for 2030. Costs are much more sensitive than technical parameters like efficiency.

Therefore, to enable comparability and generate reasonable results with rather fixed costs, fossil reference and biomass feedstock costs are taken from the year 2005.

2.4.3 Greenhouse gas reductions

Various parameters are used for GHG reduction calculations. The most common parameter indicates the percentage of GHG avoided by bioenergy compared to a fossil energy service. This analysis is based on final energy like thermal energy (kWh_{th}), electrical energy (kWh_{el}), chemical energy (biofuels) or mechanical energy in form of person kilometers. This percentual parameter is useful for single energy sectors but does not allow cross-sectoral comparisons. Moreover, the information about the area or raw biomass energy content that is initially used to produce one thermal / electrical / chemical bioenergy unit is lost and not included in percentual GHG balances of bioenergy. The limiting factors are not contained in such balances. Whether one or ten hectare or one or ten tons of biomass are used to produce a certain bioenergy unit cannot be disclosed as biomass combustion is in an ideal case 'CO_2-neutral'.

As the percentual parameter for GHG reductions by bioenergy is not answering the main question, in which application and to what extent bioenergy can reduce GHG emissions, other parameters are required that indicate absolute GHG emissions and reductions per area or raw biomass. This is done in this analysis in a first step by applying the parameter 'absolute area-specific GHG reduction' in $t_{CO2\text{-}eq.}$ per hectare and year (chapter 2.4.3.1) and in a second step by referring the 'absolute GHG reduction' of a bioenergy pathway to its initial harvested raw biomass (primary energy) that is entering the process chain at the very beginning (chapter 2.4.3.2).

2.4.3.1 Comparing area-related greenhouse gas reduction potentials

The parameter ‚absolute area-specific GHG reduction' (Figure 2.4-2) is meant to answer the question ‚Which bioenergy pathway shows the highest GHG reduction potential per area, as land is the most limiting factor for energy crops plantations?'. The following conclusions can be drawn from the analysis of this parameter with the applied methodology (see chapter A7):

Temperate energy crops

- GHG reductions range from minus 1.1 (more emissions than the fossil reference) to 17.7 $t_{CO2\text{-}eq.}$ ha^{-1} yr^{-1} (real emission reductions) for temperate energy crops on arable land, if pasture is converted into arable land for the purpose of growing energy crops, the emissions rise about 20% and the GHG reduction potential reduces respectively
- bioenergy in CHP applications achieve much higher GHG reductions on the same area than in heat or mobility applications
- CHP concepts using maize, switchgrass and grass silage achieve the highest GHG reductions (11.2 – 17.7 t $CO_{2\text{-}eq.}$ ha^{-1} yr^{-1}) along with SRC used in direct combustion (steam turbine CHP, cofiring in coal power plants) (12.0 and 10.1 $t_{CO2\text{-}eq.}$ ha^{-1} yr^{-1}) and switchgrass in electromobility (10.9 t $CO_{2\text{-}eq.}$ ha^{-1} yr^{-1})
- heat supply concepts are in the mid-range of 4.4 to 8.7 t $CO_{2\text{-}eq.}$ ha^{-1} yr^{-1}
- mobility concepts with internal combustion engines show the lowest GHG reductions (minus 1.1 to 3.3 t $CO_{2\text{-}eq.}$ ha^{-1} yr^{-1}), regardless of first or second generation biofuels; the only exception is biomethane from SRC in a natural gas vehicle (7.2 t $CO_{2\text{-}eq.}$ ha^{-1} yr^{-1}).
- maize, switchgrass and grass silage seem the most favorable temperate energy crops, which is also influenced by the applied GHG balancing methodology and especially the assumptions on indirect land-use change effects

Figure 2.4-2: Absolute area-related GHG reduction of bioenergy pathways by fossil fuel substitution related to the area used for energy crops in t $CO_{2\text{-eq}}$ per ha and year. As tropical energy crops (lower section) have higher yields than temperate energy crops (upper section), they are listed separately in different figures with different scales. GHG balances include emissions from direct and indirect (25%) land-use change effects. Negative values signify an increase of emissions by bioenergy relative to fossil energy. The resolutions of the pathway naming are listed in Table 2.1-1, Table 2.1-2 and Table 2.1-3. Source: own calculations, based on (WBGU, 2009) and data from (Fritsche et al., 2008c; Müller-Langer, 2008; Fritsche et al., 2008b).

Tropical energy crops

- GHG reductions vary from minus 83 (more emissions than the fossil reference) to plus 45 $t_{CO2\text{-eq.}}$ ha^{-1} yr^{-1} (real emission reductions) for tropical energy crops, which corresponds to palm oil plantations for CHP on rainforest (negative value) and degraded land (positive value)
- Like temperate energy crops, tropical energy crops in CHP concepts attain higher GHG reductions on the same area than in mobility applications

- Energy crops on degraded land achieve very high GHG reductions (6.6 to 45 $t_{CO2\text{-}eq.}$ ha^{-1} yr^{-1}) due to carbon sequestration in the soil (direct land-use change effects)
- The clearance of rainforest for energy crops leads to very high GHG emissions, which cannot be compensated by replacing fossil fuels by biomass
- Palm oil and sugar cane show a higher GHG reduction potential per hectare than jatropha as their energy yields per hectare are considerably higher

The variation of results is caused by different conversion efficiencies (chapter 2.2.1) and also by hectare yields and assumptions in the applied GHG balancing method (effects from land-use change, chosen fossil reference systems). For example, hectare yields in tropical vegetations are much higher than in temperate regions due to higher solar irradiation and all-season growth periods (see also energy crops characteristics in Table 2.1-1). The area-specific results cannot be used for extrapolation on a certain land area because the applied methodology allocates only for a part of the area used for bioenergy, provided that material by-products exist. Other area shares are then assigned to these by-products (see also allocation methodology in chapter A7).

2.4.3.2 Comparing raw-biomass greenhouse gas reduction potentials

The area-related parameter can indicate area-specific GHG reductions but has several drawbacks and sensitivities that influence the results strongly:

- bioenergy pathways using residues and waste cannot be represented
- the energy yields per hectare vary greatly depending on energy crop type, cropping system and soil quality
- the energy content of yielded raw biomass also varies greatly depending on the energy crop type

A possible solution for these drawbacks is to relate GHG reductions of bioenergy pathways to 'biomass primary energy', i.e. to the energy content of provided raw biomass in t $CO_{2\text{-}eq.}$ reduction per TJ raw biomass. This parameter balances these drawbacks and enables a cross-sectoral comparison, which is the main disadvantage of percentual GHG reduction parameters.

The 'raw-biomass GHG reduction' parameter (Figure 2.4-3) is the most favorable parameter for evaluating and comparing bioenergy pathways. Therefore, a sensitivity analysis is done in order to benchmark the results. The following conclusions can be drawn from Figure 2.4-3, whereby only the bioenergy allocated share of biomass is considered. Other shares of biomass are assigned to by-products (see also allocation methodology in chapter A7):

General

- GHG reductions of the investigated bioenergy pathways vary between minus 257 (more emissions than the fossil reference) and 190 t $CO_{2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$
- the use of residues and waste generally obtains better GHG reduction values than the usage of energy crops, which is primarily due to avoided land-use changes
- stationary applications of bioenergy (CHP, heat) have more potential to reduce GHG than mobile applications in transport
- bioenergy in combined heat and power (CHP) can reduce approximately the double amount of GHG than bioenergy in heat and conventional mobility applications and is therefore the most favorable option for climate protection with bioenergy
- the highest values are reached by using palm oil and jatropha on degraded land, in contrast, the lowest values result from applying the same crops on cleared rainforest
- the fuel switch (e.g. energy crops vs. residues) has a larger influence than the technology switch (e.g. SOFC vs. medium combustion CHP)

Mobility

- excepting the extreme cases of biofuels on degraded land or rainforest, the main differences result from the feedstock: using residues results in higher GHG reductions (32-116 t $CO_{2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$) than using energy crops (minus 8 to 73 t $CO_{2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$)
- second generation biofuels do not generally show better results than first generation biofuels, this is inline with results of a recent study (Jungbluth et al., 2008)
- comparing one feedstock (woody residues) applied in different technologies indicates that electromobility via direct combustion steam turbine CHP is the most favorable technology for GHG reduction in mobility (116 t $CO_{2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$), followed by a combustion engine vehicle using biomethane from gasification and polygeneration (63 t $CO_{2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$) and concluded by biohydrogen and Fischer-Tropsch-BTL-Diesel (52 and 51 t $CO_{2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$) via gasification

Heat

- similar to mobility, residues can obtain higher GHG reductions than energy crops
- the influence of applied technology on GHG reduction results is not very notable as both investigated technologies are using the same process of direct combustion

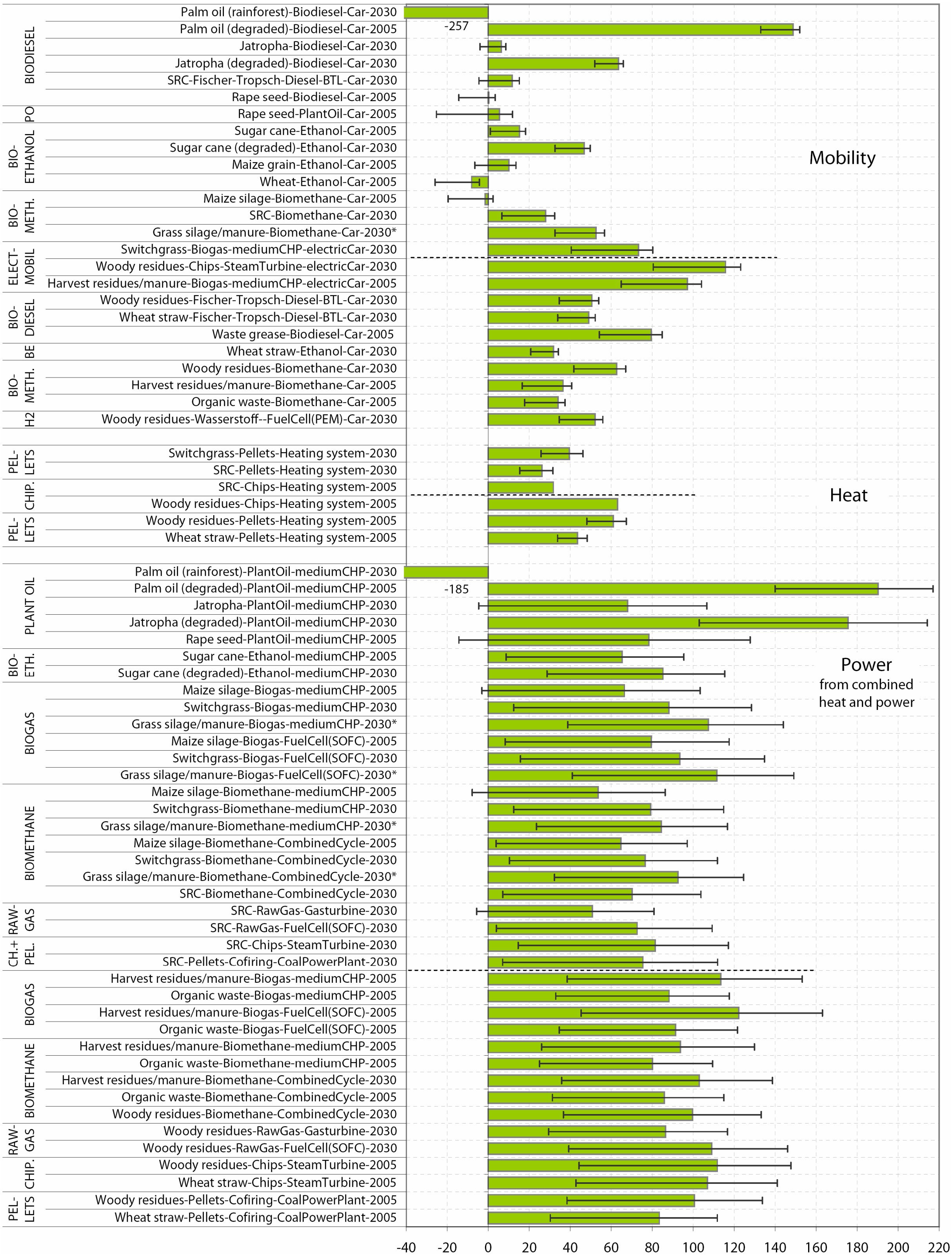

Figure 2.4-3: Absolute GHG reduction of bioenergy pathways by fossil fuel substitution related to the energy content of raw biomass in t $CO_{2\text{-eq}}$ per TJ raw biomass. GHG balances include emissions from direct and indirect (25%) land-use change effects. Negative values signify an increase of emissions by bioenergy relative to fossil energy. Error bars show the sensitivity of fossil reference systems (see Table 2.4-1). Residues and energy crops are separated by a dashed line. The resolutions of the pathway naming are listed in Table 2.1-1, Table 2.1-2 and Table 2.1-3. Source: own calculations, based on (WBGU, 2009) and data from (Fritsche et al., 2008c; Müller-Langer, 2008; Fritsche et al., 2008b).

Combined power and heat (CHP)

- with the exception of the extreme cases of biofuels on degraded land or rainforest, CHP concepts using residues show slightly higher GHG reduction potentials as concepts using energy crops; basically, the range is similar, reaching from 51 (SRC-RawGas-Gasturbine) to 122 t $CO_{2\text{-eq.}}$ $TJ_{\text{raw biomass}}^{-1}$ (Harvest residues/manure-Biogas-FuelCell)
- biomethane concepts are balanced without CO_2-sequestration; GHG reduction potentials of biomethane pathways would improve roughly by 20% if the separated CO_2 is stored permanently

The application of one feedstock in different technologies shows:

- woody residues for gasification and direct combustion processes: the most preferable option is direct combustion in a steam turbine CHP (112 t $CO_{2\text{-eq.}}$ $TJ_{\text{raw biomass}}^{-1}$), followed by gasification technologies (biomethane 100, raw gas 86-109 t $CO_{2\text{-eq.}}$ $TJ_{\text{raw biomass}}^{-1}$) and cofiring in coal power plants (101 t $CO_{2\text{-eq.}}$ $TJ_{\text{raw biomass}}^{-1}$)
- Harvest residues / manure for fermentation processes: direct use of biogas (SOFC 122, mediumCHP 113 t $CO_{2\text{-eq.}}$ $TJ_{\text{raw biomass}}^{-1}$) is superior to biogas-upgrading to biomethane (combined cycle power plant 103, mediumCHP 94 t $CO_{2\text{-eq.}}$ $TJ_{\text{raw biomass}}^{-1}$) as transmission losses and methane leakage are avoided

Sensitivity analysis of results

As mentioned in the introduction of this chapter, two parameters have a major influence on GHG reduction results: the effect of land-use changes and the choice of reference systems. The sensitivity of the land-use change parameter becomes apparent and is discussed in chapter 2.4.1. The sensitivity of choosing fossil reference systems is indicated in Figure 2.4-3 as black error bars. The values are generated by applying wide spread fossil reference systems for 2005 and 2030 listed in Table 2.4-1. The lower values origin from substituting natural gas in very efficient end energy applications; the higher values from the substitution of CO2-intensive technologies using brown coal and fossil oil. The resulting range for CHP concepts is quite wide. The highest GHG reductions can be obtained by substituting merely coal (about 100 to 160 t $CO_{2\text{-eq.}}$ $TJ_{\text{raw biomass}}^{-1}$). This is the case for cofiring of biomass in coal power plants, where a 100% substitution of coal takes place. Therefore, GHG reductions of cofiring concepts are about 20% higher than indicated in Figure 2.4-3. In contrast, the GHG reduction potential is much smaller and can even lead to more emissions than the fossil reference system, if natural gas is substituted. What kind of fossil energy is to substitute, depends greatly on country specific energy systems. If one energy sector is supplied predominantly by renewable energy (e.g. heat, power), it is more beneficial in terms of GHG savings to substitute fossil energy in another sector (e.g. long distance and heavy-duty transport).

It is recommendable to set the main target of using bioenergy to replace the most GHG-intensive energy carrier in the specific energy system.

2.4.4 Greenhouse gas mitigation costs

GHG mitigation costs are an important economic parameter and calculated as the fraction of additional costs and GHG reductions. Additional costs of bioenergy pathways are calculated by subtracting the production costs of bioenergy from the production costs of a certain fossil reference system (see Equation A7-3 in Annex A7), the same reference system that is also applied for GHG balances (see Table 2.4-1 and chapter 2.4.2). Negative values indicate that energy from biomass is more economic than fossil energy. No value is listed if GHG emissions of bioenergy pathways exceed emissions of the fossil reference system. In mobility concepts, the GHG mitigation costs are referred to person-km (mileage, vehicle kilometers traveled), i.e. the mechanical energy delivered by mobility energy services. This is done to enable a full comparison of all mobility concepts on the same baseline. In this way, electromobility and hydrogen cars can be included in the comparative analysis, which is not possible if the common reference point is liquid biofuel. More details on the GHG mitigation cost calculation methodology are given in chapter A7.

The GHG mitigation costs (minus 195 to plus 1,266 EUR t $CO_{2\text{-eq.}}^{-1}$) are given in Figure 2.4-4. Based on the 2005-related costs, the following conclusions can be drawn:

- Energy costs can be saved by using woody biomass in 400 kW heating systems with a local district heat grid and jatropha in conventional combustion engine cars
- CHP concepts using manure for biogas in a local CHP (12-13 EUR t $CO_{2\text{-eq.}}^{-1}$) or for biomethane in local CHP or combined cycle power plants (35-39 EUR t $CO_{2\text{-eq.}}^{-1}$) are very economic
- Similarly, residues cofiring concepts (47-50 EUR t $CO_{2\text{-eq.}}^{-1}$) are economic
- In general, mobility concepts using today's technology and residues or energy crops on marginal and degraded land show low GHG mitigation costs like e.g. waste grease to biodiesel (44 EUR t $CO_{2\text{-eq.}}^{-1}$) or bioethanol from sugarcane (16 EUR t $CO_{2\text{-eq.}}^{-1}$)
- Rather new concepts with high surplus costs resulting from high investment costs like fuel cell concepts or electromobility have very high GHG mitigation costs (see also production costs for comparison in chapter 2.3)

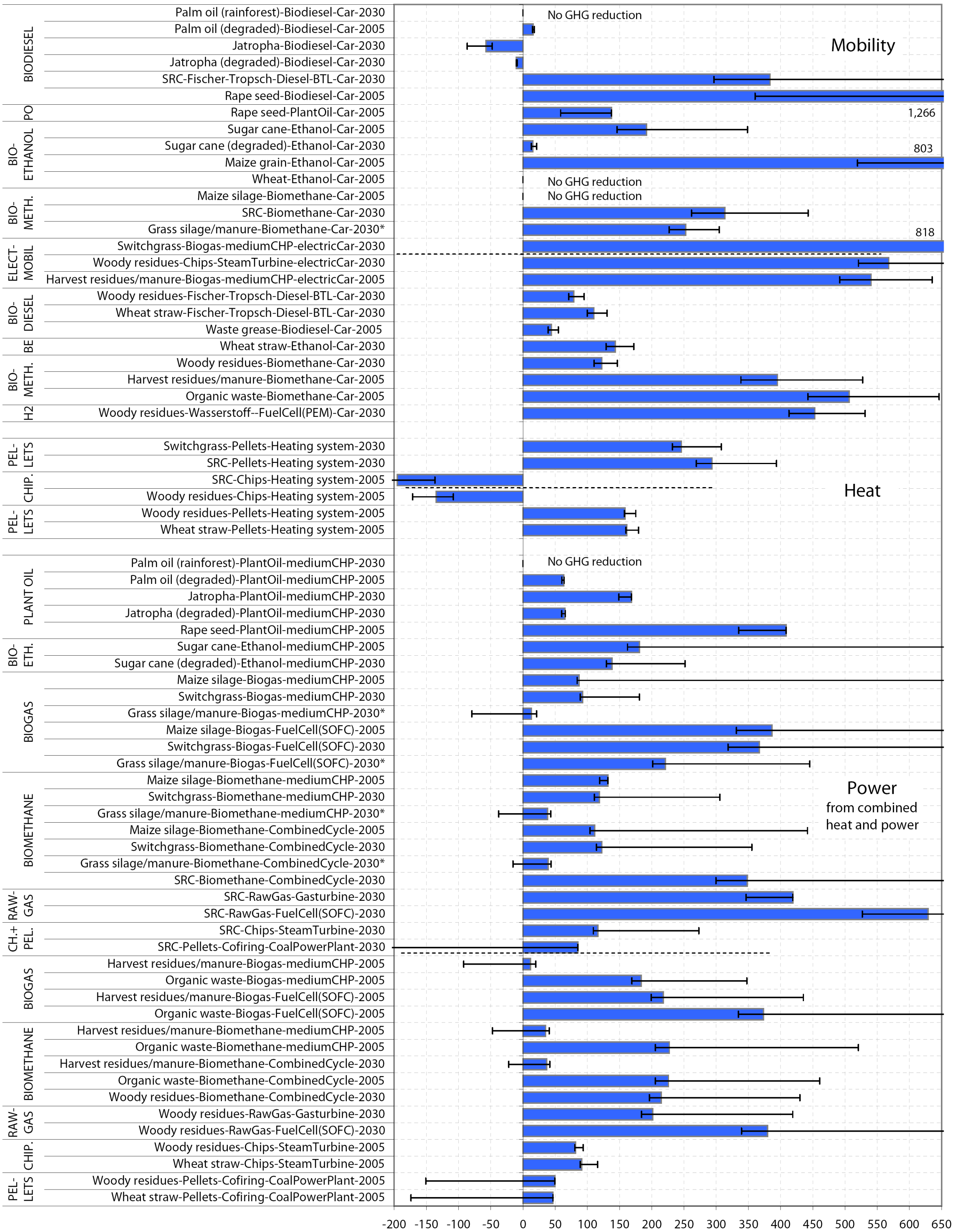

Figure 2.4-4: GHG mitigation costs of bioenergy pathways in EUR per t $CO_{2\text{-eq}}$. GHG balances include emissions from direct and indirect (25%) land-use change effects. Negative values signify cost savings by replacing fossil systems with bioenergy. Four values are not displayed as they are emitting more emissions than the fossil reference system that is listed in Table 2.4-1. Error bars are calculated using values from the year 2005 and show the sensitivity of fossil reference systems (see Table 2.4-1). Within an energy sector, energy crops and residues are separated by a dashed line. The resolutions of the pathway naming are listed in Table 2.1-1, Table 2.1-2 and Table 2.1-3. Source: own calculations, based on (WBGU, 2009) and data from (Fritsche et al., 2008c; Müller-Langer, 2008; WBA, 2007; Fritsche et al., 2008b).

Sensitivity analysis of results

The error bars in Figure 2.4-4 indicate the high sensitivity of GHG mitigation costs. Four parameters cause these large variations: (i) the GHG emissions of bioenergy including land-use change emissions, (ii) the GHG emissions of the assumed fossil reference system, (iii) the production costs of bioenergy, and (iv) the production costs of fossil energy, especially feedstock costs. In this sensitivity analysis, cost and emission assumptions are used from the past, the year 2005 (see Table 2.4-1). Although these 'fixed' figures are used, the results spread widely.

Assuming a bandwidth of future GHG emissions can be done like in the previous chapter. Assuming a reasonable bandwidth of costs for fossil fuels or bioenergy feedstocks is a challenge for 2030 and would stretch the results beyond recognition. In 2005, the production costs were in Germany at 5.2 EUR cent kWh_{el}^{-1} for coal power plants and 10.0 EUR cents kWh_{el}^{-1} for natural gas power generation. In 2008, the costs were about 50% higher due to high fossil energy prices (Statis, 2009). As these fossil prices are likely to increase in the future, bioenergy concepts may become competitive. Bioenergy production costs split roughly in 40-50% biomass feedstock ‚consumption-related' costs and 40-50% technology ‚capital-related' costs for new technologies (chapter 2.3). While technology costs are likely to decrease with further technology development and market penetration, biomass feedstock costs also almost doubled in 2008 and are very sensitive to agro-products market demand and fossil oil prices. Biomass feedstock from energy crops is exposed to increasing land-use competition, which is probable to boost prices, while residues might not be so sensitive as they avoid land-use competition.

After all, it is very difficult to estimate the GHG mitigation costs of bioenergy; for today and for future energy scenarios.

Discussion of results

The findings on technical efficiency, costs and GHG reduction potentials are in line with other major bioenergy assessments (Faulstich, 2008; WBA, 2007; Faulstich, 2007; SRU, 2007). Results on electromobility are rather new and only few other papers deal with bioenergy and electromobility. (Campbell et al., 2009) confirms that bioethanol in electromobility is favorable against bioethanol in conventional combustion engines in terms of technical efficiency and GHG reduction potentials.

2.4.5 Greenhouse gas reductions and mitigation costs of replacing traditional biomass

Greenhouse gas reductions

GHG emissions of traditional biomass conversion chains are difficult to quantify. Consequently, there is not much literature available yet (Kishore, 04.03.2009). The main traditional biomass applications are small stoves. Even though they are small in size, they are so numerous that they contribute significantly to global emissions. Traditional combustion processes are often incomplete, i.e. inefficient and have high off-gas-shares of CO, CH_4 and N_2O, which are ‘climate relevant’. These GHG can be reduced significantly by replacing traditional with modern biomass stoves. (Bhattacharya et al., 2002) estimates a GHG reduction of 60% for replacing traditional biomass-fired stoves by improved cooking stoves and reductions of more than 95% by replacing the stoves with small biogas digesters and stoves. Similar results are estimated in studies of Nepal biogas stoves (ter Heegde, 2005). GHG of traditional biomass can be also reduced by fuel switching. Fuel wood is often extracted from primary forests and therefore not sustainable and causing deforestation. Fuel wood from sustainable energy crops or woody residues creates less GHG.

To be GHG neutral, biomass combustion must be based on renewable harvested biomass and have a 100% combustion efficiency, which emphasizes the need of improving cooking stoves. Liquid or gaseous biofuels like biogas or plant oil are favorable against solid biomass, as the combustion process is usually much more efficient and less GHG intensive. The upgrading of solid biomass to liquid or gaseous fuels via thermo-chemical processes is therefore recommendable. Traditional biomass stoves show GHG emissions in the range of 80 to 150 t $CO_{2\text{-eq.}}$ $TJ_{th\ heat}^{-1}$ for firewood, residues and dung; improved cooking stoves around 20 to 40 t $CO_{2\text{-eq.}}$ $TJ_{th\ heat}^{-1}$ and biogas stoves only about 5 t $CO_{2\text{-eq.}}$ $TJ_{th\ heat}^{-1}$ if methane leakage is avoided (Smith, 2000; Bhattacharya et al., 2002).

This results in GHG reduction potentials of 15 to 50 t $CO_{2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$ (40 to 130 t $CO_{2\text{-eq.}}$ $TJ_{th\ heat}^{-1}$) for improved cooking stoves and 40 to 75 t $CO_{2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$ (75 to 145 t $CO_{2\text{-eq.}}$ $TJ_{th\ heat}^{-1}$) for biogas digesters, replacing traditional biomass-fired stoves.

Investigation on several types of cooking stoves indicates that emissions depend on both fuel type and stove type. In many cases, about 8% of biomass weight (fuel wood, charcoal, dung) is released as CO to the atmosphere. This rate is much smaller with liquid fuels (kerosene) and gaseous fuels like natural gas, LPG and biogas. The CO emission levels can be reduced by fuel switching. As fossil fuels are in many cases not affordable by rural citizen, liquid biofuels or biogas could be an economic substitute, reducing GHG emissions especially incomplete combustion and deforestation (Zhang, 1999a, Zhang, 1999b).

Greenhouse gas mitigation costs

Replacing traditional biomass-fired stoves with improved cooking stoves or biogas digesters is an economical way of climate mitigation. Using cost estimation results of chapter 2.3.2; the GHG mitigation costs of improved cooking stoves (surplus costs of 0.12 EUR cent $kWh_{th\ heat}^{-1}$) range from 2.5 – 8.5 EUR t $CO_{2\text{-eq.}}^{-1}$. Accordingly, GHG mitigation costs of efficient biogas digesters (surplus costs of 0.53 EUR cent $kWh_{th\ heat}^{-1}$) amount to 10 – 20 EUR t $CO_{2\text{-eq.}}^{-1}$.

In the end, technologies to overcome traditional biomass use are among the most economical options of GHG mitigation by bioenergy and often significantly more feasible than most of modern bioenergy pathways.

2.5 Synthesis

2.5.1 Techno-economic synthesis

Results of technical efficiency are plotted versus cost calculations in Figure 2.5-1.

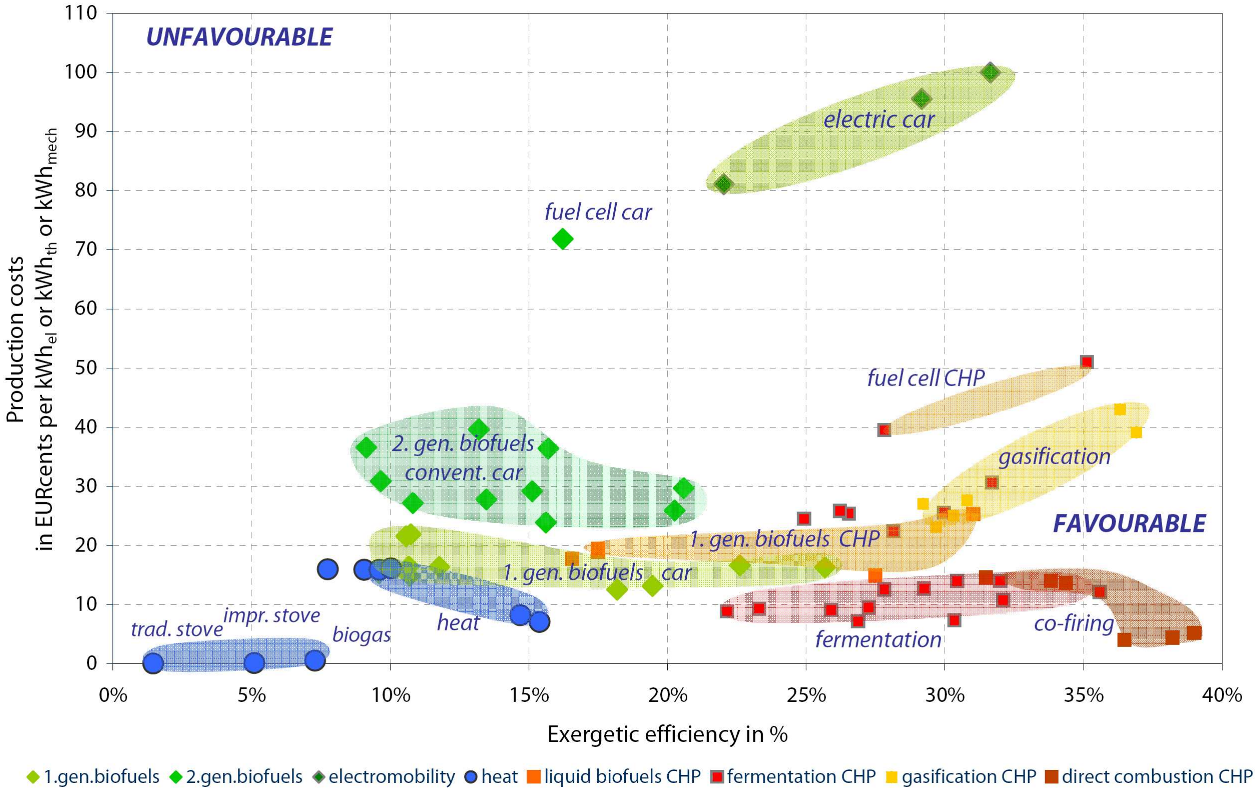

Figure 2.5-1: Technical exergetic efficiency in % vs. production costs in EUR cents per electrical, thermal or mechanical energy (kWh) of investigated biomass pathways. Source: own calculations.

Traditional stoves can be replaced by improved cooking facilities, which are also economical. In mobility, first generation biofuels are as efficient as second generation biofuels in conventional cars but show lower costs of providing mobility. Electromobility is the most efficient but as well still the most costly way of transport. The use of first generation biofuels is more favorable in CHP than in cars at similar cost. Direct combustion obtains the highest exergetic efficiency at lowest energy supply cost. Cofiring is the most cost-efficient and exergetically-efficient way of using solid biomass as existing power plant technology and infrastructure can be used without major changes. It is also a first step of integrating renewable with conventional power production. Gasification and fuel cell technologies are highly efficient but expensive. All sophisticated and future technologies like electromobility, second generation biofuels, gasification or fuel cell applications show rather high energy costs.

2.5.2 Techno-ecologic synthesis

Plotting the GHG reduction potentials vs. the exergetic efficiency in Figure 2.5-2 shows a quite proportional relation. GHG reduction potentials are sensitive to conversion efficiency. The improvement of exergetic efficiency of CHP applications from 20% to 30% is increasing the GHG reduction potential from 60 to 90 t CO_2 $TJ_{raw\_biomass}^{-1}$.

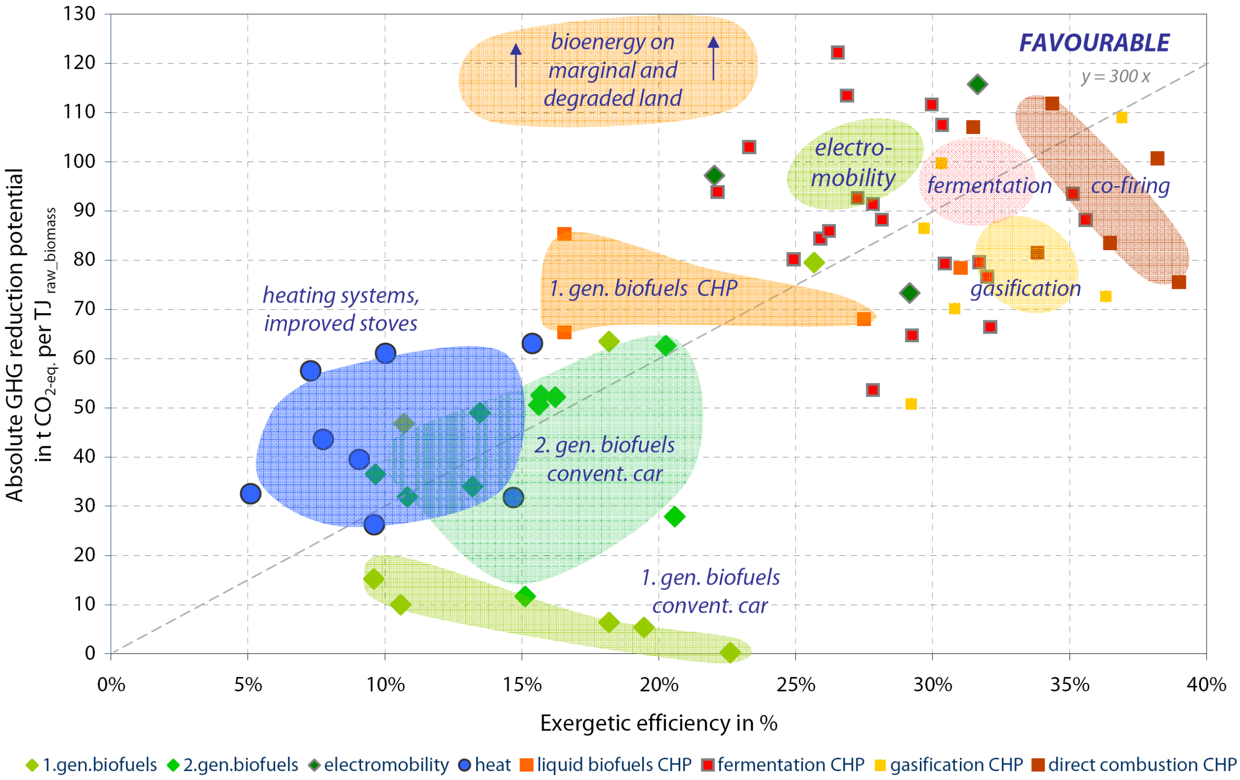

Figure 2.5-2: Technical exergetic efficiency in % vs. absolute GHG reduction potential of bioenergy pathways in EUR per t $CO_{2\text{-eq.}}$. A linear correlation between the two plotted parameters is identified (y=300x). Negative values are not shown in the figure. Source: own calculations.

CHP pathways perform better in both parameters as higher efficiencies are obtained by co-generation and substituting fossil fuels both in power and heat provision. Heat and mobility concepts are at the lower end while electromobility is in the same range as CHP applications. Bioenergy on marginal and degraded land plays an exceptional role as they reach very high GHG reduction potentials (up to 190 t CO_2 $TJ_{raw\_biomass}^{-1}$) at medium conversion efficiencies.

2.5.3 Economic-ecologic synthesis

Figure 2.5-3 compares the results obtained from the analysis of GHG reduction potentials (chapter 2.4.3) and GHG mitigation costs (chapter 2.4.4). For illustration purpose, Figure 2.5-3 is split into two sections: the upper section illustrates all examined values that obtain GHG reductions, and in the lower section a focus is set on 90% of the data excluding bioenergy pathways using marginal and degraded land and pathways with very high GHG mitigation costs above 600 EUR $t_{CO2\text{-eq.}}^{-1}$.

There was a significant positive correlation between the parameters for energy crops on marginal and degraded land due to the high carbon sequestration rate and positive land-use change (upper section of Figure 2.5-3). Results are still better for CHP applications than in conventional mobility, but the difference in the use of degraded or arable land is not as strong. Thus, energy crops on marginal and degraded land in tropical and sub-tropical countries are a favorable option for climate mitigation. In contrast, rapeseed biodiesel used in conventional cars shows very high GHG mitigation costs and low GHG reduction potentials mainly due to land-use change effects. Furthermore, these findings show the impact of the method applied: the less emissions avoided, the higher the costs to avoid them.

It is apparent from the lower section of Figure 2.5-3 that the 400-kW heating systems are the most cost effective way of reducing GHG in industrialized countries with heating demand, as the production cost is less than the fossil reference case. This cannot be generalized to all heat applications, like the smaller 15 kW heating systems testify. However, large amounts of GHG emissions can be avoided in developing countries at very low costs by replacing traditional biomass-fired stoves with improved cooking stoves or biogas stoves using biogas from small digesters. Fermentation of biomass, especially cofermentation with manure, is the most effective way of reducing GHG with bioenergy in CHPs, showing very low GHG mitigation costs. Direct combustion and cofiring biomass shows also high GHG reduction at low GHG mitigation cost.

In mobility, second generation biofuels show higher GHG reduction potentials than first generation biofuels in conventional cars, but GHG mitigation costs tend to be higher. Nevertheless, biofuels used in CHP obtain higher values generally as shown for first generation biofuels. Technologies with high GHG reduction potentials and high GHG mitigation costs due to high capital-related costs like electromobility, fuel cell or gasification technologies show promising results and are probable to become beneficial in the future by economies of scale. A sensitivity analysis revealed that the change of full-load hours of the conversion plants (0 to 8760 h per year) has almost no effect on GHG reduction potentials but a significant influence on GHG mitigation costs.

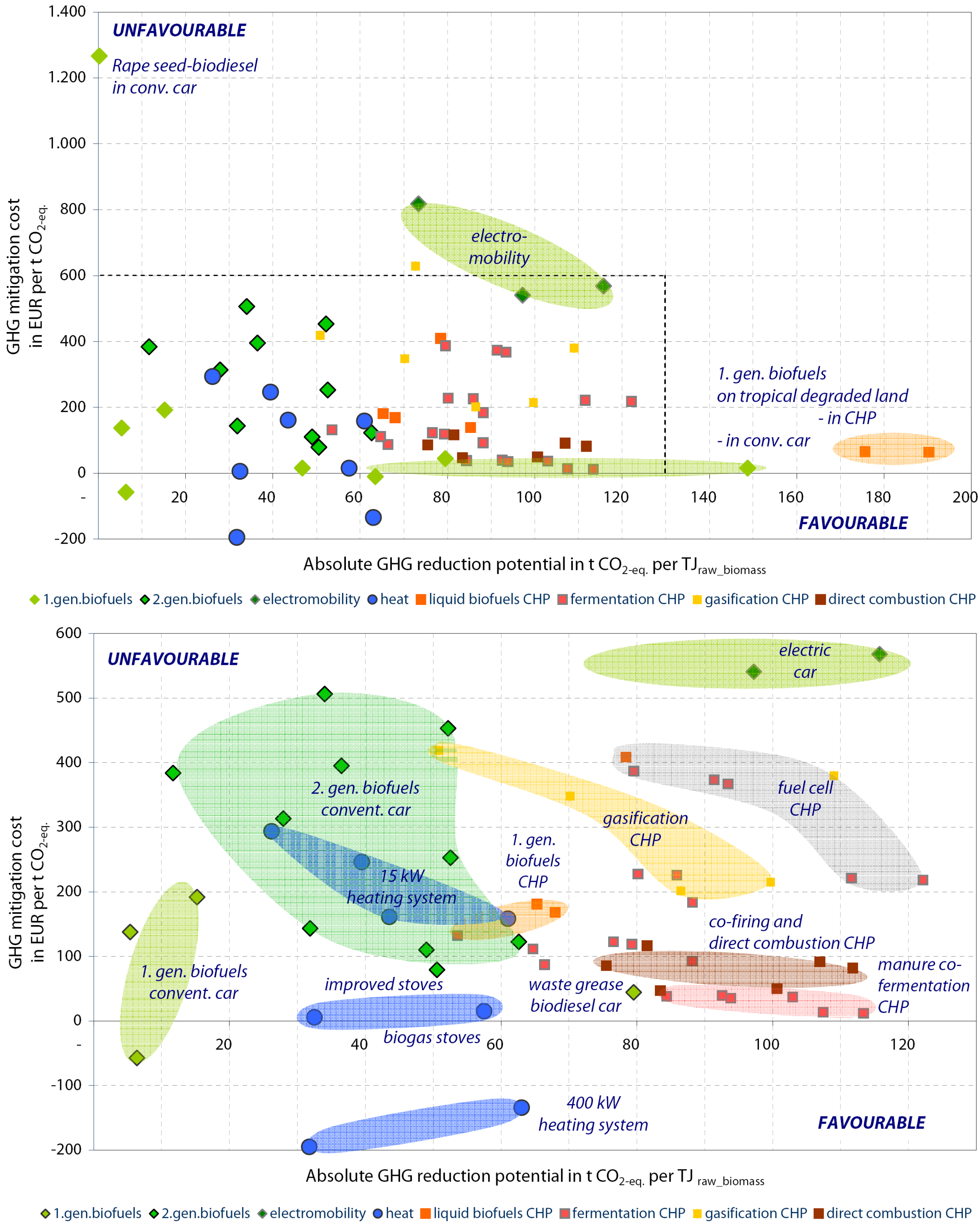

Figure 2.5-3: Comparison of absolute GHG reductions vs. GHG-reduction costs. Two scales are used: The upper section covers all values with positive GHG reduction. In the lower section, bioenergy pathways using marginal and degraded land or with very high mitigation costs above 600 EUR t $CO_{2\text{-eq.}}$ are excluded. The dashed line in the upper section illustrates the selection for the lower section. Source: own calculations.

These findings suggest that in general, bioenergy in CHP and heat applications are more cost and reduction efficient than bioenergy in mobility, except for electromobility.

3. *Integrated assessment – role of bioenergy in land use, energy systems and climate change*

The background for assessing bioenergy in the context of land use, energy supply and climate change was set in chapter 1. The detailed analysis of biomass pathways from chapter 2 forms the techno-economic and ecologic background on biomass conversion to bioenergy. In this chapter, both are brought together in an integrated assessment.

3.1 *Role of bioenergy in land use – two faces of one coin*

Most of the 'bioenergy problems' identified are dealing with energy crops that cause land-use change and land-use competition. One solution is the integration of food, material and energy production on the same area by cascade use and the use of residues from food and material production. Another solution is the use of marginal or degraded land for energy crops.

Effects of land-use (changes) by energy crop plantations

Energy crops show two faces of one coin. On one side, if primary forests, natural ecosystems, savanna, peatlands or grasslands are converted into energy crop plantations, large amounts of GHG and soil carbon are released that can hardly be recovered by substituting fossil fuels with bioenergy grown on this land. In addition, biodiversity is lost. On the other side, energy crops on degraded and marginal land can enrich soil with carbon and nutrients, improve water availability, and enrich the present biodiversity.

Table 3.1-1: Effects of land-use (changes by energy crop plantation on soil carbon stocks, soil quality, biodiversity and GHG emissions. Source: own compilation.

Effects (Trends)	**Positive**	**Negative**
Type of land-use change	Crops on degraded and marginal land	Crops on primary forests, natural ecosystems, savanna, grasslands
Type of energy crop	Perennial cultivations (woody energy crops, switchgrass, jatropha, sugar cane, oilpalm, low-input high-diversity grassland biomass)	Annual cultivations (maize, wheat, rape seed, sugar cane)

Similar impacts can be observed in the variation of crop type. Perennials require less water and fertilizer input, cause less soil erosion, conserve the vegetation cover, and enable in most cases the spread of biodiversity instead of annual crop monocultures. The effects of 'type of land-use change' are stronger than the effects of 'type of energy crop' on soil carbon stocks, biodiversity and GHG emissions (see chapter 1.3 and 2.4). Potential win-win solutions can be obtained. Perennials on marginal and degraded land are a preferable option. Short rotation coppice (SRC) crops are able to reduce soil erosion risks and nutrient leaching. Low-input high-diversity grassland biomass are another positive example for a synergy between biodiversity, low-fertilizer input, improved soil quality and high bioenergy yields (Rösch et al., 2007; Tilman et al., 2006; OECD, 2008). Table 3.1-1 summarizes these findings.

Mitigating land-use competition

Bioenergy feedstock demand can increase pressure on both agricultural land and forests (chapter 1.3.2). With ever higher fuel prices, there will be even more pressure on forests and trees outside forests to provide energy in the poorest countries.

On one hand, these trends of agricultural expansion and land-use change would continue independently of modern energy crops plantation and bioenergy production. On the other hand, care needs to be taken that energy crops and other forms of bioenergy like the use of residues do not accelerate or worsen negative environmental effects of global land-use trends and serve their main purpose, namely the protection of the climate.

Within the last years, competition between food crops and energy crops has been increasing. One factor contributing to this developing is the rising global population that is expected to demand 50% more food in 2030 than today, which requires at least 13% more agricultural land (FAO, 2006). The second factor leading to the increasing competition is diets and nutrition patterns that are changing toward a more area and resource intensive food production. After all, there is little land left for other purposes like energy crops. Therefore, priority has to be set on food and fodder production, as energy can be derived from other sources as well.

Next to food crops, energy crops are also in competition with material use. Cascade uses of forest and agricultural products or agroforestry are suitable solutions. In this way, one hectare serves two purposes and land-use competition is mitigated.

This analysis shows that residues and waste from agriculture and forestry are the preferable biomass feedstock as they avoid land-use competition and negative effects of land-use change. However, care has to be taken that enough nutrients remain on the harvested land. Some residues have to remain for soil fertility or nutrients can be recycled, e.g. by leaving some straw on the fields or returning the retreated ash of woody biomass use to the forests (Göttlein et al., 2009).

The integration of food, material and energy use would be a possible solution to diminish land-use competition and to improve income in rural regions.

In the context of climate mitigation and land-use, a land-use competition between energy crops and afforestation might possibly arise. As bioenergy serves an additional service to society in providing energy, a possible recommendation might be to use land for afforestation that is not easy to access and other land for bioenergy purposes.

Issues related to ‚land-use' are not limited to energy crops but concern all other types of land use for food, material or climate mitigation (e.g. afforestation). Therefore, land-use change and competitions have to be considered in all forms of land-use.

3.2 Role of bioenergy in energy supply systems

Residues are more favorable than energy crops. Their optimal application in energy supply systems is yet to be identified. The potential of bioenergy is limited (chapter 1.3.3.2) and will not be sufficient to cover large shares of the global energy demand. Therefore, it is important to highlight the strategic features of biomass and maximize their use in terms of energy efficiency and climate mitigation. Against this background, the role of bioenergy in energy systems is discussed for industrialized regions (chapter 3.2.1) and rural regions in developing countries (chapter 3.2.2).

3.2.1 Industrialized regions and countries – applying modern bioenergy

3.2.1.1 Efficient use of bioenergy in transport, heat and power

Overview

The overall results for modern bioenergy pathways from chapter 2 are condensed and evaluated qualitatively in Table 3.2-1.

Table 3.2-1: Bandwidth of main results from technical, economic and ecological criteria analysis in chapter 2. Source: own calculations and evaluation, based on (WBGU, 2009)

Parameter		Exergetic efficiency		Production costs		GHG reductions		GHG mitigation costs	
Unit		%		EUR cents per kWh_{el}, kWh_{th}, km		t $_{CO2\text{-}eq.}$ per TJ $_{raw\ biomass}$		EUR per t $_{CO2\text{-}eq.}$	
Transport	1. generation biofuels	10-26	-	2-4	++	- 257-149	- - / ++	- 57-1,226	++ / - -
	2. generation biofuels	9-21	-	5-14	**0**	- 2-63	-	79-506	-
	Electromobility	22-32	+	16-20	- -	73-116	++	541-818	- -
Heat	small systems	8-10	- -	16	-	26-61	**0**	158-294	- -
	large systems	15	-	7-8	+ +	32-63	**0**	-195- (-) 135	++
Power and Heat (CHP)	liquid biofuel medium CHP	17-31	**0**	15-25	**0**	- 185-190	- - / ++	63-409	**0**
	fermentation medium CHP	22-36	+	7-24	+	54-113	+	12-227	+
	fuel cells (SOFC) CHP	27-37	+	25-43	- -	73-122	++	218-629	- -
	Gasification CHP	29-30	+	23-28	-	51-100	+	82-116	**0**
	Direct combustion steam turbine CHP	31-34	++	14-15	+	82-112	++	82-116	**0**
	Co-firing coal power plant	36-39	++	4-5	++	75-101	++	47-85	+

The largest synergy between technical efficiency, costs and GHG reductions are obtained by co-firing and direct combustion steam engine CHPs. Apart from the extreme cases of energy crops on marginal and degraded land or rainforests, biofuels show better results in CHP applications than in mobility. Some technologies like electromobility, fuel cell and gasification CHP are very efficient and GHG reduction effective, but still very expensive in relation to fossil fuel systems. Therefore, the role of biomass in energy systems will be discussed for individual energy sectors in the following chapter.

Efficient use of bioenergy in mobility

The use of biomass in transport via electromobility is technically more efficient and has larger GHG reduction potentials than via biofuels in conventional combustion engines. Stationary energy conversion is beneficial, since (i) higher conversion rates are achieved by full-load operation, (ii) waste heat can be used, (iii) by-products like bagasse can be used and (iv) the possibility of future CO_2-sequestration is given. These are clear advantages of electromobility with biomass (see also chapter 5.2.4). A drawback of this new technology can be detected in the rather high production and GHG mitigation costs which are expected to decrease with an economy of scale.

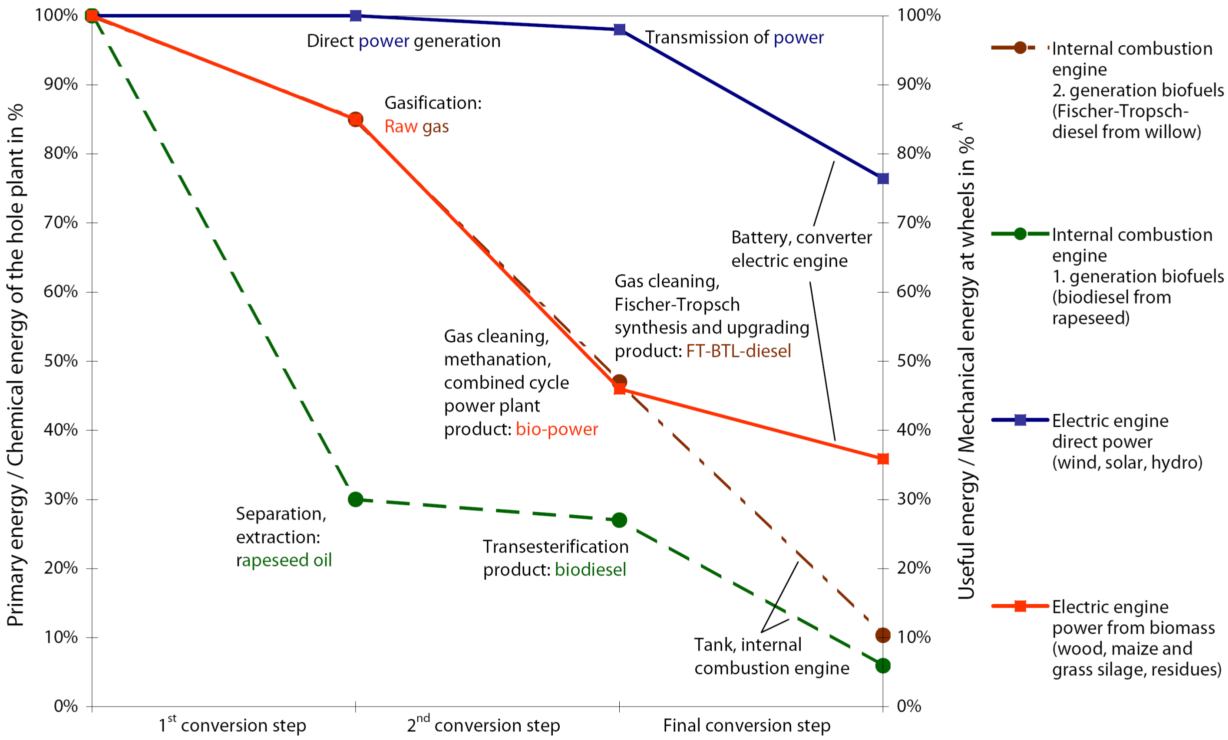

Figure 3.2-1: Well-to-wheel comparison of biomass in different transport concepts. Electromobility is superior to conventional integrated combustion engine cars. Unlike in the bioenergy pathway analysis in chapter 2, by-products like CHP heat, fiber, or fodder are not included in these calculations. FT-BTL: Fischer-Tropsch-Diesel - Biomass-to-Liquid 2nd generation of biofuels. More details on calculation assumptions can be found in (Sterner et al., 2008b). Source: own compilation, based on (WBGU, 2009; Sterner et al., 2008b; Sterner, 2007; Engel, 2007; Ahmann, 2000; Dreier et al., 2000; Kaltschmitt et al., 2003).

For example, short rotational coppice (SRC) can be gasified into raw gas with an efficiency of up to 85%. This raw gas can be cleaned and liquefied into Fischer-Tropsch-Diesel with an efficiency of 55-60% or converted into biomethane and biopower in combined cycle power plant with an efficiency of approximately 50-55%. Using BTL-Diesel in a conventional car, only 10% of the initial chemical energy of woody biomass can be utilized as shaft power. In contrast, this efficiency is about 35% for biopower in an electric vehicle. Similar results are identified using rape seed or maize for biodiesel, bioethanol and biopower respectively (Sterner et al., 2008b). Also other studies show that e.g. bioethanol is more beneficial in electromobility than in conventional cars (Campbell et al., 2009). Figure 3.2-1 illustrates both pathways for SRC plants, for rapeseed biodiesel, and electromobility using wind, solar or hydro power. It is not feasible to maintain an inefficient transport infrastructure using biofuels in conventional cars.

In general, the GHG reduction benefit of electromobility depends on the country's individual energy systems. Given that fossil fuels are being substituted by renewables like hydro power and biomass is not needed for power, it could replace fossil fuels in transport. However, the poor conversion efficiency of conventional cars remains.

Bioenergy for heat supply – CHPs and heating systems

The most preferable option in terms of exergetic efficiency and GHG reduction is the application of biomass in CHP. Heat demand is expected to decline due to energy savings from e.g. better insulation (chapter 5.2.1). The remaining shares of the heat demand can be met by heat from CHP Both decentral and central combined heat and power generation can substitute fossil fuels efficiently via district heating systems; to some extent they can also process heat. Biopower from CHP can also be used for heat supply via electric heat pumps (chapter 5.2.2 and 5.2.5). Combining both heat and power from CHP for heat supply shows larger overall efficiencies since ambient heat can be utilized using biopower in heat pumps.

As a second option, biomass heating systems can replace fossil fuels efficiently at low cost. Large systems with district heating system show better results than small systems.

Bioenergy for power supply – combined heat and power and control power

CHP technology is in general more efficient than separate power and heat generation (chapter 5.2.2). Almost all forms of biomass can be used in CHP. Especially direct combustion of solid biomass in steam turbine CHPs is a technology with many benefits. Wood chips or pellets can substitute coal in central coal power plants via co-firing directly, which is one of the most favorable option to use bioenergy (see Table 3.2-1). Decentral biomass can be used very efficiently, save fossil fuel costs and avoid emissions. In regional concepts, heat from biomass CHP can supply district heat for example to official buildings, schools, groceries, or baths (Roy, 2008). Decentral biogas plants as well as biofuel CHPs are state-of-the-art. Woody biomass gasifiers CHP are not yet established in a commercial scale because of unsolved technical challenges in gas cleaning (Vogel, 2007). Gasification technologies are especially interesting for biomass feedstocks with difficult properties that cannot be used otherwise. By generating biomethane via gasification and fermentation (Annex A4), the gaseous fuel can substitute natural gas. Distributed to households, biomethane can be used in small CHP decentrally in an efficient way.

Many other CHP technologies for biomass like organic-rankine-cycle plants or special biomass combined cycle power plants are successfully developed (OTTI, 2008). A precondition for large scale CHP implementation is the extension of district heat supply or close-by heat consumer. Biomass CHP can thus contribute in a small and large scale to energy efficiency and climate mitigation.

3.2.1.2 Strategic functions of bioenergy in power supply

Major strategic functions of bioenergy are (i) its geographic broad availability, (ii) its flexibility to be used in all energy sectors and (iii) its storage capability and high energy density. The latter are the most important strategic characteristics of biomass. The energy storage capacity of biomass can serve as balancing power. The high energy density of biofuels can play an important role in special transport segments. In the future, other technologies (e.g. renewable methane – chapter 4) may take over these two strategic functions of bioenergy, and biomass can be used as raw carbon supply material for the chemical industry when fossil fuel is no longer available for that. Another strategic function of bioenergy is carbon sequestration from the atmosphere.

High energy density for special transport segments

Electromobility cannot cover all transport segments. Aviation, navigation, and heavy-duty transport (e.g. machinery in agriculture, forestry, construction) require fuels with high energy density. Electromobility can hardly substitute fossil fuels in these transport segments since batteries are not feasible or technically able to provide energy for these transport segments. Liquid biofuels from oil crops are ideal since the extracted straight plant oil can be produced efficiently with good fuel properties. It is technically possible to fly with biofuel blends as first flight tests with jatropha-plant oil have shown (Air New Zealand, 2009). Other strategic valuable options for biofuels in transport are to produce Fischer-Tropsch kerosene for aviation rather than Fischer-Tropsch diesel for road transport, which can be substituted by renewable electromobility.

Energy storage capacity and use for balancing power

Future energy systems, based on renewable power, will require backup power to balance high shares of fluctuating wind and solar power penetration. Today, most of this balancing is done with fossil fuels (Heuck et al., 2007). In the future, extended super smart grids will provide large power transfer capacities and interconnect power storage systems like pumped hydro storage, compressed air storage, and electromobility. The energy storage capacity of bioenergy will be needed for balancing power as well. Especially biomethane can fulfill this function, as it can be produced by a wide range of residues and energy crops via gasification and fermentation and be stored as flexible energy carrier in the natural gas grid. From there, it can be distributed and used in fuel cell CHP, gas turbine or combined cycle power plants to generate balancing power. Today's biogas plants in Germany are not designed to provide these ancillary services

(Scholwin, 2007). Plants can be redesigned with gas tanks and double installed CHP capacities and provide peak load power on a daily basis. Further, some flexibility in biogas production is given in operating the fermenter. CHP heat utilization concepts have to be considered in power-mode operation. In the future, the energy storage capacity of bioenergy will be increasingly utilized in form of balancing power in electrical networks (Gerhardt, 2008; Kirchner, 2008).

Carbon sequestration – decarbonization by biomethane

Biomass is extracting CO_2 from the atmosphere. If CO_2 is captured in the bioenergy conversion process and stored underground, it can be sequestrated permanently. A first step of decarbonization is already done in the state-of-the-art production of biomethane, were it is necessary to separate the CO_2 from methane anyway. This feature of biomethane combined with the easy way to store, distribute and utilize biomethane as balancing power makes it an attractive component of future energy systems.

3.2.1.3 Three stages of sustainable biomass application

Three stages of sustainable biomass application are described, based on the elaborated knowledge and identified constraints. Stage 2 and 3 match with the blueprints of sustainable energy system structures in chapter 5.3.

Stage 1: low hanging fruits first – replacing carbon-intensive energy at low cost and with low conversion efficiency losses

In a first step, it is recommendable to use established technologies that show high efficiency and GHG reduction potentials and at the same time low production and GHG mitigation costs. This is the case for many direct combustion processes like large heating systems, co-firing of biomass in coal power plants and fermentation of residues to biogas (Table 3.2-1).

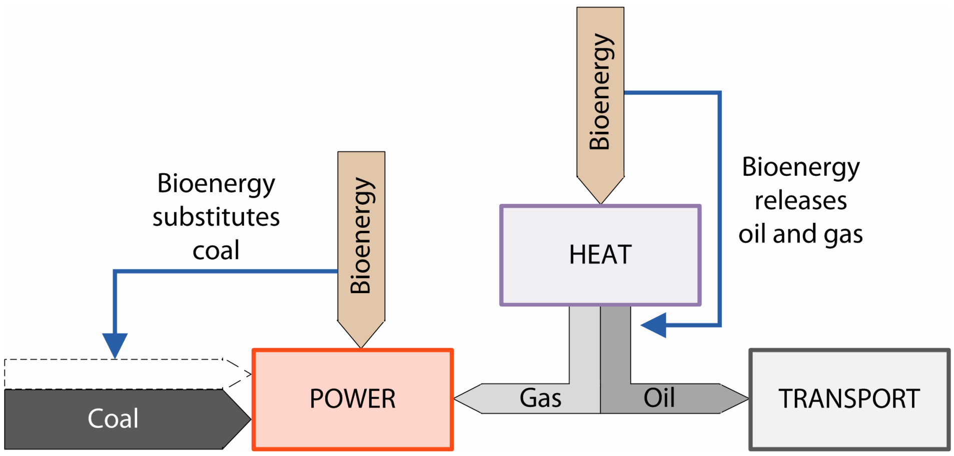

Figure 3.2-2: First stage of sustainable biomass application in industrialized countries and regions. Bioenergy is used in state-of-the-art technologies to replace fossil fuels efficiently and at low cost, i.e. mainly to replace coal in power generation and oil and gas in heat supply. Source: own compilation, based on (WBGU, 2009).

For example, woody biomass can replace 100% coal in co-firing and 100% crude oil in heating systems, but only about 45% in transport as seen with Fischer-Tropsch diesel (chapter 2.2.1). Natural gas can be used for low-carbon power generation and crude oil in transport (Figure 3.2-2).

Stage 2: strategic functions – tapping all / maximizing the benefits of bioenergy

Bioenergy will be largely used as balancing power and for special transport segments (Figure 3.2-3). As the five steps toward an efficient energy systems are taken (see chapter 5.2), less heat will be demanded due to better insulation and the use of CHP heat and more power will be required for heat pumps and electromobility. Most of the power demand will be covered by CO_2-free renewables like wind, solar, geothermal, ocean and hydro power. Biopower will fulfill a strategic function in balancing fluctuating renewable power generation and stabilizing power supply. Biopower will also be used in heat and transport via heat pumps and electromobility. Biomethane in decentral CHP and central combined cycle power plants is a very preferable option in this context. The available gas grid can be utilized and the already separated CO_2 can be sequestrated.

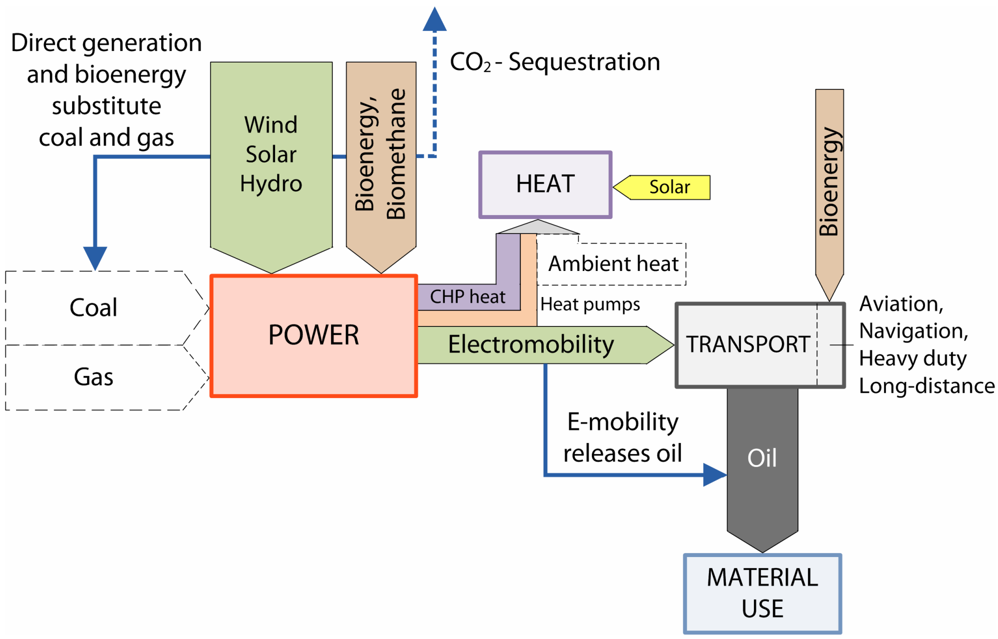

Figure 3.2-3: Second stage of sustainable biomass application in industrialized countries and regions. Bioenergy is used according to its strategic functions: as balancing power, e.g. as biomethane for CO_2-sequestration and as transport fuel with high energy density in aviation, navigation and heavy-duty transport. Fossil crude oil is release and used as material feedstock for carbon-based products. Source: own compilation, based on (WBGU, 2009).

Beside these two strategic functions of bioenergy, the third (high energy density) will be employed in future energy systems. Liquid and gaseous biofuels are used as fuel for long-distance transportation like aviation, navigation and heavy-duty tasks, i.e. in all fields where electromobility can hardly substitute fossil fuels. Fischer-Tropsch kerosene or jatropha for aviation are hereby promising options (Braun-Unkoff et al., 2009). Released fossil oil is used as raw material in chemical industry for plastics, pharmaceutical products and other carbon-based products.

Stage 3: carbon source for biomaterials – replacing fossil fuels in chemical industry

In the far future when fossil fuels are no longer available for carbon-based products, the most important function of biomass will be to provide the material carbon basis for chemical products like plastics, pharmaceutical products, lubricants, cosmetics, soaps, fertilizers, or textiles; i.e. to produce biomaterials in biorefineries.

The strategic energy function in power supply will be taken over by demand side management, new storage options like 'renewable power methane' (chapter 4), and a combined operation of renewable power generation (Mackensen et al., 2008). Electricity networks will be 'intelligized' and carry energy plus information (Smartgrids, 2008). Energy supply will be almost 100% CO_2-free and thus biomass for carbon sequestration is no longer needed. That point might be far into the 23rd century, but as energy can be derived from other sources, this function of biomass is probably the least replaceable once fossil fuels are depleted. Energy can be derived by other means, carbon not.

Woody biomass is another good example for material use. Already today, 47% of the annual global wood harvest is used as material. Wood as construction material outperforms steel and concrete on an environmental basis, since it is far less CO_2-intensive. After usage, biomaterials can be recycled or used as waste for energy.

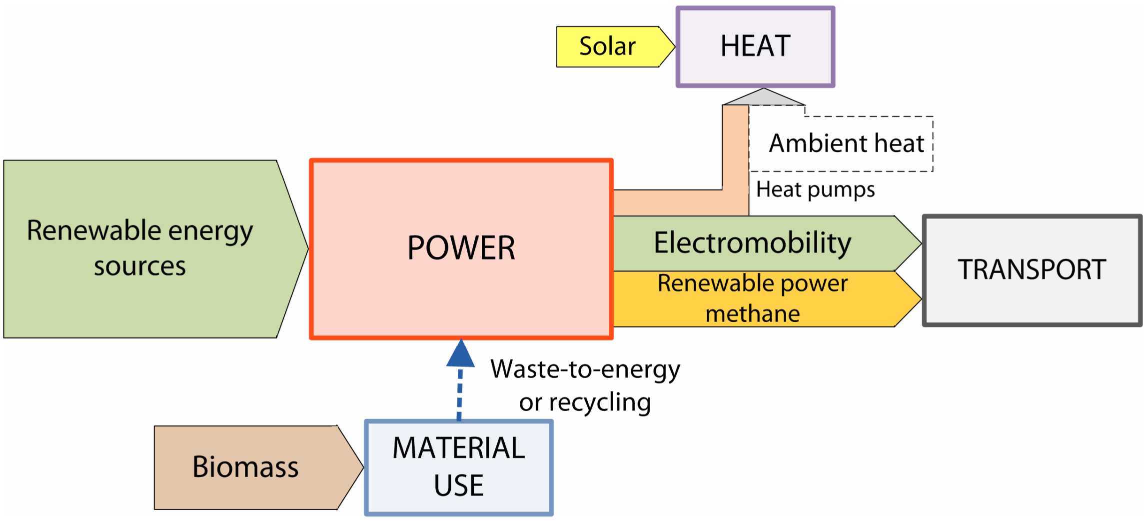

Figure 3.2-4: Third stage of sustainable biomass application in industrialized countries and regions. Biomass is solemnly used as material feedstock to replace fossil fuels. All energy demand will be covered by renewable energy sources. Source: own compilation.

3.2.2 *Overcoming traditional biomass in developing and emerging countries*

The principal uses of traditional biomass are heating and cooking in developing countries, causing severe problems. New technology has to be affordable and easily manageable in installation, maintenance and use to ensure its successful implementation.

Modern bioenergy can reduce deforestation and dependence on imports, improve energy supply and generate income in rural regions. It will remain an important energy source and form together with other renewables future sustainable energy systems in rural regions of developing and emerging countries.

Problems caused by traditional biomass use

Traditional biomass use is a burden in many ways. Fuelwood collection leads to deforestation and takes up to three hours per day and household - time that could be spent in other economic or educational activities (ter Heegde, 2005).

Fuelwood is then combusted inefficiently causing indoor air pollution with high share of particles and toxic carbon monoxide. Chronic exposure is affecting health and causing lung cancer. As most of the cooking is done by women, the CO daily exposure time for women and children is three times higher than for men, (Zhang, 1999b). An estimated 1.3 million deaths are caused by this pollution burden (WHO, 2006; IEA, 2007b).

Energy efficiency revolution in traditional biomass use – heat and light

Exchanging traditional biomass fired-stoves with improved cooking stoves can double or even triple fuel efficiency and reduce GHG emissions drastically (chapter 2.2.3 and 2.4.5). The costs for improved cooking stoves are rather low and affordable (chapter 2.3.2). Switching to gaseous or liquid biofuels for cooking and lighting (plant oil, biogas) results in GHG and CO levels that are below the heath-based standards and WHO guidelines. Improved air quality also lowers the expenses for medication, workload and increases life expectation. Locally produced biofuels for heating and cooking can stabilize supply security and reduce deforestation (Zhang, 1999b).

In Uganda, the share of improved cooking stoves was raised within 6 years from 2.7% up to 8% of Ugandan households (GTZ-EAP, 2007). About 200,000 small biogas digesters are installed in Nepal and Vietnam and more than 4 million in India, of which about 70% are still in use (ter Heegde, 2005). The combination of agriculture and animal husbandry is essential for a successful integration of biogas digesters. Crop farmers usually do not have dung from animals and nomads do not collect dung. Crop farming and animal husbandry are separate business in large parts of Africa. Combined farming is found more often in Asia, where biogas digesters are an well-accepted option for rural energy supply (SNV, 2008).

Biomass gasifiers are used for process heat and substitute fossil gas and oil. Gasifiers convert residues like coconut shells, coffee and rise husk or woody biomass. Typical applications are (crop) drying processes in small industries but also gasifiers for cooking on a household level (Dasappa, 2009). In the future, biomethane from gasification and fermentation can be used via gas grids as low-emission heat supply technology. In India, about 1 million biomass gasifiers for process heat are installed and about 85% of the beneficiaries are local producers who possess less than two hectares of land (TERI, 2008; REN21, 2008b).

Many people in developing countries use kerosene lamps and stoves. Locally produced plant oil from e.g. jatropha can substitute expensive and emission-intensive kerosene. Besides bioenergy, renewable power from e.g. solar home systems can be used for lighting such as LED-lamps. For cooking however, solar power (PV) systems have too small capacities and only few indoor solarthermal systems are practical and accepted by users (Sterner, 2001).

Rural electricity and motive power supply with bioenergy and other renewables

Biofuels can power gensets and motors. Diesel gensets are very common in many rural regions. These motors can be modified for the use of locally grown and pressed plant oil from jatropha or other oil fruits. On one hand, biofuel gensets generate electricity for local grids to supply schools, hospitals, or entire villages. Batteries can be charged for decentral household use and operate mobile phones, radios and LED lamps. On the other hand, biofuels drive motors for motive power (mechanical power) that is used for grinding cereals or pumping water; both very common energy needs in rural areas (Sterner, 2001). Besides biofuel gensets, biomass gasifiers are suitable for ecologic electricity generation (TERI, 2008).

Similar to industrial nations, biopower will be used along with other renewables. Electricity grids can be powered by hybrid systems of photovoltaic, small wind turbines, small hydropower and biopower. Motive power for water pumping and irrigation purposes can be supplied by mechanical wind pumps as well. According to the experience of the author, new technologies like photovoltaic take a long way to find acceptance as maintenance and operation are not an easy issue for local people. Technologies using the best known fuel, which is biomass in most cases, are often more successful. The (biofuel) genset technology is more robust, easier to handle and easier to maintain than solar home systems (Sterner, 2001).

Using residues is very beneficial in terms of land-use and GHG emissions. In rural regions, many residues are generated by farming and agroindustry. These can be used energetically. Fisheries, textile industries, sugar cane farms or coffee and tea plantations have valuable residues like husk or bagasse, which is a valuable feedstock for biogas CHP and direct combustion CHP. Integrated into the production process, heat of the CHP can be utilized as process heat for e.g. drying purposes.

Biofuels and electromobility for transport in rural regions

First generation biofuels are state-of-the-art technology in developing countries. By growing oil plants like jatropha, oilpalm or pongamia on marginal land that is not suited for food production, competition with food can be avoided. Locally produced biofuels are used in heavy-duty transport, minibuses, cars and bikes. As electrification is spreading increasingly, electromobility is as well an option for rural regions. First steps in this direction are electrical bicycles. About 30 million e-bicycles are in operation in China (Schmid, 14.11.2008). They can improve mobility in regions without a grid of petrol stations. Charged locally by solar home systems, biomass, wind or hydropower, e-bicycles can help people to cover long distances. Furthermore, biopower can support long distance transport via electrical railways.

Depending on the share of renewables in power generation, bioenergy is more beneficial in transport. Countries with a high share of fossil power like China can save maximum GHG emissions in power generation by substituting coal. Countries like Uganda and Brazil with a high share of hydropower can substitute fossil fuels in transport by biofuels and gain maximum GHG reductions. The individual decision is determined by prices, which will likely include costs for CO_2 emissions in the future. In this way, bioenergy can contribute to overcome energy poverty, reduce GHG emissions and generate income and sustainable development in rural regions, if land-use competition is avoided, food security ensured and basic standards of the International Labour Organization are fulfilled (e.g. security, health care, fair salaries and working times, neither child labor nor slavery) (ILO, 1998; WBGU, 2009).

3.3 Role of bioenergy in climate protection

3.3.1 Energy crops, residues and traditional biomass

Energy crops

The net effect of energy crops on climate change depend mostly on two parameters: the land-use change done for energy crops and the fossil fuel replaced by energy crops. The effects of land-use change on the climate protection potential are severe. If primary forests are cleared, energy crops cause more GHG emissions than fossil fuels for the same energy service. Planted on marginal and degraded land, the same crops can avoid GHG emissions to a great extent. Besides these emissions from direct land-use change, indirect land-use change also causes considerable amounts of additional emissions. These can be avoided by reducing pressure on land-use. A long-term solution for emissions related to land-use changes would be a global ‘cap and trade’ emission trading system (Fritsche, 30.03.2009). In addition, perennials show better GHG balances than annual monocultures (chapter 2.4 and Table 3.1-1).

The second parameter, the substitute fossil fuel, is decisive for the GHG balance of energy crops as well. If bioenergy is used in CHP to replace coal, about two times more GHG emissions can be avoided than if fossil oil is replaced in transport by biofuels. This is also valid for residues (chapter 2.4).

Residues

The net effect of residues on climate is positive, since no emissions from land-use change occur and land-use competition is avoided. Cascade use of agricultural and forestry products is recommendable.

Traditional biomass

Traditional biomass use is causing relevant amounts of GHG emissions (chapter 2.4.5 and 3.2.2). So far, these emissions are not accounted in the Kyoto Protocol (UNFCCC, 1998). By modernizing traditional biomass use, global GHG emissions from biomass are reduced significantly and in a cost effective way, as 86% of total bioenergy is traditional biomass. About 20-30 EJ of bioenergy can be saved annually by replacing traditional biomass-fired stoves with improved cooking stoves or biogas digesters.

3.3.2 Comparing bioenergy with other forms of land-use and renewables

GHG emissions potentials of energy crops and mitigation costs of bioenergy are compared with other land-use options listed in chapter 1.3.3.1.

GHG reduction potentials

Afforestation can sequestrate about 1-35 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1}, depending on tree species and land type. The upper values are obtained in tropical vegetations. Excluding negative GHG balance values, the examined bioenergy pathways are in the range of 0-31 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1} for mobility, 4-6 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1} for heat supply, and 6-45 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1} for CHP settings. Surprisingly, bioenergy on marginal and degraded land shows very high GHG reduction potentials per hectare. For example, palm oil results in a GHG emission reduction of 31 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1} when applied in mobility and in reductions of 45 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1} applied in a medium CHP. Results on temperate crops for first and second generation biofuels in mobility indicate only an GHG reduction of 0-3 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1}, while energy grass for electromobility gain higher values at 7-11 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1}. Similarly, values for temperate crops in CHP concepts (6-18 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1}) are higher than in heat applications (4-9 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1}).

Solar energy technologies like photovoltaic can convert about 15% of solar irradiation into electrical energy. Crops using photosynthesis are less efficient and use maximum 2% of solar irradiation due to a more limited solar spectrum absorption (Kaltschmitt et al., 2003). Accordingly, values for area-related GHG reductions are greater than for all plant cultivations. Depending on the latitude, an average solar irradiation of 150-250 W m^{-2} can be used and generate annually about 1,000-2,000 kWh per kW_p installed (Twidell et al., 2008). A capacity of one kW_p requires 8 m^2. In theory, 1,250 kW_p fit on one hectare and deliver 1.25-2.5 GWh per year and avoid about 1,075-2,150 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1}, when the same reference system as used for bioenergy in this study (935 g kWh_{el}^{-1}, see Table 2.4-1) and an average value (75 g kWh_{el}^{-1}) for GHG emissions of PV systems are applied. On good wind sites with average wind speed of 6-8 m s^{-1}, GHG reductions per area are even higher for wind energy and can be as high as 45,500 t $CO_{2\text{-eq.}}$ ha^{-1} yr^{-1}, calculating an average area requirement of 0.1 ha of a 2.5 MW wind turbine operating with 2,000 full-load hours per year and GHG emissions of 25 g kWh_{el}^{-1} (Wagner et al., 2008; Hahn, 17.05.2009). Moreover, wind and solar energy harvesting avoids land-use competition, as settlement areas, deserts (solar) and sea area (offshore wind) can be used.

All values for afforestation and energy crops depend strongly on assumptions like land fertility and fossil reference systems, which are based on the German energy system 2005. Results show that bioenergy is approximately as effective in GHG reduction as afforestation. Compared to other renewable energy sources like wind or solar energy, GHG reduction potentials per hectare are rather low.

GHG mitigation costs

GHG mitigation costs for afforestation are estimated at 0.5-7 US$ t $CO_{2\text{-eq.}}^{-1}$ in developing countries and at 1.4-22 US$ t $CO_{2\text{-eq.}}^{-1}$ in industrialized countries. Avoided deforestation is even cheaper and estimated at 1-2 US$ t $CO_{2\text{-eq.}}^{-1}$ and black carbon sequestration rather high with 40 US$ t $CO_{2\text{-eq.}}^{-1}$ (chapter 1.3.3.1).

The examined bioenergy pathways vary strongly between -195 to 1,266 EUR t $CO_{2\text{-eq.}}^{-1}$, whereby about 2/3 show GHG mitigation costs above 100 EUR t $CO_{2\text{-eq.}}^{-1}$. Only jatropha biodiesel in transport and wood chips in heating systems show negative mitigation costs. Among the remaining pathways, CHP concepts using woody biomass for direct combustion or manure for co-fermentation have the lowest GHG mitigation costs. These values vary strongly with the assumed fossil fuel prices taken from 2005 on a rather low level. In the future, the GHG mitigation costs of bioenergy will be lower. Replacing traditional biomass-fired stoves with improved stoves and biogas digesters shows very low mitigation costs in the range of 2 to 20 EUR t $CO_{2\text{-eq.}}^{-1}$.

Electricity from photovoltaic can be produced at 25-42 €-ct kWh_{el}^{-1}, depending on the site (assumption based on Staffhorst, 2006). Compared to the production costs of the fossil reference system of 6.16 €-ct kWh_{el}^{-1} (see Table 2.4-1), GHG mitigation costs of solar PV energy vary between 220 and 420 EUR t $CO_{2\text{-eq.}}^{-1}$. Wind energy has average production costs of 3.5 to 8 €-ct kWh_{el}^{-1} in Europe and is already competitive with fossil power generation at good wind sites (Krohn, 2009). GHG mitigation 'costs' of wind energy are much lower than GHG mitigation costs of solar PV energy and range between minus 30 and plus 20 EUR t $CO_{2\text{-eq.}}^{-1}$. Large hydro power in Germany is generated at 2.5-6.5 €-ct kWh_{el}^{-1} and at quite low emissions of 25 g kWh_{el}^{-1} (Fichtner, 2003; Wagner et al., 2008). Hydro power is often more economic than conventional power generation and obtains GHG mitigation 'costs' of minus 40 to plus 3.7 EUR t $CO_{2\text{-eq.}}^{-1}$.

The fundamental difference between costs of bioenergy and solar, wind and hydro power is the feedstock costs. Steep declining production costs and learning curves are observed for wind and solar energy since the only matter of expense are technology costs. Feedstock costs only appear in bioenergy and are the most sensitive parameter in bioenergy production and GHG mitigation costs, which vary strongly depend on the chosen fossil reference system (chapter 2.4.2).

Comparing all examined GHG mitigation costs, wind energy, hydro power, jatropha biodiesel and wood chips for large heating systems are the most favorable, since in many cases no GHG mitigation expenses occur and energy costs can be even saved. The second most favorable option is avoiding deforestation, afforestation, future black carbon sequestration, fermenting manure to biogas and combusting, i.e. co-firing woody biomass in steam turbine CHP and coal power plants. All other bioenergy and solar options still show very high GHG mitigation costs. Some are expected to decrease with 'economy of scale' for cost-intensive technologies like photovoltaics, electromobility, fuel cells and gasification technologies.

3.3.3 *Maximum greenhouse gas reduction potential of bioenergy*

In the following, the bioenergy potential of chapter 1.3.3.2 is linked with a reasonable bandwidth of GHG reduction potentials of the examined bioenergy pathways from chapter 2.4 to estimate the GHG reduction potential of global bioenergy use.

Linking the sustainable bioenergy potential with GHG balances

The technical bioenergy potential is estimated in a range of 65 to 300 EJ yr^{-1} of which half of the potential (30-150 EJ yr^{-1}) is assumed to be mobilized as economic potential by 2050. GHG reduction potentials vary between minus 257 and plus 190 t $CO_{2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$, whereby most values are in the range of 40 to 110 t $CO_{2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$. It is assumed, that predominantly residues and energy crops without negative emissions from land-use change are used in the most efficient pathways like in CHP applications substituting primarily coal so that high average GHG reduction potentials of 80 to 100 t $CO_{2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$ are achieved.

In this way, GHG emissions of about 2.4 to 15 Gt $CO_{2\text{-eq.}}$ can be avoided by modern bioenergy per year. Avoided emissions from traditional biomass can be added to this value. If in theory all 43 EJ traditional biomass with GHG emissions of about 0.3-1 Gt $CO_{2\text{-eq.}}$ are replaced by modern bioenergy, GHG emissions can be reduced by approximately 50% with improved cooking stoves and about 95% by small biogas digesters (Bhattacharya et al., 2002).

This results in GHG reduction potentials of 15 to 50 $t_{CO2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$ (40 to 130 $t_{CO2\text{-eq.}}$ $TJ_{th\ heat}^{-1}$) for improved cooking stoves and 40 to 75 $t_{CO2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$ (75 to 145 $t_{CO2\text{-eq.}}$ $TJ_{th\ heat}^{-1}$) for biogas digesters, replacing traditional biomass-fired stoves.

An assumed 50% replacement of traditional biomass (conversion efficiency 5-15%) by improved cooking stoves (GHG reduction potential 15-50 $t_{CO2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$) and 50% by low emission biogas plants (GHG reduction potential 40 to 75 $t_{CO2\text{-eq.}}$ $TJ_{raw\ biomass}^{-1}$) is corresponding to an GHG reduction of about 0.1-0.9 Gt $CO_{2\text{-eq.}}$ (Smith, 2000).

The total GHG reduction potential of bioenergy can therefore be estimated to about 2.5 to 16 Gt $CO_{2\text{-eq.}}$ per year.

In relation to 2004 GHG emissions of 49 Gt $CO_{2\text{-eq.}}$ (chapter 1.1.1), this results in a overall reduction of about 5-33% of today's emissions. In the future, as GHG emissions are expected to rise, this percentage will be proportionally lower.

In the discussion of climate mitigation potentials of biomass, energy crops are always linked to both areas: land-use emissions and fossil energy emissions. What is very crucial in this discussion is the combination of these two effects and the time period considered. Energy crop plantations need a certain time until the additional emissions emitted by land-use change are 'paid-back'. It is necessary that this time period does not exceed several decades or centuries as climate mitigation is rather urgent.

Effect of CO_2 sequestration potential by modern bioenergy on atmospheric CO_2 concentration

If all bioenergy is used as biomethane, about 40% of biomass carbon can be sequestrated in the process as CO_2. In this way, a carbon sink is generated and CO_2 withdrawn from the atmosphere. The share of 40% can still be raised by generating hydrogen from biomass. Biomass integrated gasification combined cycle (IGCC) can in theory sequestrate up to 55% of biomass carbon (Rhodes et al., 2005). A sequestration rate of 50% is chosen as a realistic assumption. Thus, 1.2 to 7.5 Gt $CO_{2\text{-eq.}}$ can be sequestrated by bioenergy annually in theory.

Using these maximum sequestration technologies, the increase of CO_2 concentration could be slowed down or even reverse CO_2 emissions as fossil fuels are depleted.

An CO_2 emission of concentration of 7.8 Gt $CO_{2\text{-eq.}}$ corresponds to 1 ppm in the atmosphere. Nevertheless, withdrawing 7.8 Gt $CO_{2\text{-eq.}}$ from the atmosphere does not result in a lowering of 1 ppm CO_2, since about 33% of CO_2 emissions are absorbed by the ocean and 12% by the terrestrial biosphere. Both carbon sink processes are accelerated by increasing CO_2 concentrations but will come into saturation at some time. The oceans stop sequestrating CO_2 if the partial pressures between ocean and atmosphere are zero (WBGU, 2006). CO_2 sequestration by the terrestrial biosphere is forwarded by a intensified photosynthesis due to higher CO_2 concentrations (fertilizer) (House et al., 2002). Assuming that both processes come not into saturation in this century, two times 7.8 equal 15.6 Gt $CO_{2\text{-eq.}}$ have to be withdrawn from the atmosphere to lower the CO_2 concentration by 1 ppm.

Consequently, 1.2 to 7.5 Gt $CO_{2\text{-eq.}}$ sequestrated annually by bioenergy can lower the CO_2 concentration by 0.1 to 0.5 ppm. Today's annual increase of CO_2 concentration is about 2 ppm, which means that modern bioenergy can 'cap' roughly one tenth of global CO_2 concentration growth (GCP, 2008; IPCC, 2007d).

4. *Renewable Power Methane – solution for renewable power integration and energy storage*

4.1 *Challenges in renewable energy systems - balancing power, energy storage and special transport segments*

Challenge balancing power – bioenergy is not sufficient

The main challenge of renewable energy supply is to match the available energy with the energy demand in time, place and quantity. High shares of fluctuating renewable power from wind and solar energy will shape future energy supply. Storage of renewables is a key element in sustainable energy structures. About 20% of total power generation will be required as balancing power to ensure technical supply security and stability of grid operation (Czisch, 2005). So far, mostly fossil power plants and hydro power serve this function. Nuclear power plants are neither designed for fast ramp up and downs nor economic in intermittent operation; plus technical and security challenges remain unsolved. Large base load power plants are incompatible with high shares of renewable energy to a large extent (SRU, 2009b). As fossil fuels are finite, today's power plant structure is incompatible with future power supply dominated by renewables and the potential of hydro power is limited, other options for balancing power are necessary.

Bioenergy is storable and can thus provide balancing power, which is one of its strategic functions (chapter 3.2.1.2). Yet, bioenergy fulfills other strategic functions on one side and on the other side, its potential is limited, too. Using the maximum estimated economic bioenergy potential of 150 EJ yr^{-1} for 2050 in power generation with a conversion efficiency of 25% (average value of examined 39 CHP pathways in chapter 2.2), 37 EJ yr^{-1} or about 10,000 TWh yr^{-1} balancing power can be generated from biomass in theory, neglecting the fact that there will be demand for biofuels and biomaterials.

Global electricity generation has grown on average by 3.5% in the last decade and is currently about 20,000 TWh yr^{-1} (BP, 2009). Assuming continuous growth rates of 2.5% until 2050, the electricity demand rises up to 55,000 TWh. However, by assuming all efficiency improvements proposed in chapter 5, the global annual electricity demand could be limited to 18,000 TWh. Additionally, surplus power will be required for powering electromobility and heat pumps. The electrification of the heating and the transport sector will require another 35,000 TWh yr^{-1} in addition to conventional power demand, according to the scenario in chapter 5.3.3. Thus, the total electricity demand results in a bandwidth of 53,000 - 90,000 TWh with and without efficiency measures. Bioenergy will therefore not be able to provide the necessary balancing power for grid stability in energy systems with major shares of wind and solar energy; i.e. an energy system that shifts towards renewable power as main energy source.

Challenge energy storage – current storage systems are limited

In addition to what has been described so far, large amounts of surplus power will be available as wind and solar power generation will exceed often the actual power demand. Energy has to be ‘shifted’ from periods of high renewable generation and low power demand to times of low renewable generation and high power demand (Mackensen et al., 2008). Although electrical networks will be extended and grid operation will be optimized by enhanced energy and load management, new energy storage capacities will be required as balancing and reserve / backup power (DENA, 2005; von Bremen, 2009). Today, only pumped hydro and compressed air storage systems are capable for storing large amounts of electricity. Both storage systems are limited geographically and have a limited range, i.e. are operated as short-term storage in daily periods (Leonhard et al., 2008). In Germany for example, the installed capacity of pumped hydro lasts for about 6 hours. Batteries are used for uninterruptible power supply, but only few electrochemical storage devices are in general suitable for large-scale power storage and again a short-term storage option (Oertel, 2008). Sodium-sulphur (NaS) accumulators are applied in medium scale (34 MW) in Japan but face high cost (NGK, 2008). Electromobility as storage option is as well limited and only suitable as short-term option. In theory, a full electrical fleet in Germany (45 million cars with 10 kWh_{el} storage capacity) could supply 70 GW for about 6 hours.

The necessity to bridge two weeks of wind calms can only be met by long-term storage facilities. So far, the only option available for this purpose was hydrogen. However, hydrogen as storage option is limited due to high costs, security challenges, missing infrastructure and short lifetimes of fuel cells. The gas network is the largest existing storage facility with proven and available technology (Cerbe, 2008). It has a capacity of hundreds of TWh and is therefore able to bridge the gap of weather periods with zero or low renewable energy availability; enabling a seasonal storage of renewable energy.

Covering energy segments that require fuels with high-energy density

The transport sector depends heavily on crude oil (Boerrigter et al., 2004). Electromobility can replace much of it, but some segments like aviation, navigation, and heavy-duty transport require fuels with high energy density. Liquid biofuels can serve for this function and replace fossil fuels, but its potential is limited. Converting the maximum economic bioenergy potential of 150 EJ yr^{-1} for 2050 into biofuels with a conversion efficiency of 45% (average value of examined 25 CHP pathways in chapter 2.2) results in 67 EJ yr^{-1} energy from biofuels. Currently, the total transport energy demand is about 160 EJ yr^{-1} and expected to rise (chapter 5). Therefore, bioenergy is and will not be sufficient to replace all fossil fuels for global transport energy demand.

In the long term, the most important function of biomass is to provide carbon-feedstock for the chemical industry to produce biomaterials (chapter 3.2.1). The need for a high-energy density fuel, which shows the same benefits as fossil or biofuels but not their drawbacks, is obvious.

4.2 *Basic concept of Renewable Power Methane (RPM)*

4.2.1 *Fundamental description*

The three problems - grid stability, power storage and carbon-free energy supply of special transport segments - can be met by renewable methane from wind, solar, ocean and hydropower. The power network and natural gas network are linked mutually.

(Surplus) renewable power, which cannot be fed into the grid due to stability or lacking demand, can be stored in the natural gas grid. Renewable methane can be reconverted into power and stabilize grid operation by providing ancillary services. In this way, renewable power generation can be shifted both temporarily and spatially. Renewable power can be made available in the heat and transport sector in the form of renewable methane and provide energy for special transport segments like aviation with a high-density renewable fuel. Other fuels like dimethylether or renewable kerosene can be also generated from H_2 and CO_2 or renewable power methane. In a further step, even carbon-based raw materials like methanol, ethanol, ethylene can be produced for the primary industry from wind, water and CO_2 via this technology.

Storing renewable power as methane by linking electricity and gas networks

The basic concept of ‚renewable power methane' (RPM) (or also 'renewable methane', 'renewable SNG', 'renewable natural gas', 'real natural gas' (RNG)) is based on the mutual linking of the power grid with the natural gas grid.

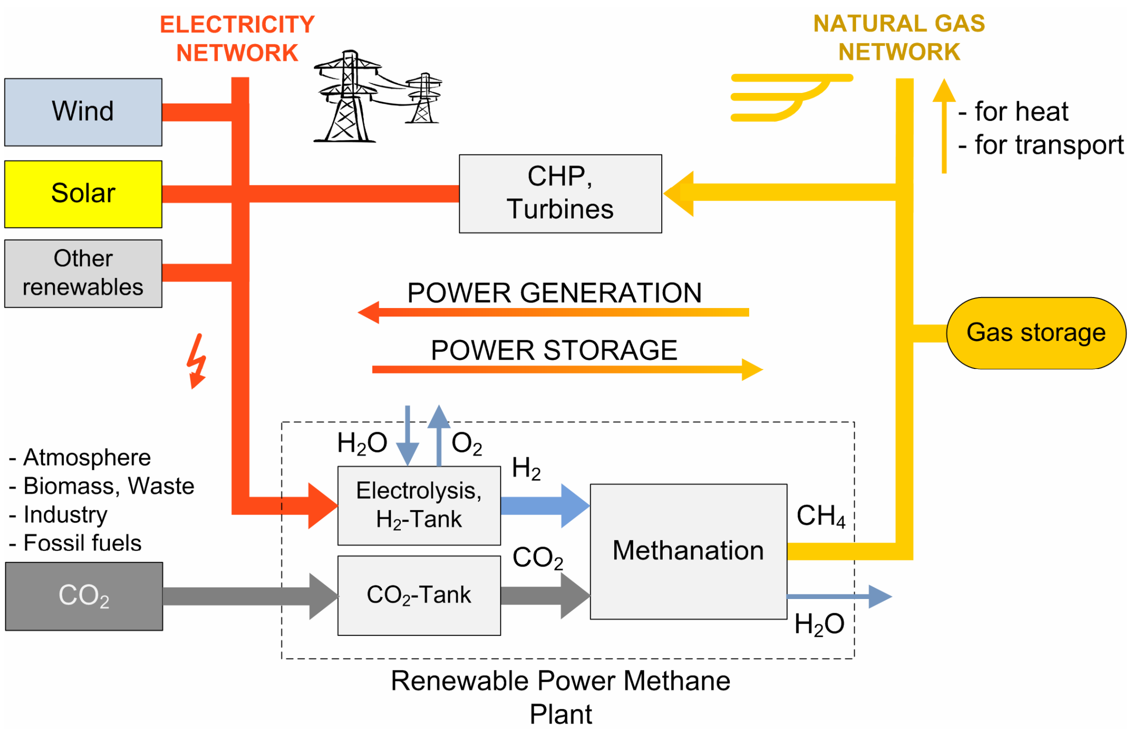

Figure 4.2-1: Basic concept of a renewable power to methane plant (Wind/Solar-to-SNG) with concentrated CO_2 from a tank, integrated into power and gas grid. Optionally, surplus heat from methanation can be used in an ORC-CHP-plant to generate power. Source: own compilation.

Generating power from gas is state-of-the-art technology. The new innovative concept converts renewable power to gas, i.e. a natural gas substitute. Renewable power (e.g. surplus wind or solar power, a fixed share of renewable power generation) is converted via electrolysis into hydrogen. H_2 can be also generated directly from solar thermal energy or from direct current solar power, saving the PV inverter and electrolysis rectifier. Hydrogen is combined with CO_2 and converted into methane in a thermochemical synthesis (methanation). Possible CO_2 sources are e.g. fossil power generation, CCS, biogas plants, gasification, upgraded and purified CO_2 from industrial processes like lime or cement production, or CO_2 recovered from the air. The renewable natural gas substitute (SNG) can be stored, distributed and reconverted on demand in balance power e.g. in gas turbines or combined cycle power plants (Figure 4.2-1).

In this way, renewable electrical energy is stored as chemical energy in existing storage capacities, which is an advantage vs. hydrogen. Storage and power conversion technologies for natural gas are state-of-the-art and commercial unlike hydrogen technologies. A further advantage for storage is the higher energy density of methane. Energy transfer capacities of gas pipelines are an order of magnitude larger than electrical power lines, which is another advantage of using the existing natural gas network for storing renewable power.

Another possibility of providing positive balancing power and ancillary services is to include a hydrogen storage tank and to control electrolysis power according to grid operation demands, e.g. reduce electrolysis power if grid load increases or power generation capacities drop out.

In this way, renewable power generation and power demand can be adjusted to each other in space and time and damping / curtailing of renewable power can be avoided. Renewable power generation plus the RPM concept can provide base load, cover the power demand at any time and substitute conventional power generation as a whole.

Use of 'waste' heat for heat and power

To any concept, an ORC-plant for combined heat and power generation can be connected that uses the waste heat from methanation, which is an exothermic reaction at 250-450°C. Waste heat can be also integrated into industrial processes or fed into district heating networks, like waste heat from power generation of RPM.

Flexibility of use, energy vector and independent methane production

The RPM concept enables to use renewable power like wind or solar energy in heat supply and transport and substitute high-energy density fuels. It is therefore an energy vector for renewable power (wind, solar, hydro) into the heat and transport sector.

RPM can be compressed or liquefied and used for long distance traffic and in special transport segments like aviation, navigation, or heavy-duty tasks. The concept is fully compatible with the transition of the road transport sector towards new power trains like plug-in hybrid electric vehicles with or without range extenders. Electricity can be used directly in battery electric vehicles, hydrogen in fuel cell electric vehicles and RPM in compressed natural gas vehicles. RPM can be used as well for process heat applications and even as feedstock for the chemical industry to produce renewable materials and substitute limited fossil hydrocarbons in the material cycle.

Further, this concept can improve independence in energy supply and reduce geopolitical tensions. As renewable power methane is generated from wind, solar, or hydro power plus water plus CO_2 from air, a substitute for natural gas can be generated in almost any country and used for transport, heat and balancing power. Carbon-neutral RPM corresponds thus more to the term 'natural gas' than fossil 'natural gas'.

The generated oxygen can be integrated into the concept or used as technical oxygen in industry or for fuel production. It is of special interest in the oxyfuel process as combustion agent for RPM: CO_2 can be separated more easily using O_2 in combustion of RPM in gas power plants and recycled for use in RPM generation.

4.2.2 Conversion efficiency, conversion technology and costs

The renewable power to methane conversion efficiency is the product of the electrolysis efficiency and the methanation efficiency.

Electrolysis for hydrogen production

The conversion efficiency of electricity to hydrogen is in the range of 62-80% (Cerbe, 2008; Miltner et al., 2008). Water is decomposed to hydrogen and oxygen in electrolysis. Typical standard technology is alkaline electrolysis, using a caustic potassium hydroxide (KOH) solution at process temperatures of 70-140°C. Such electrolyzers work at pressures of 1-200 bar and are available at capacities > 0.1 MW_{el}. Two other technology lines are currently developed: Polymer Electrolyte Membrane (PEM) electrolyzers do not require a liquid electrolyte and only use H_2O, which enables a simple design. However, the major drawback are small capacities (< 50 kW) and limited lifetime of the membranes. Similar to SOFC technology for power generation of biomethane or biogas (chapter 2), high temperature electrolysis (e.g. with solid oxide electrolyzer cells) is available for hydrogen production, working in a temperature range of 700-1,000°C (Ullmann, 2003).

Methanation

Methanation is standard technology for coal gasification and developed for biomass gasification. The efficiency of methanizing syngas (main components H_2, CO, CO_2) ranges from approximately 75-85% (Jurascik et al., 2008; Müller-Langer, 2008). Methanation synthesis is a catalytic exothermal process at temperatures of 180-350 °C and pressure levels from 1-100 bars (Schmidt, 1970). However, the operational temperature range has to be adopted individually according to the synthesis gas

(Mozaffarian et al., 2003). Several demonstration projects run in Europe on biomass gasification to SNG (Beil, 2008). For example, the Austrian Güssing project runs a circulating fluidized bed gasifier with a downstream methanation unit of 1 MW_{SNG} thermal capacity (Hofbauer, 2009; Seiffert et al., 2008). CO_2 methanation (Equation 4.2-1) is a combination of a reversed endothermal water-gas-shift-reaction (Equation 4.2-2) and an exothermal CO methanation (Equation 4.2-3). This reaction is called the 'Sabatier process' and was discovered in 1913, but never applied in energy systems.

$4\ H_2 + CO_2 \leftrightarrow CH_4 + 2\ H_2O$	$\Delta H_R = -164.9\ kJ\ mol^{-1}$	Equation 4.2-1
$H_2 + CO_2 \leftrightarrow CO + H_2O$	$\Delta H_R = 41.5\ kJ\ mol^{-1}$	Equation 4.2-2
$3\ H_2 + CO \leftrightarrow CH_4 + 2\ H_2O$	$\Delta H_R = -206.4\ kJ\ mol^{-1}$	Equation 4.2-3

A pure CO_2 methanation is not yet state-of-the-art and currently under research. First laboratory tests show CO_2 methanation rates of up to 95% at a pressure of 6-7 bars and 280°C (Specht, 02.04.2009). If required, $C_{2\text{-}4}$ hydrocarbons like propane and air can be added to RPM after methanation to fulfill the standards for a natural gas substitute. Also other fuels (DME, FT-Diesel, renewable kerosene, etc.) that are attractive for transport or basic raw materials (ethanol, methanol) can be derived from H_2 and CO_2.

CO_2 recovery from the air and flue gas

It is possible to recover CO_2 from the air (chapter 4.3.1). The energy effort to extract 1 kg CO_2 varies by process and amounts to 8.2 MJ_{el} in the ZSW process. The energy demand for CO_2 extraction from flue gas (biomass or fossil fuels) are far smaller, as the concentration is much higher (about 10%-vol) and not included in the calculation of the energy storage efficiency.

Efficiency of renewable power to methane use

Combining the efficiencies of electrolysis and methanation results in RPM generation efficiency in the range of 46-75%, on average 63%. The RPM to power efficiency is equal to standard gas power generating technologies like gas turbines and CHPs with an efficiency of up to 60% in combined cycle power plants. The power storage efficiency is thus in a range of 28-45%, without accounting surplus heat from CHPs or energy losses of gas feed-in, transmission and withdrawal. The overall energetic efficiency can be improved by using surplus heat for power generation in an ORC plant or CHP heat for district heating and combined small CHP and heating systems in households respectively. CHP efficiency of this concept is in the range of 50-60%. Figure 4.2-2 illustrates the conversion efficiency of the RPM concept with wind power in a sankey diagram.

Alternatively to pure RPM production, pure hydrogen can also be used directly and fed into the gas network to a certain extent or be mixed to RPM at a share of e.g. 5 vol%. The overall efficiency increases by ideally 3-9%, average 6%, as methanation is avoided.

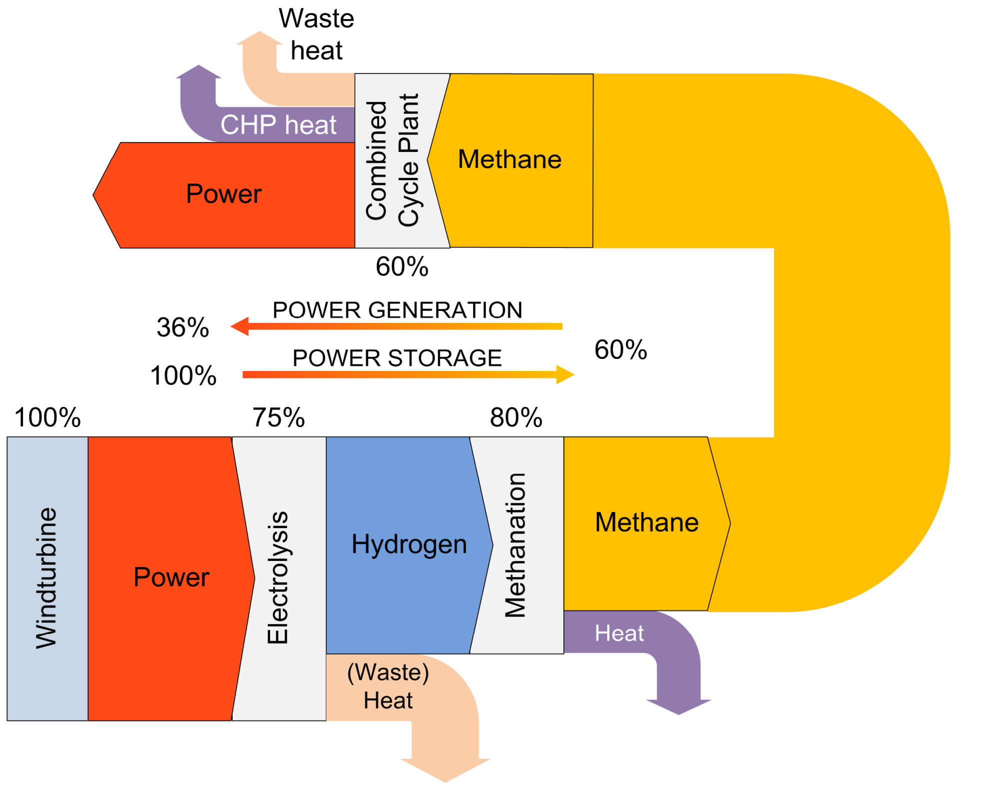

Figure 4.2-2: Sankey diagram of the renewable power methane concept for wind power with conversion efficiencies of 60% for power storage and 60% for power generation. Overall methane production efficiency: 46-75% - about 50-70&. Overall power storage efficiency: 28-45 – about 30-40%; overall CHP efficiency: about 50-60%; versus 0% efficiency of power curtailing. Source: own compilation.

Using atmospheric CO_2 reduces the renewable-power-to-methane efficiency by approximately 15% down to 48%. Generating 10 MJ_{th} (0.28 m^3) of RPM requires 16 MJ_{el} for electrolysis including thermal 'energy losses' of the methanation (mean efficiency 63%) and about 4.8 MJ_{el} for CO_2 recovery to extract 0.29 m^3 (0.58 kg) of CO_2. Reconverted into power, the overall power storage efficiency is then about 30%. The energy effort for CO_2 compression is not included in this calculation but is expected to be not very high, as the methanation unit requires maximum pressures of 10 bars.

Concluding, depending on the energy usage of RPM (power storage, CHP, transport), about 30-60% of renewable power can be used. On one hand, this imposes some energy losses; on the other hand, it is more useful to use some part of surplus power than to curtail all of it and use 0%, i.e. accept 0% efficiency of renewable power. The necessity for long-term energy storage and carbon-neutral energy carriers with high energy density for transport is there and has to be met. In this context, RPM is an efficient concept to serve this purpose and fill existing gaps in the transformation towards renewables-based energy systems.

Efficiencies of an integrated RPM plant with a biogas plant for biomethane

The typical biogas pathway 'Maize-silage-Biomethane-mediumCHP-2005' from chapter 2 is used as an example. This plant produces a biogas flow rate of 470 $m^3\ h^{-1}$ of which 220 $m^3\ h^{-1}$ (2.2 MW_{th}) biomethane can be generated from a raw biomass input of

3.2 $MW_{dry\ matter}$. The conventional medium CHP converts biomethane to electricity with an electrical capacity of 0.9 MW_{el}.

The first operating biogas plant with biomethane feed-in to the natural grid in Germany runs in Pliening/Bavaria with a biogas flow rate of 920 $m^3\ h^{-1}$ and a biomethane output of 430 $m^3\ h^{-1}$ (700 ha crop land with crop rotation) (Aufwind, 2009). This corresponds to the double capacity of the calculated biogas pathway.

The flow rate of the separated CO_2 in the biogas pathway is about 400 $m^3\ h^{-1}$. The required hydrogen flow rate to methanize this amount of CO_2 is 720 $m^3\ h^{-1}$ (4.8 MW_{th}). This corresponds to an electrolysis power input of about 6 - 7.5 MW_{el}. Therefore, using 10% of a 120-150 MW_{el} wind farm in the 'variable load operation' mode (chapter 4.4.1) is sufficient to operate the RPM plant and double methane output.

Using a methanation unit with a high efficiency of 85% can generate an RPM flow rate of 400 $m^3\ h^{-1}$ (4.0 MW_{th}). Therefore, the overall renewable-power-to-methane conversion efficiency results in 57-68%.

The (re-)conversion of renewable methane in a combined cycle power plant with an efficiency of 60% allows an overall power storage efficiency of 34-41%. Energy losses for methane and CO_2 compression and feed in, and transmission losses of gas and power are neglected in this back-of-the-envelope calculation, but can be estimated to 1-3%. The overall methane output flow rate of the biogas plant can thus be almost doubled or even further increased, if the biogas upgrading unit is saved and replaced by an RPM plant and biogas passes directly through the methanation unit. This has another important advantage: methane leakage from biogas upgrading can be avoided.

Cost of methane production in RPM plants and upscaling

Fixed costs are investment costs and grid connection costs. At a demo scale, investment costs are estimated at 2000 EUR kW_{el}^{-1} for a 5-10 MW_{el} plant and account for the following units: electrolyzer, methanation, electrolyzer, compression, power electronics, piping, civil construction and control systems. After upscaling to a commercial scale of 20-200 MW_{el} by 2020 and later, investment costs are likely to drop below 1000 EUR kW_{el}^{-1} and power-to-gas efficiency are likely to rise to 65-68%.

Grid connection costs can be derived from biomethane plants and amout to 250 EUR $kW_{th\_methane\_output}^{-1}$ and include engineering, feed-in station, compression and branch line (Urban et al., 2009). These costs can be calculated as variable operation costs by referring the gas connection costs to the relative methane (energy) fed into the network.

The possibility of upscaling is given as electrolysis can be built up modularly and the methanation technology is the same on a 100 kW_{th} scale or a 10-100 MW_{th} scale. Basically, the only significant modification in methanation are larger diameters of the reactors pipelines and fitting concepts for using surplus heat, e.g. in district heating or process heat. A modular setup allows the concept to fit to available storage facilities, (gas and power) network requirements, surplus heat use concepts and gas power plants.

Operation and maintenance costs split in fixed and variable costs. Variable costs arise from the purchase of electricity, which is the most volatile parameter in cost calculations. In future power grids, wind power is likely to be very economic and available at 0-2 EUR-cents kWh_{el}^{-1} in times of high wind penetration and low residual load. In addition, CO_2 and transporting CO_2 may cause additional cost or create income – in a first simplified approach, it can be assumed to be free of charge.

Feed-in costs for RPM are in the same range as feed-in costs for biomethane, i.e. about 0.15 EUR-cents $kWh_{th\_methane\_output}^{-1}$ for gas network connection at 16 bars and 200 m distance and constant methane feed-in (Urban et al., 2009). On one hand, these costs decrease with higher pressure levels but require more energy for gas compression on the other hand. Variable revenues from selling O_2 can be expected to be about 70 EUR t_{O2}^{-1} or 1.3 EUR-cents $kWh_{el\_input}^{-1}$.

Fixed operation and maintenance costs appear for example for the exchange of nickel catalyst or the sulphur adsorber, usually a zinc oxide adsorber. These costs vary with operation modes, described in chapter 4.4, but are expected to be covered by 3% of the investment costs, i.e. 30-60 EUR kW_{el}^{-1} a^{-1}.

Technical lifetime of an RPM plant is estimated to 15-20 years. Taking into account these simple assumptions, RPM can be generated at 8 EUR-cents kWh_{th}^{-1}; at electricity costs of 2-5 EUR-cents kWh_{el}^{-1} and at 2000-4000 full load operating hours. If RPM can be sold for 10 EUR-cents kWh_{th}^{-1}, renewable power may cost 3-6 EUR-cents kWh_{el}^{-1} at the same full load operating hours in order to break even.

Today, the costs of conventional gas is at about 1.6-2.5 EUR-cents kWh_{th}^{-1} (IEA et al., 2008). However, RPM is likely to become competitive in the future, as it is CO_2-neutral, which gives additional value to 'green gas'. At the same time, fossil gas prices are expected to rise in relation to the scarcity of fossil gas. The break-even point depends on the intensity of both trends.

Additional significant revenues are expected from offering ancillary services like control power in different operation modes (chapter 4.4), lowering RPM production costs.

The conversion of RPM to electrical power (power plants), mechanical power (vehicles) and heat are standard gas conversion technologies and have therefore the same costs.

The benchmark for RPM plants as storage facilities are the costs for power network expansion or other long-term storage options like hydrogen. The benchmarks for RPM as vehicle fuel are the costs of biomethane, other biofuels or electromobility, integrating the vehicle into the considered pathway. The economic optimum between these options and renewable power curtailing has yet to be identified in detailed simulations.

4.3 *Four Renewable Power Methane concept categories*

4.3.1 *Stand-alone concepts – independent production of a carbon-neutral natural gas substitute by CO_2 recovery from the air*

The stand-alone concept for renewable power methane production is very attractive for countries with high natural gas import dependence and vast remote renewable resources. Wind, solar, hydro power or other renewables plus water for electrolysis and CO_2 extracted from air are sufficient to produce a natural gas substitute (Figure 4.3-1).

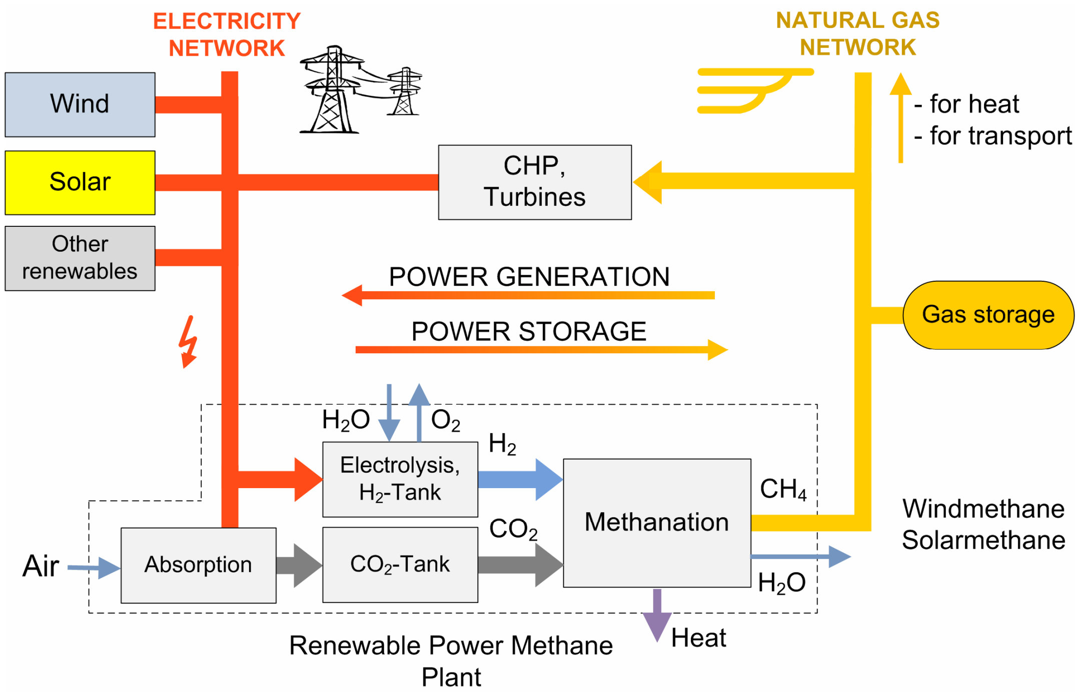

Figure 4.3-1: Stand-alone concept of a renewable power methane plant using CO_2 extracted from the atmosphere by absorption and electrodialysis for independent and climate-neutral methane production. Source: own compilation.

Direct capture of CO_2 from the air

By using CO_2 from the atmosphere, a CO_2 emission-neutral substitute for natural gas or other hydrocarbons can be produced. If the CO_2 is later separated from the combustion process and stored, even a carbon sink is possible with the combination of RPM with CCS technology.

Various technologies exist for CO_2 extraction from the atmosphere. In thermodynamic theory, the minimum energy demand to extract CO_2 with a partial pressure p_0 in a gas mixture to generate a pure CO_2 stream is the Gibbs free energy $\Delta G = RT \ln(p/p_0)$. This is proportional to the chemical potential μ, where R is the specific gas constant (8.31 J mol^{-1} K^{-1}), T the ambient temperature in Kelvin, p the ambient pressure and p_0 is 0.38 mbar. This energy demand is only 0.45 GJ per t CO_2 or 20 kJ mol^{-1}. Nevertheless, in real process technology, the energy demand is much higher since activation energy is required (Stolaroff et al., 2008; Petrak, 2006).

(Specht et al., 2000) categorizes CO_2 extraction processes from a gas mixture in

(i) adsorption – on solid sorbents like mol sieves (e.g. pressure-swing adsorption),

(ii) absorption – in different solutions (e.g. ZSW concept),

(iii) condensation – in cryogenic distillation processes (e.g. linde process) or

(iv) membrane separation (e.g. air separation units).

The latter two processes are rather energy intensive and used in air separation units in industrial nitrogen, oxygen and argon plants. The condensation process requires an extreme cooling of air and the membrane separation process a high pressure increase of the air. Both processes are energy-intensive and thus not suitable for CO_2 recovery from air (Specht et al., 2000).

Adsorption processes like the pressure-swing adsorption (PSA) are standard technology for gas cleaning and conditioning. The drawback of CO_2 recovery via PSA is the mutual adsorption of CO_2 and water vapor. To recover the absorbent and separate CO_2 from water vapor is again very energy intensive. Recovering a CO_2/water mixture consumes 20-times more energy than recovering pure CO_2. Further, membrane sieves are sensitive to air impurities like dust (Specht et al., 2000).

Therefore, the only promising pathway for atmospheric CO_2 concepts are absorption processes, which are developed in different concepts.

An efficient CO_2 recovery process with low specific energy consumption is the ZSW process of absorption and electrodialysis (Bandi, 1995).

CO_2 is absorbed by a caustic NaOH scrubbing solution to form a Na_2CO_3 carbonate solution. Absorption rates of 10-70%, on average 45%, can be achieved at an energy demand of 2.7 GJ per t CO_2, which depends mainly on the concentration of the scrubber solution. CO_2 is recovered from the produced carbonate by acidifying the solution with sulphuric acid. The caustic scrubber solution and the sulphuric acid are regenerated in an electrodialytical unit with bipolar membranes, consuming 7 GJ (t CO_2)$^{-1}$. This two stage neutralization process enables a full CO_2 recovery and a modular setup of electrodialysis units (Bandi, 1995; Specht et al., 2000).

Experimental results show an energy demand for the absorption process of 1.8 GJ (t CO_2)$^{-1}$ and for the electrodialysis process 6.4 GJ (t CO_2)$^{-1}$ (Specht et al., 2000). In total, 8.2 GJ are necessary to extract 1 t CO_2 for the atmosphere. About 2,300 m^3 of air have to be processed to extract 1 kg of CO_2 (Weimer, 1996).

Figure 4.3-2 shows a pilot scale plant, which was set up for methanol production (Specht et al., 2000).

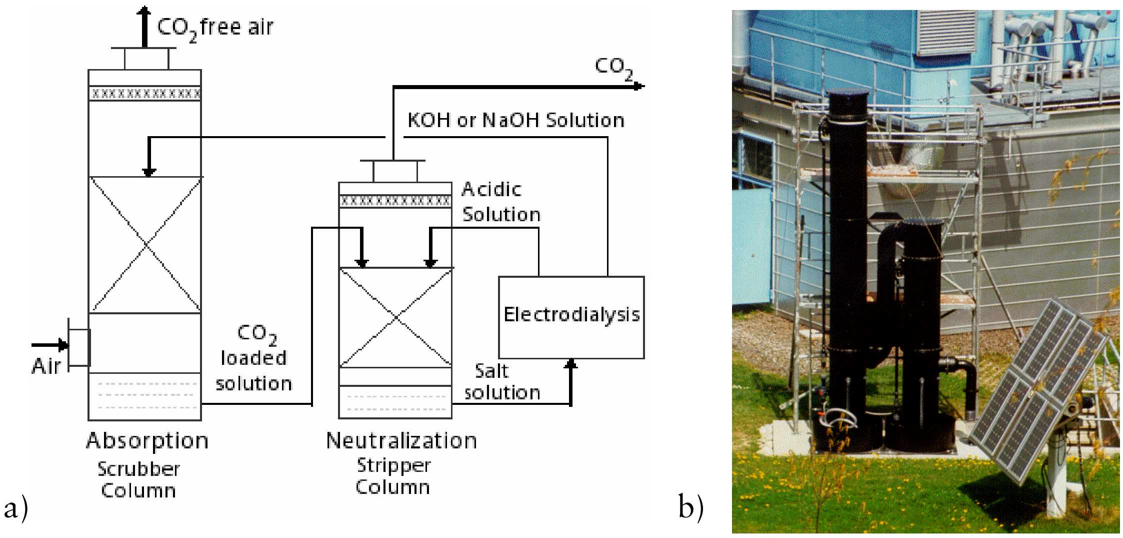

Figure 4.3-2: Pilot scale plant for CO_2 extraction from air, set up at ZSW/Stuttgart; a) process design; b) installed absorption unit (scrubber and stripper column). Source: adopted from (Specht et al., 2000).

Other methods for CO_2 recovery by absorption exist with several advantages and drawbacks (Table 4.3-1). Another low energy consuming and thus promising option is a new concept using 'frustrated' phosphine-borane Lewis pairs that chemically bind CO_2 at low pressures and release it as the mass is heated or solvents are applied (Mömming et al., 2009).

Table 4.3-1: Other methods besides the ZSW concept for atmospheric CO_2 recovery; [A] no experimental proof yet. Source: own compilation.

Main concept components	Solution / Absorbent	Source
Packed column SO_2 scrubbing / energy tower[A] Artificial trees[A]	$Ca(OH)_2$ NaOH	(Zeman, 2007) (Lackner et al., 2001)
Precipitation pools Calcination kiln	$Ca(OH)_2$	(Dubey et al., 2002)
Hollow fiber membranes Chamber electrolysis	KOH	(Stucki, 1995)
Contactor for NaOH spray (improvement of contact area) Absorber tower	NaOH	(Stolaroff, 2006) (Stolaroff et al., 2008)
Solution of ‚frustrated' phosphine-borane Lewis pairs, heating chamber	Non metal-containing catalyst	(Mömming et al., 2009)

As long as concentrated CO_2 sources are available, it is economic and efficient to use those. However, in the long run, atmospheric CO_2 recovery by renewable energies can be an interesting climate mitigation option. CCS technology is rather expensive and maintenance costs for permanent CO_2 storage is expected to be high. Most likely, the most important advantages of atmospheric CO_2 recovery are the possibility to capture past emissions and diffuse emissions of small and mobile sources like airplanes or buildings where CCS it is neither possible nor economic (Stolaroff et al., 2008; Keith, 2009). Atmospheric CO_2 recovery may become a necessity in future, if active and large-scale climate mitigation is delayed by some years or decades and fossil fuels – especially coal – are continuously burned for a long time to come.

Onshore concepts

Vast unexploited renewable power potentials are available in remote, sparsely populated areas, far away from large energy consumers. Conventional wind and solar power technologies can be used in combination with an RPM plant to tap these potentials, generate methane and transport it over long distances via pipelines or trucks for distribution in industrialized regions. The need to built dams for large hydro power plants might be reduced by converting hydro power into methane.

For example, Chile is a country with a high import dependence on natural gas from neighbor countries. At the same time, it offers large potentials of wind energy in the south (Patagonia) with very high average wind speeds of 10 m s^{-1}. In the north (Atacama desert) vast potentials for solar power are available. One third of the population is living in Santiago de Chile in central Chile, both 1,500 km away from north solar and south wind regions (Sterner et al., 2005). By setting up wind turbines and solar power plants in combination with renewable power methane generation, Chile could supply itself with 'natural gas' and mitigate import dependency and political tensions. The surplus O_2 from RPM production could be used in copper mining and substitute coal power plants for O_2 generation.

A European option would be the generation of RPM via solar thermal power plants, cheap PV parks or wind parks in northern Africa or Turkey and its transportation via the existing natural gas network. For example, a gas pipeline between Algeria and Spain exists already today. Therefore, the RPM technology enables the use of these renewable energy potentials in form of a common, storable and transportable energy carrier.

China could use solar energy from the Gobi desert, India from Gujarat. In USA, California could be supplied with RPM from Nevada or Arizona. New Mexico or Texas could supply itself with 'natural gas' or other 'solar fuels'.

Similar matchings for wind energy are possible.

Offshore concepts

Anywhere around the world, offshore wind farms can be used to generate methane. RPM can be compressed or liquefied and transported via pipelines or shipped by tankers for onshore use. Another possibility is to built sea power transmission lines, convert renewable electricity into methane near the shore and feed it into the natural gas grid.

Similar concepts combine offshore wind power farms with compressed air storage and nitrogen-rich low calorific gas from old natural gas sites in the North Sea, which is converted into power on an offshore platform if necessary (Changhui et al., 2005). The difference to RPM, however, is that the weak gas is fossil and a limited resource like any other fossil fuel. However, the infrastructure of old natural gas sites could be reutilized.

4.3.2 *Concepts with bioenergy plants – biogas upgrading and SNG gasification*

The basic concept can be combined with two main bioenergy conversion lines: fermentation and gasification. Biomethane production is beneficial as CO_2 is already separated in the process and out of other reasons similar to RPM (chapter 3.2.1). A CO_2 sink can be created in power generation with RPM in combination with CCS. CO_2 is extracted by photosynthesis and stored in biomass, released in biomethane production, bound again in RPM production and captured and stored in the combustion process of RPM, which is operated ideally with surplus O_2 from RPM production.

Integration in biogas plants

The RPM concept can be integrated into biogas plants by using CO_2 from the biogas upgrading process. Current technology separates CO_2 by e.g. pressure-swing-absorption, but it is released to the atmosphere and not stored permanently. Separated CO_2 can be converted into methane. If hydrogen is short, only parts of the separated CO_2 are used.

Another option is the direct feed in of biogas (CH_4 + CO_2) into the methanation unit of the RPM plant for methane production. The CO_2 tank can be used in that case as biogas storage tank. This saves the costs for a biogas upgrading unit. If there is a lack of hydrogen and not all biogas can be hydrogenated to methane, surplus biogas can generate power in a CHP or a gas turbine (Figure 4.3-3).

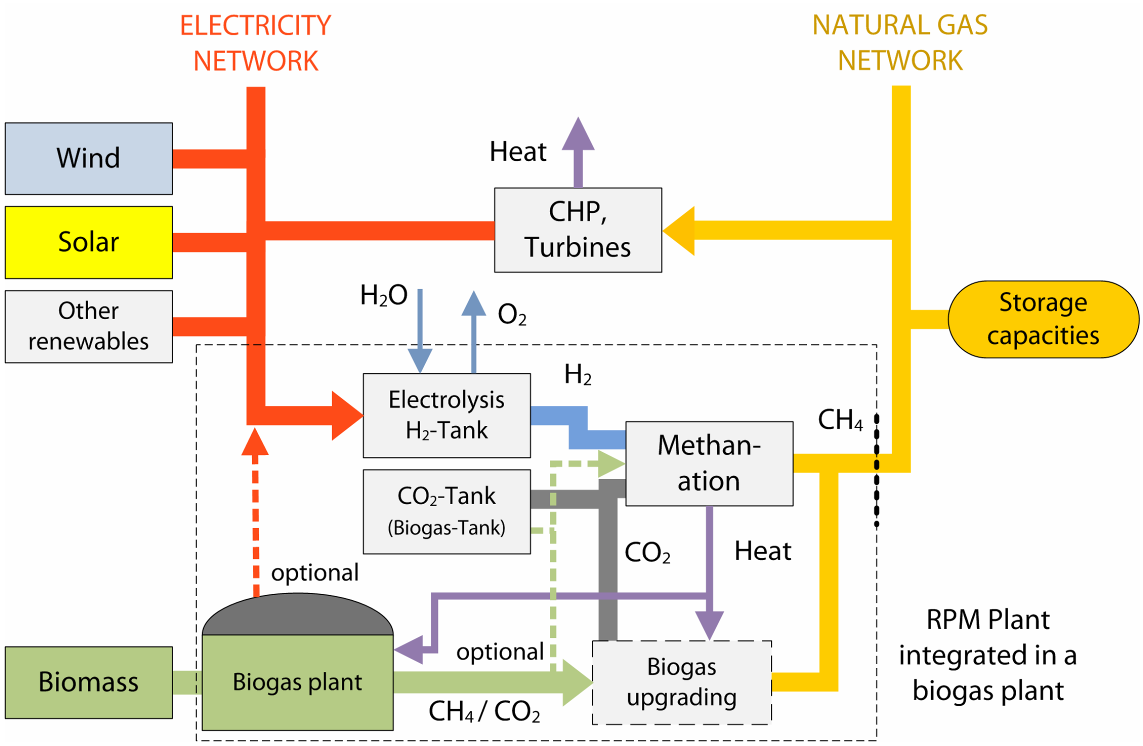

Figure 4.3-3: Concept of a renewable power methane plant integrated into a biogas-SNG-plant (biomethane production) – beneficial is the use of one common entry point, the use of the separated CO_2 and the integration of waste heat in the overall process. Source: own compilation.

In both cases, methane leakage can be minimized, methane yields almost doubled and waste heat used within the biogas plant in the upgrading unit or in the fermenter itself. Optional, surplus oxygen can be used in the fermentation process.

Integration in biomass gasification plants

Solid biomass feedstock can be converted into biomethane via gasification and methanation. Various technologies are developed successfully (chapter A4.1 and 2.2).

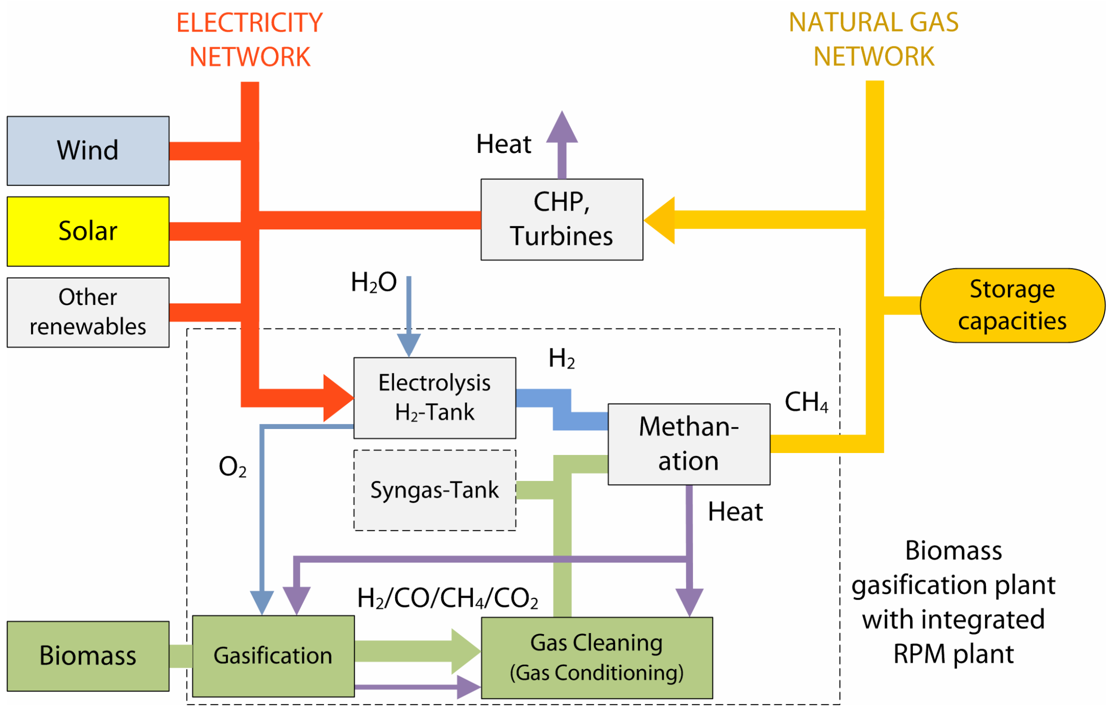

Figure 4.3-4: Concept of a renewable power methane plant integrated into a biomass gasification plant for SNG (biomethane production) – waste heat can be integrated and surplus oxygen used as gasifying agent. Source: own compilation.

Like in biogas plants, the RPM concept can be integrated 'after' methanation, using the separated CO_2 and one common entry point into the gas network (Figure 4.3-3).

Another option is the integration of the RPM plant in a bio-SNG (substitute natural gas) gasification plant. Biomass is gasified to raw gas. After cleaning, syngas (H_2, CO, CH_4, CO_2) is fed into the methanation unit (Sterner, 2007). Merely an electrolysis unit is added to generate missing H_2, which is added to the clean gas stream. Surplus O_2 is used as gasification agent in autothermal gasification of biomass. Cellulosic biomass can be added to the natural gas network by this pathway.

4.3.3 *Concepts with waste management - sewage plants, landfill sites and CO_2-intensive industries*

Various combinations of the RPM concept with waste management facilities are possible. Sewage plants make use of surplus oxygen, landfill sites are similar to biogas plants and CO_2 intensive industries can make use of waste CO_2.

Integration in sewage plants

Large sewage plants have a high demand of oxygen for the activation of sludge, which has a specific biochemical oxygen demand. Comparable to biogas plants, sludge from waste water is processed and digested to CH_4 and CO_2 and thus RPM plants can be integrated very easily (Figure 4.3-5). A further synergy is the optimal use of surplus oxygen from electrolysis in the waste water treatment.

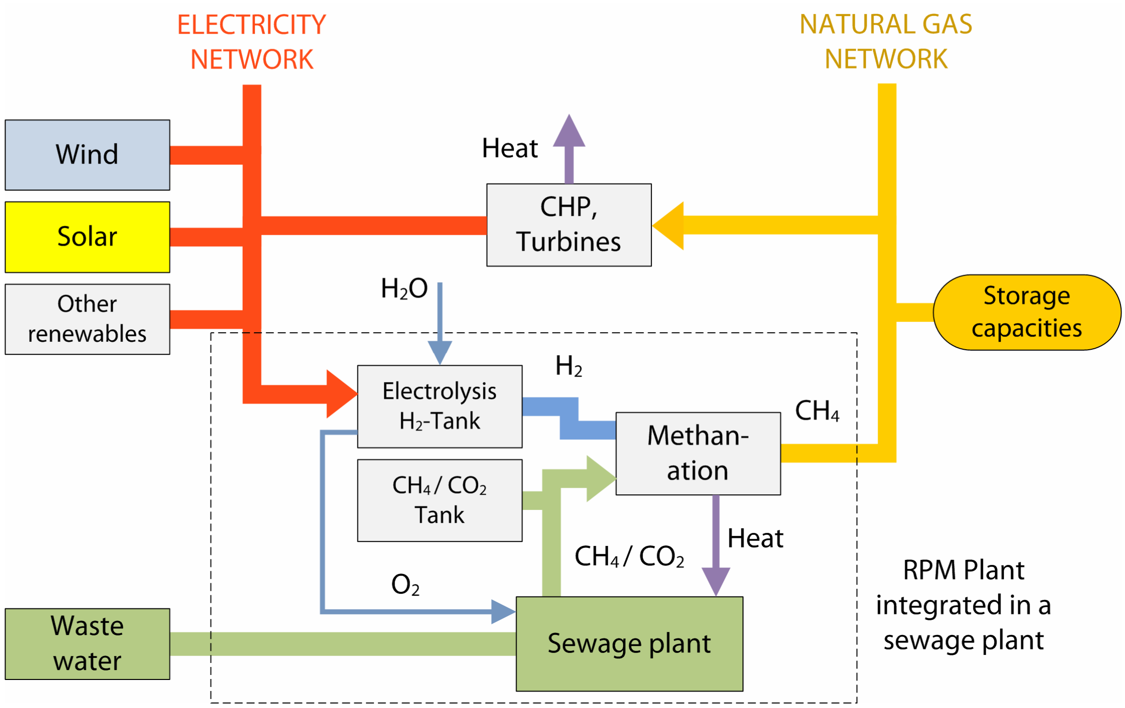

Figure 4.3-5: Concept of a renewable power methane plant integrated into a sewage plant – synergy can be created by using surplus oxygen and heat in the waste water treatment and the use of waste gases CO_2 and CH_4. Source: own compilation.

Integration with landfill sites

The integration of an RPM plant in a landfill site is similar to the integration in a biogas plant (Figure 4.3-3). Waste disposed in landfills is broken down by bacteria and microbes, producing landfill gas. This gas is mainly composed of CH_4 and CO_2 and is often burned off in a flare. Using an RPM plant, landfill gas can be upgraded to methane and used energetically, avoiding GHG emissions of landfills and substituting fossil fuels.

Integration in CO_2-intensive industries

Many industrial processes have CO_2 as waste gas that can be used in RPM processes. For example, cement production sites show high CO_2 emissions as limestone is emitting large quantities of CO_2 when heated up to 1,500°C and this calcination process is very energy and thus emission intensive (Alsop, 2007). Other processes are steal manufacturing, refineries, chemical industry like material and plastic production (e.g. melamine, ammonia, aluminum). Integrating carbon capture and an RPM plant can reduce GHG emissions from cement production. CO_2 can be also compressed or liquefied and transported to RPM plant sites. The techno-economic benefit of industrial CO_2 sources can be their 100% pure CO_2 stream availability at very low or even zero cost, which makes these sources attractive for RPM plants: using inevitable CO_2 before it is released to the air.

4.3.4 *Concepts with fossil fuels - fossil power plants and natural gas sites*

The RPM concept can be also combined with fossil power plants like coal power plants, store the separated CO_2 in the natural gas grid and thus increase the utilized renewable power share. By separating CO_2 from RPM combustion, CO_2 recycling is possible.

Integration in fossil power plants – as seen in the coal oxyfuel process

Various capture technologies exist for fossil power plants. CO_2 can be separated after the combustion process (post-combustion), in the gasification process (pre-combustion) or in the combustion with oxygen (oxyfuel process). Captured fossil CO_2 can be liquefied and transported by trucks, trains, pipelines or tankers to the RPM plant site and converted into methane by use of renewable hydrogen. Figure 4.3-6 illustrates such a fossil concept with the oxyfuel process. Surplus oxygen from renewable electrolysis can be used as combustion agent and substitute oxygen from the air separation unit.

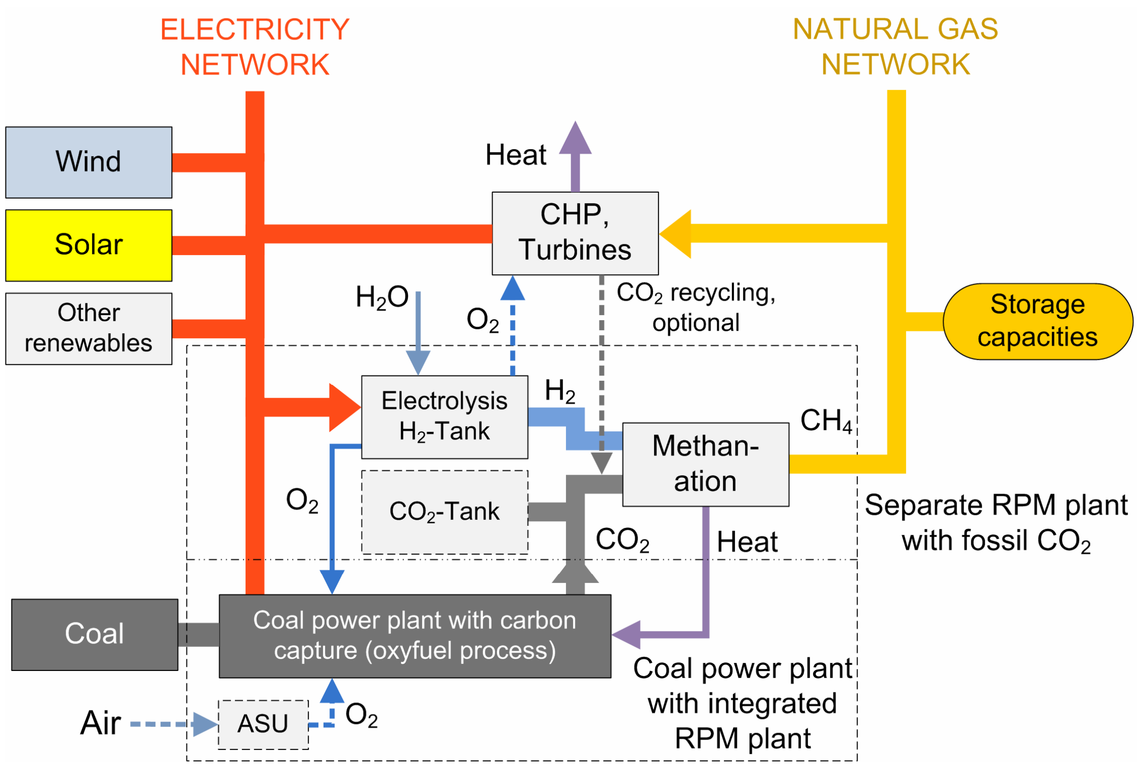

Figure 4.3-6: Concept of a renewable power methane plant integrated into a coal power plant with CO_2 separation via the oxyfuel process – waste heat can be integrated and surplus oxygen used as combustion agent for coal or RPM. Difficult carbon storage can be avoided and surplus wind/solar/renewable energy stored as carbon-neutral methane in the natural gas grid. Another option is the separate operation of the RPM plant with fossil or industry CO_2 from e.g. pipelines, tankers, ships. ASU = air separation unit and the recycling of CO_2 within the energy system. Source: own compilation.

The produced RPM is not 'climate neutral' like RPM from biomass or stand-alone concepts since fossil CO_2 is used. However, as surplus renewable power is used and stored, it can replace fossil fuels by power generation of RPM, whereby the stored fossil CO_2 is emitted and other fossil CO_2 is avoided. The net effect is climate positive, since e.g. wind power is utilized and not dumped due to electric grid stability problems and fossil CO_2 is stored temporarily in form of RPM in the natural gas network.

Applying the same concept for RPM combustion in gas power plants, part of the CO_2 can be recycled within the energy system itself, which makes RPM CO_2 neutral like using biomass. Thus, CO_2 can be used as a 'vehicle' for hydrogen in the energy grids, until a hydrogen grid plus end user devices and meters are realized in the far future. As RPM plants with electrolysis units will be established, the first step into such a direction is taken.

Integration in coal gasification with carbon capture

Similar to a biomass gasification plant (Figure 4.3-4), the RPM concept can be integrated into coal gasification power generation like and internal gasification combined cycle power plant (IGCC). The raw gas from coal gasification is cleaned and combined with hydrogen from renewable power for methanation. Waste heat can be integrated and surplus oxygen used as gasifying agent.

Wind offshore concepts with fossil or industry CO_2

Anywhere around the world, offshore wind farms can be used to generate methane. It can be transported via pipelines or shipped by tankers that deliver CO_2 from industry or fossil fuel use and load renewable power methane for onshore use.

On- and offshore concepts at natural gas sites

Many natural gas production sites exist offshore, which have CO_2 as waste product. Installing a wind park near the natural gas site could create synergy and reduce CO_2 emission from natural gas exploration. Combined offshore wind farms and natural gas sites in Europe's North Sea are an example of using existing energy networks, avoiding the expensive construction of long distance power networks. CO_2 from natural gas production in the middle east can be utilized with solar power to generate RPM.

4.4 Operation and grid integration

Renewable power methane plants can be controlled and integrated into power management in several ways. Two ways are described as examples: (i) matching power supply and demand by power shifting using power storage and (ii) balancing power. Many other grid integration and operation concepts are possible, like a pure 100% renewable power methane generation in the stand-alone concept for material use or feedstock for the chemical industry. Some of them are described in the concept descriptions in chapter 4.3. The following operation concepts are of a 'raw' nature and need to be optimized in terms of efficiency, costs, and GHG reduction potentials.

4.4.1 Control concept 'power storage and power shifting'

Demand-oriented renewable power supply by power shifting (storage operation)

Fluctuating renewable power supply can be matched with fluctuating power demand by storing and using renewable power methane.

If high wind power supply matches a high power demand, wind power can be used at maximum capacity. If high wind speeds occur at low power demand periods, wind turbines are shut down and renewable power is dumped / curtailed. To avoid this, power storage facilities like RPM are required. It is thus essential to consider both renewable power generation and power demand (electrical load) simultaneously.

Subtracting renewable power from power demand results in the 'residual load', which corresponds to the power demand that has to be covered by conventional fossil and nuclear power generation. The residual load can be estimated in advance. Wind and solar power can be predicted by using meteorological forecasting models, which is state-of-the-art technology. Standard 15 min load profiles exist for power demand, differentiated in daytime, weekdays and seasons (Schmid et al., 2009). In the European ENTSO-E network, hourly values for load profiles exist for the vertical bulk load.

To stimulate the demand-oriented feed-in of renewable power, incentives can be set by law that classify each day in different time zones: times with high residual loads (HRL – yellow zones), and low residual loads (LRL – red zones) (Schmid et al., 2009). Figure 4.4-2 illustrates this method applied on a winter's day (Jan, 8, 2007) in Germany by using the German total load profile and the feed-in of all German wind farms.

The time slots for charging (HRL zones) and discharging (LRL zones) renewable power are set to 8 hours. This value is orientated at the storage capacity of conventional pumped hydro storage plants and also used for the operating concept of the RPM plant to ensure a continuous operation of the methanation unit. However, RPM can be 'stored in' basically without capacity and time limits, as the existing storage and pipeline capacities of the natural gas network (e.g. in Germany 200 TWh_{th}) are very large vs. the storage capacity in the power network (0,04 TWh_{el} German pumped hydro storage).

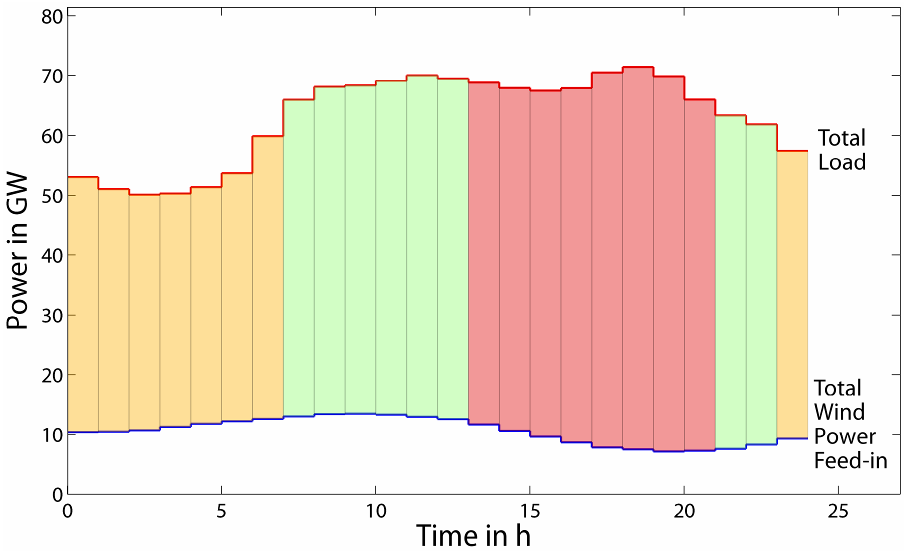

Figure 4.4-1: Standard load profile for a weekday (red line) and forecasted wind power (blue line) on Jan 08, 2007; daytime is classified in time zones with high residual load (HRL - red zones – long bars), with low residual load (LRL – yellow zones – short bars) and neutral zones (green zones – medium bars). Source: own compilation, adapted from (Schmid et al., 2009).

However, this time frame is a first approach. The RPM plant does not have storage constraints as the natural gas network serves as large storage capacity for renewable power. The hydrogen tank of the RPM plant can be used as well for buffering intermittent renewable energy before the downstream methanation. This buffering brings more flexibility in operating the RPM plant.

These times zones indicate when it is technically beneficial to convert power to gas (LRL - yellow zones) or re-convert gas to power (HRL – red zones). During the green time zones, renewable power can be used directly or for RPM generation at a certain part load to keep the methanation unit at temperature.

The example of chapter 4.2.2 of a combination of biogas, wind farm and RPM plant is used to illustrate this operation concept.

The total residual load is downscaled by factor 1,000 (black line) and the feed-in of a 73 MW_{el} wind farm (blue line) illustrated in Figure 4.4-2. The assumed electric capacity of the RPM plant is 10 MW_{el} and the overall power storage efficiency is 35%. RPM is produced during low-residual-load times and re-converted into power during high-residual-load times and not operated during neutral times (black dashed line).

The use of the RPM plant in combination with the natural gas network and power generation from RPM in gas power facilities reduces the fluctuation of the residual load considerably and stabilizes the renewable power supply (see simulation of 100% renewable power supply in chapter 6.2 and annex A1). This increases grid stability and technical supply security and enables 100% renewable power supply concepts with large capacities of gas power plants as backup, operated with RPM.

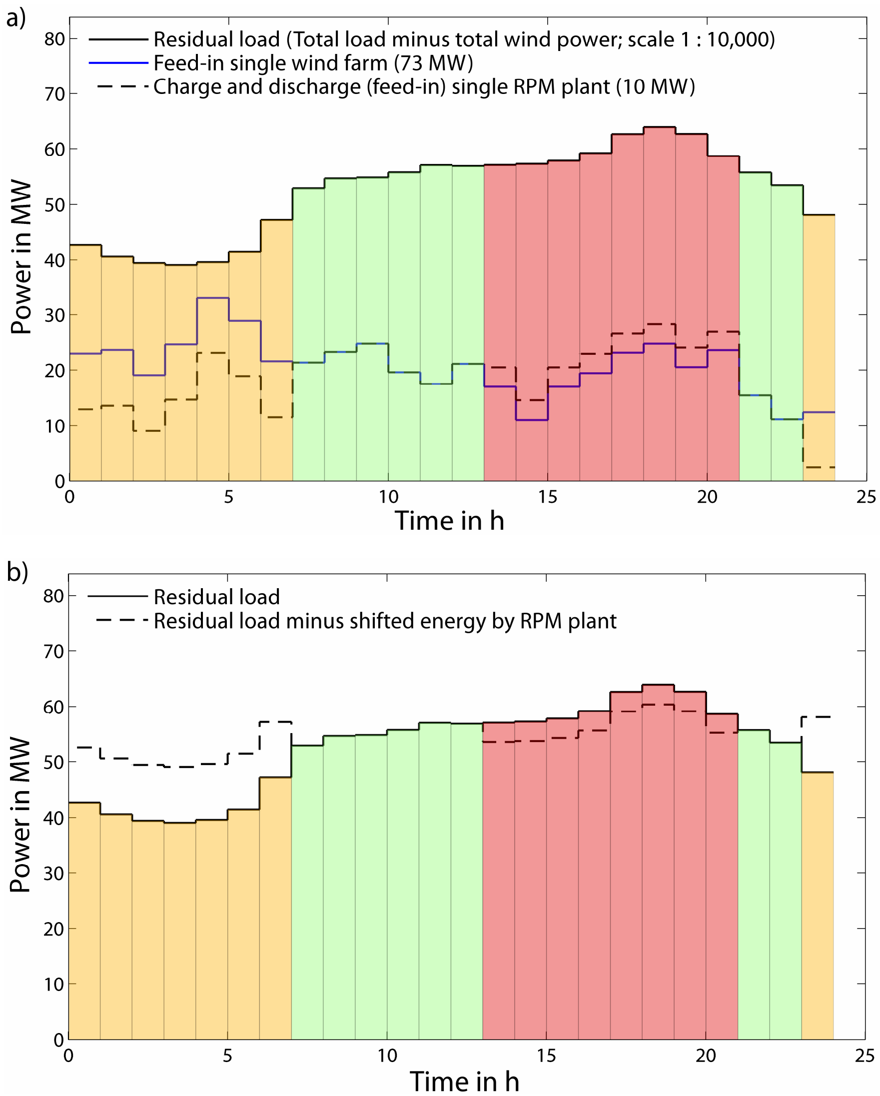

Figure 4.4-2: Demand-oriented control concept for a RPM plant simulated for Jan 08, 2007;
a) German residual load on a scale of 1:1,000 (solid black line) and forecasted wind power (blue line); generation of renewable power methane an re-conversion into power (dashed black line);

b) German residual load on a scale of 1:1,000 without operating the RPM plant (solid black line); and with the RPM concept integrated into renewable power supply (dashed black line), the RPM plant avoids fluctuations and thus contributes to grid stability; daytime is classified in time zones with high residual load (HRL - red zones), with low residual load (LRL – yellow zones) and neutral zones (green zones). Source: own compilation, adapted from (Schmid et al., 2009).

Permanent RPM production (variable load operation)

Beside the operation in time zones, renewable power methane can be produced permanently by using a forecast-dependent, specific share of renewable power input, e.g. 5-10% for electrolysis. There are four advantages of this operation mode: First, this enables a permanent operation of the methanation unit, which is essential for a cost-effective RPM plant operation. Second, costs for balancing wind power forecast errors can be avoided. Third, by branching some share of wind power into the gas grid, a reliable, controllable an predictable band of wind power generation can be provided and fed in, which is facilitating power network operation. Fourth, the wind park or system operator can react flexibly to energy market signals as direct marketing of renewable energy is likely to be introduced at some point of time. As there is high wind power generation, electricity prices can be expected to be low during times of low power demand. If the size of the RPM plant is large enough, the operator can decide flexibly, whether to generate electricity or to generate gas and feed in accordingly. A drawback is the missing balancing function of RPM for fluctuations, which can be compensated by a flexible operation of the electrolysis unit and the use of a hydrogen storage tank.

Challenge technical and economic operation

The RPM concept faces the same challenge like hydrogen options for balancing fluctuating renewables: High shares of surplus wind and solar power occur only about 500-2,000 FLh (full load hours) per year that challenges an economic operation of RPM plants (see cost calculations in chapter 4.2). A technical constrain is the lifetime of the catalyst (usually nickel) in methanation that is reduced by many ramp ups and downs. The number of necessary exchanges and associated minimum down times depends strongly on the operation mode. The RPM plant can be operated very flexible: very steep ramp ups and downs in few seconds are possible, since the electrolysis unit is rather robust and flexible. Similar, power generation with gas power plants includes the possibility to ramp up and down in the full operation range within 30 minutes. The only bottleneck so far is the methanation unit, which can be operated in a range of 25-100% very flexibly; similar to electrolysis in few seconds (Specht, 02.04.2009). However, once the methanation reactor is cold, the start requires some time (minutes to few hours, depending on the RPM plant size). This time gap can be bridged by a buffer for hydrogen or by operating the plant at a very small part-load, to keep the methanation reactor warm and at stand-by. This reduces the thermal inertia of the methanation system, which is intrinsic in any thermal plant.

However, various flexible parameters are likely to make RPM plants economically feasible: First, costs for electrolysis and methanation units are reduced with economies of scale. Second, technical flexibility increases by integrating an intelligent use of hydrogen tanks. Third, technical problems with catalyst can be minimized by a high process integration and steady heating of the methanation unit by e.g. minor part load operation at few % of nominal power. Fourth, future markets may show a strong demand for renewable power methane as stored energy for transport, heat or balancing power; similar to peak load power plants that operate economically at only 500 to 2,000 FLh and are already today gas power plants. The same power plants can continue to serve this purpose by switching fuel from natural gas to RPM.

In a first approach, the RPM concept is simulated as a key element of a 100% renewable power supply with an installed capacity of 5.38 GW_{el} power-to-gas and 5400 FLh at minimum 8 h operation per ramp up (RPM plants) plus a capacity of 50 GW_{el} gas power plants in chapter 6 and in annex A1. These high FLh can be achieved by accessing vast surplus renewable power in a quasi-steady operation mode and further increased in the ‘variable load’ operation mode. However, once an RPM plant exceeds 7000 FLh, it does no longer serve the purpose of ‘balancing’ power but rather can be regarded as renewable fuel production for the transport sector. Excess renewable power capacities (overcapacities) may be used for this purpose.

In a 100% renewable power supply scenario – alike the sample simulation in chapter 6, a mixture of both described operation concepts is likely as little residual load is left.

4.4.2 Control concept ‘balancing power’ – electrolysis control and methane storage

The RPM concept can be used to provide ancillary services like balancing active power. This creates additional income for RPM plants and increases return-of-invest. Two control concepts for positive balancing power are outlined: (i) by flexible use of RPM for power generation and (ii) by flexible operation of the electrolysis unit.

Renewable power methane as flexible balancing power in gas power plants and CHPs

By storing renewable power as methane, it can be distributed and converted in combined cycle power plants or CHPs at crucial grid nodes and supply balancing active power. RPM can be used in ordinary peak and medium load gas power plants as it is stored in gas caverns or the gas network. Ideally, the gas power plants are connected to the high voltage grid with a large reserve capacity to provide balancing power. If gas power plants operated with RPM are the only existing back-up facility; their installed capacity has to meet minimum the bottleneck capacity of the individual power system.

Another option is the use of distributed, small scale CHPs with RPM. Thousands of distributed engines can be coupled over the internet / smart grid and controlled as one large unit from one central spot like a large gas power plant (swarm power principle). In this manner, CHP heat can be used efficiently and ‘balancing power’ distributed widely. Another advantage is the independency from large power system failures, as RPM can be still supplied from the gas grid and power produced right at the consumers place. (Lichtblick, 2009) intends to install 100,000 of these units in Germany with a cumulated power of 2 GW_{el} – planned with biomethane – but also suitable for RPM.

Using the electrolysis unit as positive or negative load and buffering hydrogen

By switching off the electrolysis unit, positive balancing power can be provided for certain time slots. The consequence is an interrupted hydrogen production, which is not in favor of the methanation unit that can be operated between 25-100% but is most feasible in maximum load operation (Specht, 02.04.2009). Since the methanation unit requires a rather steady hydrogen flow rate, it is recommendable to buffer hydrogen and use a hydrogen storage tank. Thus, the power input can be decoupled from methane output and ancillary services provided by the RPM plant as flexible load in demand side operation mode.

5. *Development of a sustainable integrated energy system*

Beside solar energy, bioenergy was the major global energy source until the first industrial revolution since the beginning of humanity (Goldemberg, 2000). Compared to this very long period, fossil fuels will be used only for a few centuries. The foreseeable end of fossil energy supply and its harm to the climate require a transition towards sustainable renewable energy systems. Based on the draft description of four elements of a low-carbon energy supply (chapter 1.2.3), the potential role of bioenergy in energy systems and climate protection (chapter 3.2 and 3.3) and the newly developed concepts on renewable power methane (chapter 4), a sustainable energy system is developed in this chapter.

5.1 *The supply and emission dilemma*

The two major challenges in energy supply are supply security and emission reduction.

Limited fossil, nuclear and bioenergy resources

Dependency on fossil fuels is very high, especially in the transport sector. For example, 98% of the European transport energy demand for road transport is covered by crude oil (Boerrigter et al., 2004). Fossil fuel prices will remain volatile and unpredictable, which is hindering long-term investment security and energy economy planning (Seltmann, 2009). Crude oil and natural gas resources will be exhausted by the end of this century. Nuclear sources are finite too, not sustainable and with many risks to society (chapter 1.2.2). The examined bioenergy potential is also limited. Increasing food demand and area-intensive nutrition patterns leave limited space for energy crops. The potential of bioenergy from residues and waste is restricted as well (chapter 1.3). By the middle of this century, the material use of agricultural and forestry products for biomaterials will become increasingly important for the chemical industry and displace energy crop plantations (chapter 3.2).

Decarbonizing the energy system

Bioenergy can solve neither the energy supply challenge nor the climate change challenge. New technologies to make fossil energy or bioenergy use less CO_2-intensive like carbon capture and storage (CCS) are currently developed but it takes years until they are available (minimum 2030). Time that is not available as mitigating climate change is an urgent issue. Carbon capture technology reduces about 80–90% of the CO_2 emissions of a plant, which requires about 10-40% more energy (compression, capture) for an equivalent energy output than a non-CCS plant. Major problems are faced in transporting and storing CO_2 permanently and avoiding leakage. Geological or ocean storage reservoirs have to be tested on leakages before being put into operation, which can take several years. Moreover, CCS is expensive as the following estimations show: costs for capturing CO_2 from coal or gas-fired power plants: 15-75 US$ t CO_2^{-1}, costs for transporting CO_2 via pipelines: 1-8 US$ t CO_2^{-1}, costs for storing: 1-8 US$ t CO_2^{-1} and costs for monitoring CO_2 storage sites: 0.1-0.3 US$ t CO_2^{-1} (IPCC, 2005; Rochon et al., 2008). For example in Germany, a future economic operation of coal power plants with CCS is not guaranteed (Groscurth, 2009). CCS is therefore today not a feasible, preferable option for mitigating climate change and possibly a long-term future option. A similar conclusion applies to other climate mitigation options like geoengineering.

GHG emission reduction has to happen rather fast to limit global warming to 2°C. GHG reductions of 80-95% until 2050 are necessary to keep this goal (Meinshausen et al., 2009). As fossil fuels are ending and it is not easy to capture and store their emissions, they need to be replaced by carbon-free energy like solar, wind, hydro, geothermal, and ocean energy. This requires not only a simple fuel switch but rather a transformation of the entire energy system.

5.2 *Five steps towards an efficient energy system*

To create a sustainable energy system in terms of climate change and supply security, five steps are to be taken:

1) avoid inefficient technologies, i.e. increase energy efficiency and energy savings
2) shift to carbon-free direct power generation from renewable energy,
3) maximize the use of fossil, bioenergy and renewable methane by co-generation,
4) implement renewable electromobility, and
5) use geothermal heat via renewable powered heat pumps for heating and cooling.

5.2.1 *Energy efficiency by energy savings*

Lower energy consumption is possible by energy savings in all energy sectors. Energy savings can achieve GHG emission reductions at low cost (IPCC, 2007d).

Heating and cooling

Heat insulation of buildings can reduce heat losses. In new designs of commercial and residential buildings, passive heating and lighting by solar energy, energy-efficient windows and doors can be integrated. For heating and cooling, solar-assisted, biomass or geothermal systems can be installed. Efficiency of all kinds of boilers, stoves and radiators can be improved. Co-generation offers a possibility of heat provision and power generation for own consumption. In the future, new houses and buildings will be 'passive houses' or zero-energy buildings. Plus-energy buildings will generate more energy than they consume by internal CHPs or PV systems for example (Twidell et al., 2008; DOE, 2009). At an industry level, boiler efficiency can be improved as well and heat leakages avoided. Insulation of steam and condensate return lines raises overall thermal efficiency (DOE, 2009).

Power consumption

Power savings can be realized by improving efficiency of home appliances, avoiding appliances with stand-by, exchanging conventional light bulbs by compact fluorescent light bulbs, and many other possibilities. Improved IT technology design can contribute to power savings as well (VDE, 2008a).

In industry processes, compressed air systems and electric drives are among the largest power consumers. Optimizing both by installing variable speed drives advances energy efficiency. Improved sealings and measures to prevent air leaks are another way of realizing energy savings. New power electronic devices are more energy efficient than most common technology (VDE, 2008a).

Transport

Energy consumption of all vehicles and airplanes can be improved by better aerodynamics (reduced drag), lower weights, less rolling resistance and optimal tire inflation. Improved fuel efficiency of combustion engines also contributes to energy savings. Socio-economic measures like an improved organization of public transport, improved capacity utilization of busses, trains and airplanes and improved traffic flows lowers overall energy consumption in the transport sector (DOE, 2009).

5.2.2 *Increasing energy efficiency by combined heat and power*

Conventional thermal power generation has a global average efficiency of 36% (REN21, 2008a) and does not make use of waste heat, whereas combined heat and power (cogeneration) converts up to 90% of primary energy into useful power and heat. Heat from CHP can be used for process heat, district heat and lower both primary energy demand and GHG emissions (Figure 5.2-1). The full potential of CHP, independent of fuel, can be tapped by placing new thermal power generation facilities near large heat consumers and by integrating CHPs in district heat supply.

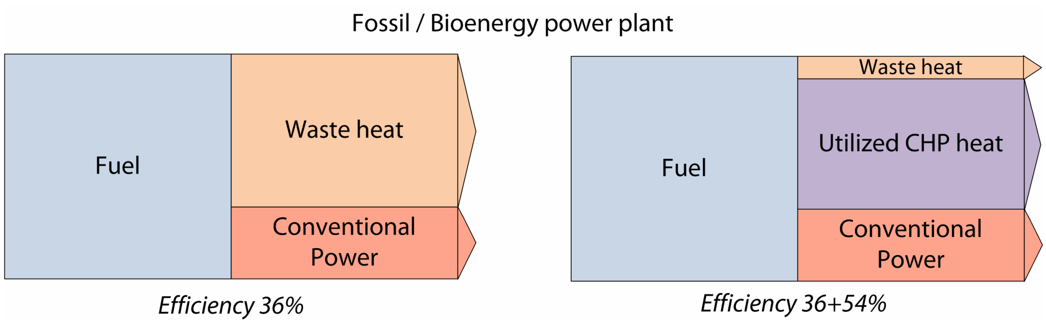

Figure 5.2-1: Element CHP – combined heat and power generation increases fuel efficiency. Source: (Sterner et al., 2008c) in (WBGU, 2009).

5.2.3 *Replacing fossil and nuclear thermal power generation with direct renewable power generation*

Conversion efficiency of thermal power generation is rather poor: 36%; therefore, on average, 64% of primary energy is lost, if waste heat is not used. Power generated directly from wind energy, solar energy (PV and solarthermal), hydro power, and other renewables avoids waste heat and thus contributes to energy efficiency (Figure 5.2-2). Only minor shares of harvested energy are converted to waste heat (e.g. friction losses), why primary energy efficiencies of up to 100% can be used. Since no carbon-containing feedstock is required, direct power generation itself is CO_2 emission-free and more economic than thermal power generation in the long run (Teske et al., 2008). Increasing direct power generation from renewables decreases primary energy demand in the power sector and decreases directly proportional CO_2 emissions in form of fossil fuels.

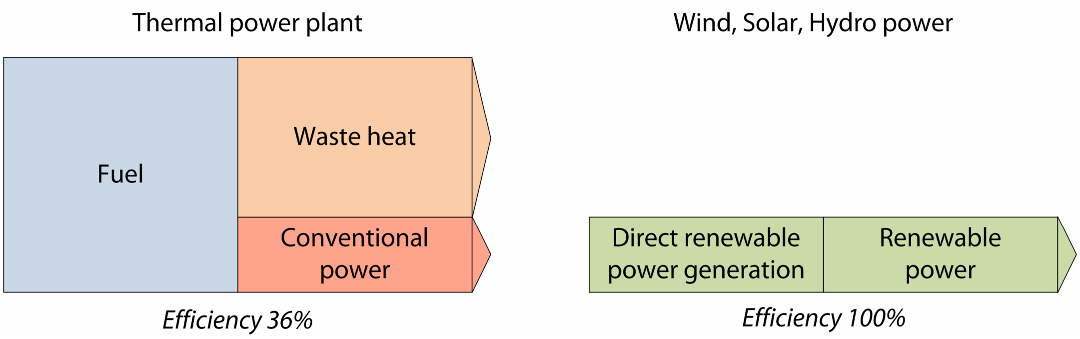

Figure 5.2-2: Element direct power generation – Conversion efficiency of thermal power generation vs. conversion efficiency of direct power generation from solar, wind, hydro and other renewable power. Source: (Sterner et al., 2008c) in (WBGU, 2009).

5.2.4 *Increasing energy efficiency by shifting towards renewable electromobility*

Electromobility can increase efficiency of public and private transport by factor 3-4 (Figure 5.2-3). The present transportation concept based on liquid fuels is highly inefficient. On average, only 18-25% of tanked energy (fuel) can be converted into shaft power in conventional cars with internal combustion engine (ICE). 75-80% of the fuel is waste heat that is not used, apart from a very small fraction used for heating in winter. In contrast, cars with electric engines make use of 75-80% of the tanked energy (power) (Ahmann, 2000; Engel, 2007). High-tech power inverters store and withdraw power in/from the onboard battery with an efficiency of 95%. High performance lithium-ion batteries have storage efficiencies of up to 95% per charge and discharge cycle (Schuh, 7.11.2007). Electric motors obtain efficiencies of up to 90%. The increased vehicle weight by batteries is balanced by less weight of the power train.

The way power for electromobility is generated determines the overall conversion efficiency and GHG balance. If fossil energy is converted with an efficiency of 36% (Figure 5.2-1) and used with 75% in an electric car, the overall efficiency is 27% and thus only slightly higher than a conventional car.

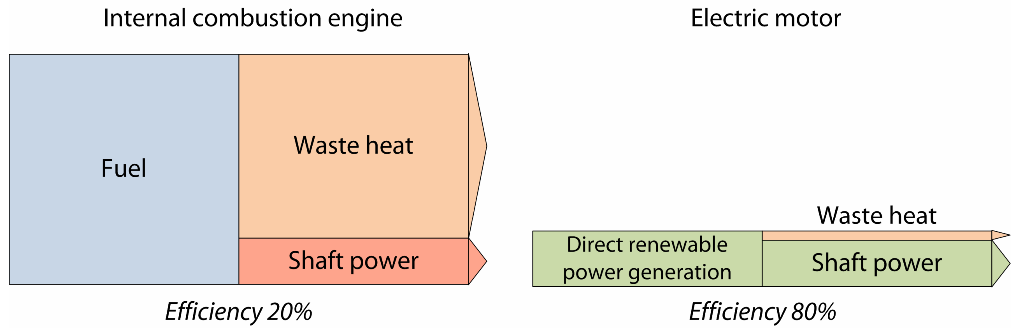

Figure 5.2-3: Element renewable powered electromobility – less primary energy is required by electromobility and the efficiency is three to four times higher than conventional cars with internal combustion engines. Source: (Sterner et al., 2008c) in (WBGU, 2009).

Similarly, the GHG emission balance does not improve much. If power generation is done via CHP and waste heat is used, the overall efficiency is about 80% and the fuel utilization rate of electromobility definitely higher than conventional transport concepts. For these reasons, electromobility is only beneficial if power conversion is more efficient than approximately 35% or its waste heat is used. The combination of electromobility (Figure 5.2-3) and direct renewable power generation (Figure 5.2-2) maximizes the energy efficiency potential of electromobility (Figure 5.2-4) (Sterner et al., 2008b).

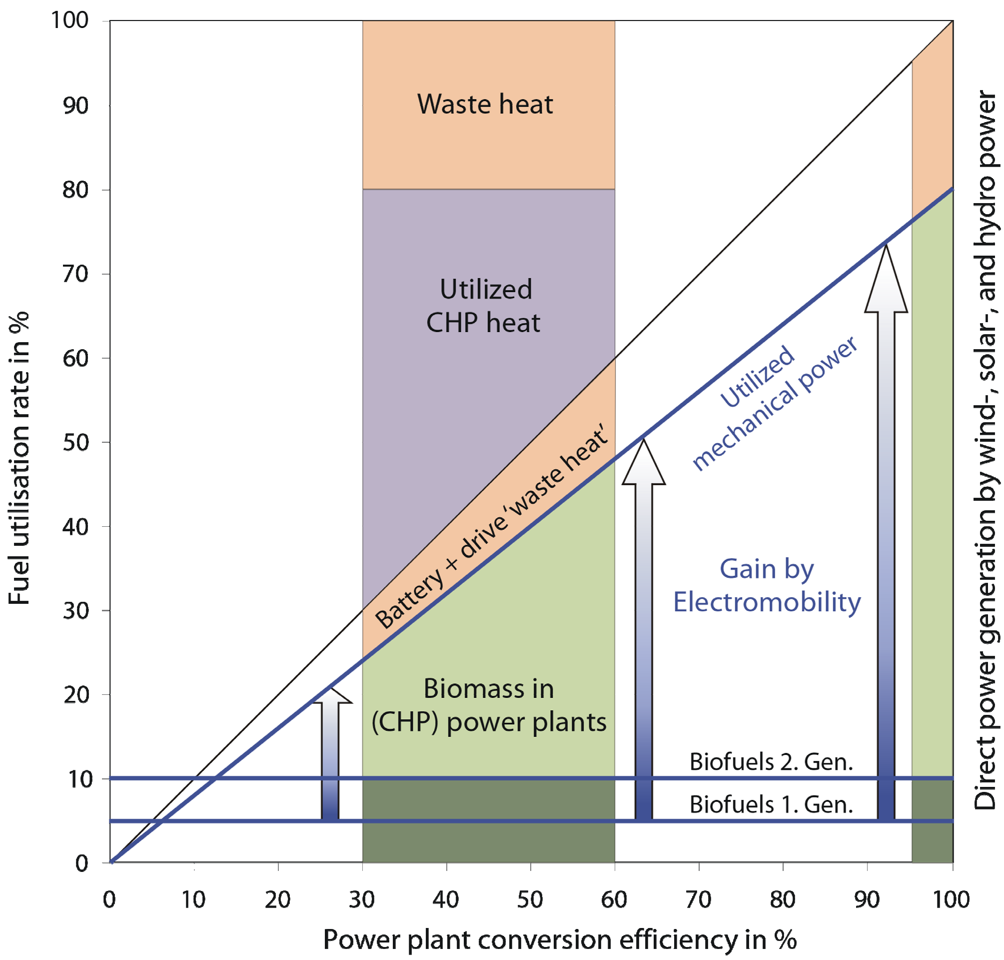

Figure 5.2-4: Comparison of fossil fuels and biofuels with electromobility in relation to the feedstock utilization rate and the power conversion efficiency. Source: (Sterner et al., 2008b) in (WBGU, 2009).

The benefits of stationary power conversion come into effect: waste heat can be utilized, emissions can be reduced and CO_2 sequestration in the combustion process is possible, which is not the case in mobile combustion power trains. In conclusion, environmental problems in large urban communities with high air and noise pollution can be reduced.

Further, electromobility can play a significant role in integrating and balancing fluctuating power penetration of renewable sources like wind and solar energy. Private vehicles are parked up to 90% of daytime. Connected to the power grid and the internet, electric cars can be used today as flexible loads. In ideal case, e-mobility can be used as future power storage devices, whereby the necessity for large power storage facilities won't disappear, as full electrification of transport offers large power potentials (GW) but at a very limited capacity (TWh): e.g. even 45 million e-cars in Germany with a storage capacity of 10 kWh_{el} (0.45 TWh_{el}) could sustain power supply (average load 70 GW_{el}) for only 6.4 hours.

Due to 3-4 times more efficient electric power trains, electromobility outperforms conventional internal combustion engine (ICE) concepts at the same primary energy input. Figure 5.2-5 shows the range of an automobile using one kWh of primary energy in different power train concepts (Sterner et al., 2008b).

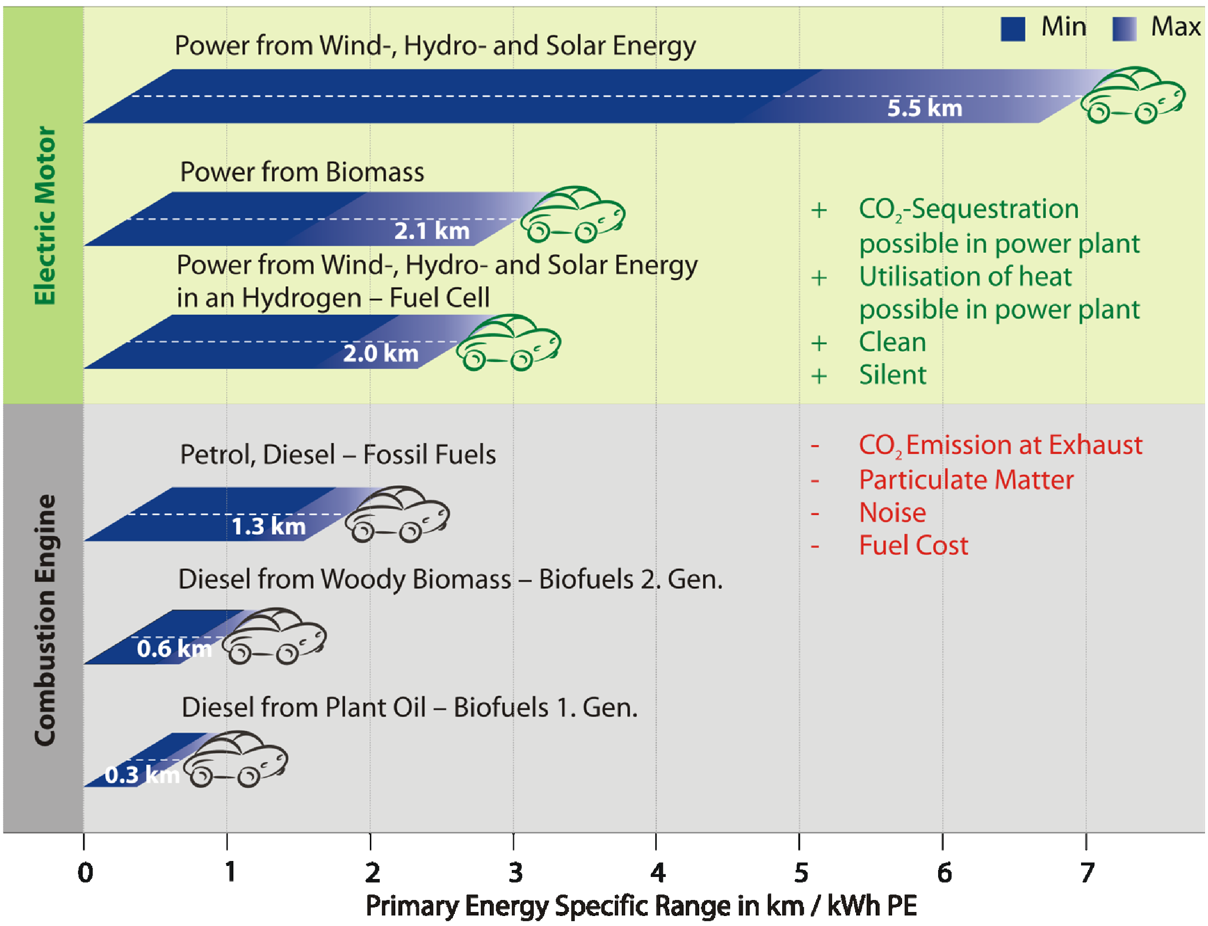

Figure 5.2-5: Comparison of the range of a car related to one kWh of primary energy (PE). The following assumptions were used: energy consumption of the electric car 15–22 kWh_{el} per 100 km, ICE car 60-80 kWh_{th} per 100 km. More details are found in the source: (Sterner et al., 2008b) in (WBGU, 2009).

Electromobility, especially in combination with CHPs and renewable power generation, brings a considerable energy efficiency potential to the transport sector and is one key element of the transition towards sustainable energy systems. E-mobility and hybrid cars will play a key role in the reduction of the transport sector's emissions (IPCC, 2007e).

5.2.5 Providing heating and cooling energy with less energy by using ambient heat via electric heat pumps

Renewable powered heat pumps can increase efficiency of heat supply by factor 2-4 in using ambient heat, i.e. reduce the primary energy consumption of heat supply by using ambient heat. Conventional heating systems with oil and gas have a conversion efficiency of 70–110%, related to the lower heating value (condensing boiler technology) (BHD, 2008). More heat can be provided by electric heat pumps that use ambient heat – which is free of charge – and elevate its temperature level to 50-80°C. A characteristic parameter of heat pumps with similar function like 'conversion efficiency' is the 'coefficient of performance' (COP). COP is calculated as the benefit/effort ratio of useable heat to the energy consumption of the compressor (DIN, 2008a, DIN, 2008b; VDI, 2009). With an average COP of 3.5, 1.0 kWh_{el} electricity can provide 3.5 kWh_{th} heat, whereby 2.5 kWh_{th} are supplied by ambient heat (Figure 5.2-6) (Baumann et al., 2006).

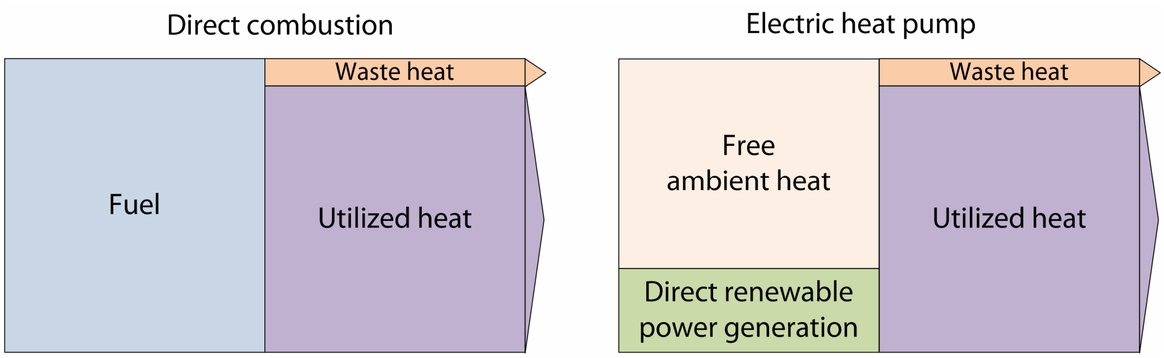

Figure 5.2-6: Element renewable powered heat pumps – heat pumps use free ambient heat and provide thus more heat with less primary energy than fossil heat supply via direct combustion. Source: (Sterner et al., 2008c) in (WBGU, 2009).

However, for the overall annual energy balance, not only the COP is relevant but also the seasonal performance factor. High overall seasonal performance factors can be achieved by a well-designed integration of heat pumps in heating systems. To operate heat pumps in an optimum energy efficient way, its operation has to be adopted individually, considering relevant parameters like the energy consumption of auxiliary devices, the heat source temperature, the difference between supply and return temperatures of the heating system and their variations during the year plus the buildings thermal inertia itself (VDI, 2009). To simplify further calculations, only the COP is used in this work.

Similar to electromobility, the overall effect of heat pumps is determined by the way, electricity for heat pumps is generated. Heat pumps are in general not more efficient than fossil heating systems, which is illustrated in the following example.

If one kWh of fossil energy or bioenergy is converted with an efficiency of 30% to 0.3 kWh_{el} and used in a heat pump with a COP of 3.5, 1.0 kWh_{th} heat can be supplied and the overall effect of using heat pumps is zero. As conversion efficiency is increased by using combined cycle power plants with efficiencies of up to 60%, 2 kWh_{th} can be supplied. If waste heat of thermal power generation is used for district or process heat, the overall fuel utilization rate can be raised too. Again, the combination of direct renewable power generation (Figure 5.2-2) and heat pumps (Figure 5.2-6) maximizes the use of ambient heat and minimizes the primary energy demand for heat.

Heat pumps can also be used for process heat applications (high temperature heat pumps) or cooling and air conditioning in countries with high ambient temperatures. An integration of heat pumps in ventilation technology is possible (Schwarz, 20.12.2008).

Heat pumps can be included in an efficient demand side management to improve the integration of renewable power generation into the energy system. Power supply for heat pumps can be decoupled from heat demand by using thermal heat storage devices like large well-insulated water tanks. In this way, surplus power from wind or solar energy can be utilized in the heat sector, which otherwise would be dumped due to power grid stability. Similar to renewable electromobility, heat pumps can be integrated in an intelligent, smart energy management. The overall effect of electric heat pumps is improving constantly with higher shares of renewable power in the power mix.

Further, heat from geothermal energy can be provided directly or via CHP heat from geothermal power generation.

5.3 Transformation towards sustainable energy systems

The transformation applied for energy systems in this thesis is a combination of the main results of the role of bioenergy in energy systems of chapter 3.2, the newly developed renewable power methane concept of chapter 4, the five steps to energy efficiency in chapter 5.2 and various renewable power grid integration options like super smart grids in chapter 5.3.1. In a top-down approach, three variations of 100% renewable energy system structures are established and the transformation outlined accordingly. These blueprints for energy structures apply to industrialized regions and nations and also for emerging nations. Sustainable future energy systems for rural regions in developing countries, mainly to overcome traditional biomass, are discussed in chapter 3.2.2. However, in the overall transformation in chapter 5.3.3 and 5.3.4, traditional biomass is included and variation 2 of the following 100% renewable energy structures also applies for rural regions without major energy networks.

5.3.1 Super smart grids, grid integration tools, virtual power plants and energy management

Since the beginning of electrical power supply, the system was designed, operated and optimized to the flexible power demand. From now on, the system needs to be optimized to the flexible power supply as well. Thus, 'energy management' has to be done on both sides. According to the North American Electric Reliability Corporation, there are fundamental changes ahead "the way the system is planned, operated, and used – from the grid operator to the average residential customer" (NERC, 2009).

Prerequisite strong, intelligent and interconnected energy networks – super smart grids and virtual power plants

The transformation of energy systems requires more flexible and stronger networks of electricity, district heat and natural gas. Especially the power network needs to be extended to a so called 'super grid' to enable an efficient integration and distribution of renewable power (SmartGrids TP, 2008). Connecting offshore wind power or solar power from the Mediterranean region with the pumped hydro storage capacities in Scandinavia could supply Europe with economic renewable electricity (Czisch, 2005). However, not only the capacity and interconnections between these networks have to be enhanced; also, the information exchange and real-time availability of energy flow states of consumption, storage capacities and demand. 'Smart grids' are required (European Commission, 2005; VDE, 2008b). The increasing number of distributed generators requires new grid control approaches. In combination as virtual power plants, distributed generators can supply ancillary services like conventional power plants (Braun, 2009; Degner et al., 2006). Future electricity networks with decentralized power generation will have a different design than today's grids (Figure 5.3-1). Adaptive grid protection and management technologies will be required that manage faults like short circuits locally in the low voltage grid (Shustov, 2009).

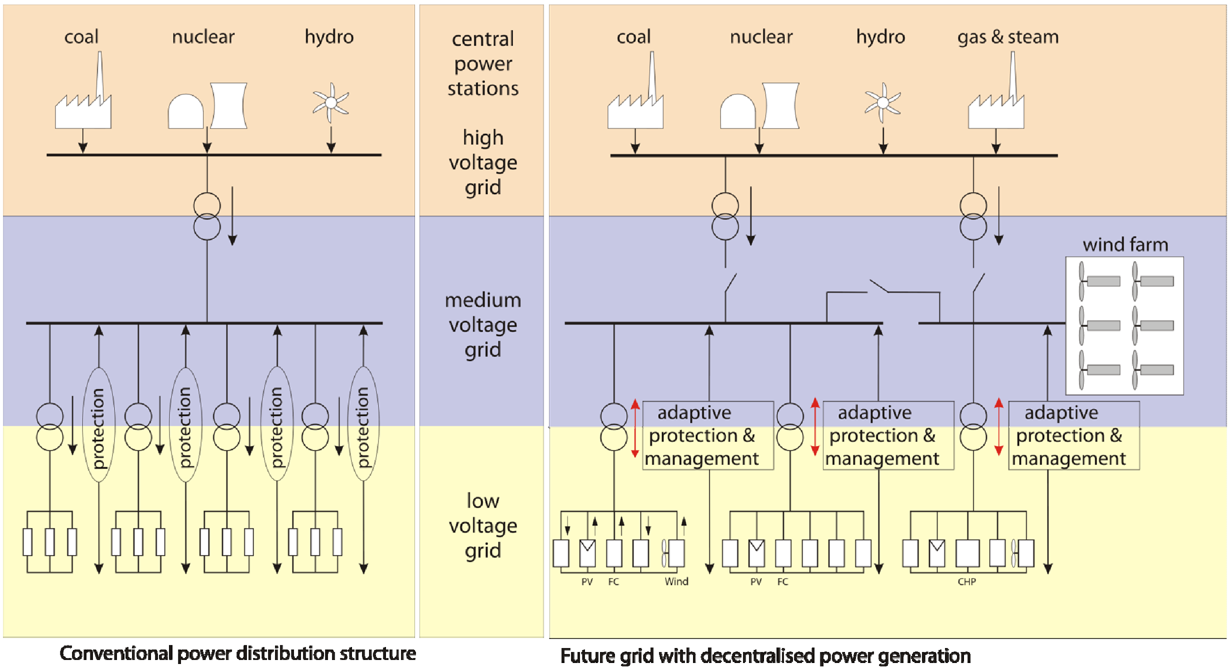

Figure 5.3-1: Difference between conventional and future power distribution structures with decentralized power generation. Source: adapted from (Shustov, 2009).

Combining renewable power generation with storage capacities, strong networks, and energy management enables a 100% renewable power supply. First demonstration projects have been successfully conducted, controlling wind farms, solar PV parks, biogas plants, pumped hydro storage in real-time, covering Germanys electricity demand (Mackensen et al., 2008). Energy storage will be an important component but not erase the need for network expansion (Leonhard et al., 2008). Vice versa, an ideal power network is not sufficient for an economic full renewable power supply and does not erase the need for storage facilities (von Bremen, 2009).

Applying existing renewable energy integration technologies – renewable power forecasting, cluster management and demand side management

Renewable power forecasting is an important element for the control of virtual power plants and energy management systems (Rohrig, 2004). Using data from weather predictions, the penetration of renewable power (wind, solar) is forecasted day-ahead or short-term (4h or 2h) by using artificial neural networks (von Bremen, 2008). The day-ahead forecast of wind power has a forecast error of 5.5%. That means that 94.5% of wind power generation can be predicted reliably, which facilitates wind power integration significantly (Wessel, 08.11.2008).

Geographical distributed wind farms can be aggregated to wind farm clusters, e.g. one cluster for every transmission system node. Such clusters can be built also from PV systems and support the transmission system operator in stabilizing network operation tasks. First field tests are conducted in Portugal and Spain. Cluster management enable the supply of active power control for e.g. congestion management, reduction of gradients, balancing power and the supply of reactive power control for e.g. voltage control by renewable distributed generators (Wolff et al., 2009).

Managing energy demand and supply by an intelligent information exchange

Conventional power supply structures do not interfere with the energy demand side. In future power systems, energy management and communication interfaces (smart grids) are important features to match fluctuating power supply with power demand.

Households can be connected via a bidirectional energy management interface (BEMI) at the distribution grid level and manage energy consumption and optionally installed distributed generators (PV systems, small CHP). Pilot BEMIs run in laboratory and field tests. By applying such an energy management, the share of renewable energy can be increased and energy demand reduced by up to 30% (Nestle, 2008).

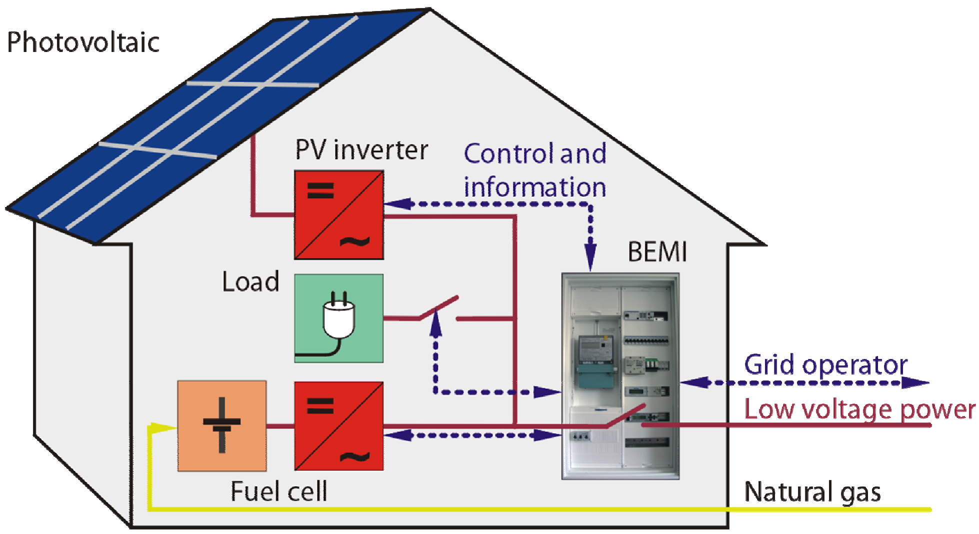

Figure 5.3-2: Laboratory operation of the bidirectional energy management interface to enable smart energy use and demand side management at the household level. Source: (Nestle, 30.06.2009).

5.3.2 *Blueprints of sustainable integrated energy system structures*

The fundament for all three outlined energy systems is an interconnected, intelligent energy network, combining electricity, natural gas, and district heat networks. All three networks have storage capacities and are in continuous information exchange. The electricity network is equipped with power generation and energy management technologies.

Variation 1: 100% carbon-free renewables without bioenergy

Exclusively carbon-free renewable energy sources cover the total energy supply (Figure 5.3-3). Applying CCS would enable a full renewable energy supply system that acts even as a carbon sink. A part of the CO_2 can be recycled within the energy system.

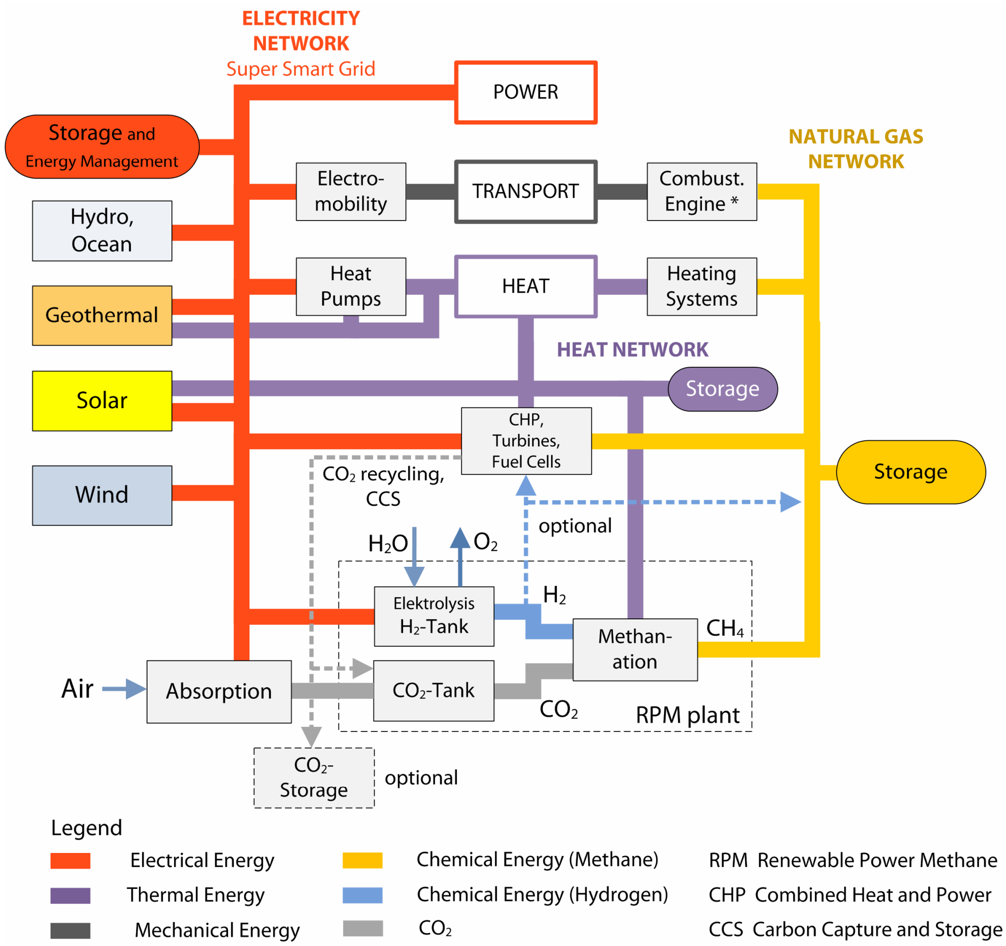

Figure 5.3-3: Blueprint of a sustainable energy supply structure in industrialized regions and nations – Variation 1. Based on the interconnection of electrical, thermal and chemical energy networks with information networks, energy management (supply and demand side) and storage capacities, (fluctuating) renewable energy supply can be matched to the fluctuating energy demand. CO_2 is recycled via renewable power methane that is used as balancing power, for special transport segments (aviation, navigation, heavy-duty; * also via other renewable fuels derived from H_2 and CO_2) and heat supply. Passenger transportation is done via electromobility. Most of the heat supply is covered by CHP heat, geothermal and solar thermal energy; the rest (process heat) by RPM. Source: own compilation.

Balancing power is provided by direct power storage capacities (e.g. pumped hydro storage) and renewable power methane (RPM) via electrolysis (negative balance) and gas power plants or CHPs (positive balance and reserve power) (see also chapter 4.4.2). RPM serves also all segments in heat supply (e.g. process heat) that cannot be covered by CHP heat, geothermal and solar energy. Passenger transportation is covered widely by renewable electromobility. Special transport segments are served by RPM (which can be compressed or liquefied) and other fuels derived from H_2 and CO_2 (e.g. renewable kerosene). These renewable fuels from renewable power are used for aviation, navigation and heavy load traffic or as range extender in hybrid vehicles.

This variation corresponds to the final, third stage of sustainable biomass application, whereby all biomass is used for material use as carbon-containing feedstock to substitute fossil feedstocks with biomaterials (chapter 3.2.1.3).

An alternative would be the use of pure hydrogen and the establishment of a hydrogen network. One benefit is the higher overall efficiency, since methanation losses can be avoided. Drawbacks are that neither distribution network, infrastructure (metering) nor final energy consumer products are existent and hydrogen is more difficult to handle and store than methane. Further, methane has a volumetric energy density that is three times higher than hydrogen and therefore requires less storage space, i.e. caverns. In addition, RPM relaxes competition on underground sites (CCS, hydrogen, geothermal, compressed air, gas), as both CO_2 and energy (H_2) can be stored as gas at the same time.

The ‘renewable power methane’ concept has to deal with the same problem in terms of low utilization rates when methane generation is only used to cap surplus renewable power peaks (chapter 4.4). Therefore, optimum operation concepts are to be verified.

In contrast, the main advantage of renewable power methane is that it is compatible with current gas networks and gas devices. However, the benefit of higher conversion efficiencies can be utilized by blending a certain percentage of hydrogen into the methane network (e.g. < 5 vol%), which is still compatible with gas end user devices. If hydrogen technology becomes available and cost-effective in the far future, the methanation units can be decoupled from the RPM plants and part of the hydrogen infrastructure is already established in the form of decentral electrolyzers.

Variation 2: carbon-free renewables with low-carbon bioenergy

Variation 2 is much the same like variation 1 with the difference that bioenergy is used in three to four applications: (i) for heat and power supply via direct combustion in steam power plants; (ii) for biomethane via gasification and fermentation, integrated into an RPM plant; (iii) for special transport segments as biofuels via extraction and fermentation, and (iv) optionally in rural areas for heat supply to overcome traditional biomass use. An advantage is the good integration of biofuels in current transport infrastructure and technology (airplanes, ships, etc.), similar to renewable kerosene.

Bioenergy is converted into renewable methane using renewable power hydrogen and serves as balancing power, and for aviation, navigation, and heavy-duty tasks or range extender in hybrid vehicles. Surplus oxygen from electrolysis can be used as gasification agent in biomass gasification. Variation 2 corresponds to the second stage of sustainable biomass application (chapter 3.2.1.3).

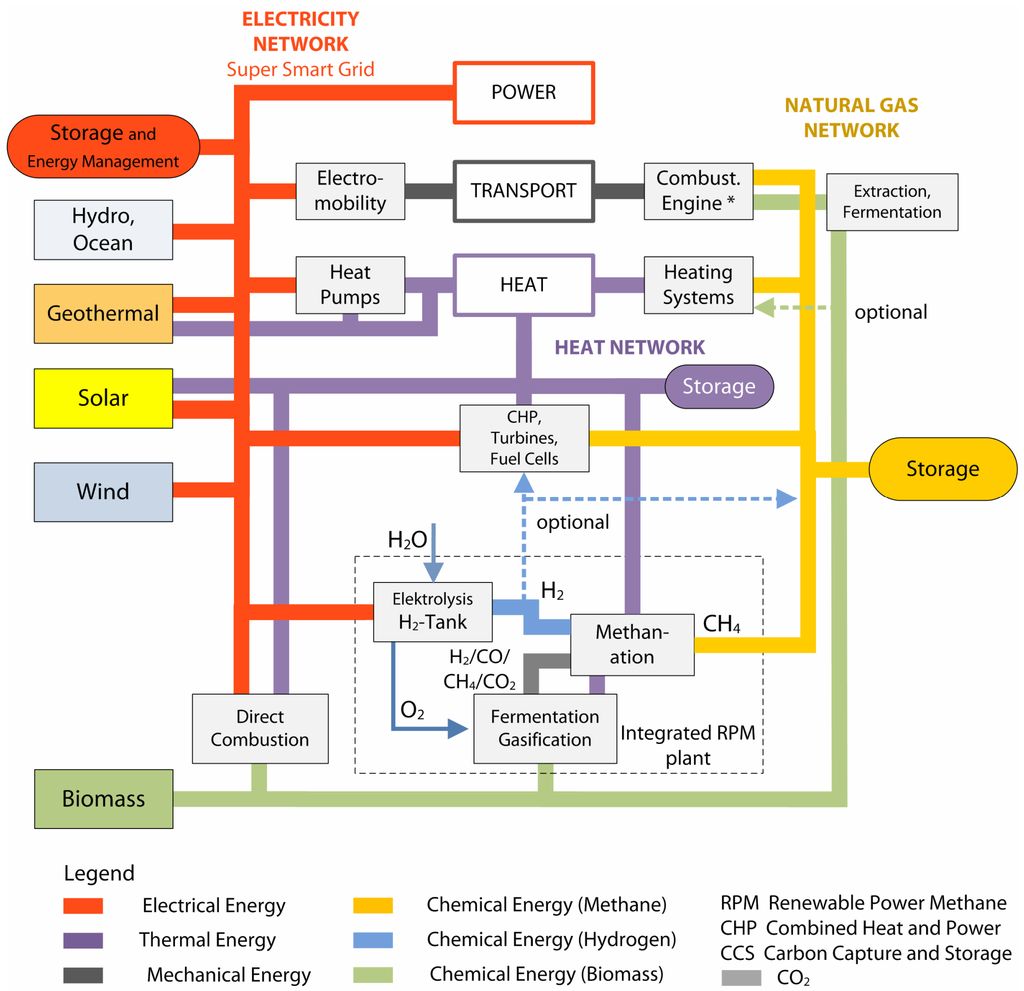

Figure 5.3-4: Blueprint of a sustainable energy supply structure in industrialized regions and nations – Variation 2. Based on the interconnection of electrical, thermal and chemical energy networks with information networks, energy management (supply and demand side) and storage capacities, (fluctuating) renewable energy supply can be matched to the fluctuating energy demand. Biomass is gasified or fermented into a synthetic gas that is converted into methane using renewable power hydrogen from electrolysis and oxygen as gasification agent. Optionally, biomass is used in rural areas for heat supply to overcome traditional biomass use. Renewable methane is used as balancing power, for transportation and heat supply. Biofuels and renewable methane (* and also via other renewable fuels derived from H_2 and CO_2) supply special transport segments (aviation, navigation, heavy-duty). Passenger transportation is done via electromobility. Most of the heat supply is covered by CHP heat, geothermal and solar thermal energy; the rest (process heat) by RPM. Source: own compilation.

Variation 3: 100% carbon-free renewables with CCS-bioenergy from residues

Figure 5.3-5 shows variation 3, which is a mixture of Variation 1 and 2. All bioenergy (preferably residues) is converted into biomethane, because part of CO_2 can be recycled in this way. Biomethane is used preferably in CHP, since this is the most efficient application for bioenergy. In the same way, coal power plants and other fossil power generation facilities can be integrated into the transition phase too. Optionally, CO_2 can be sequestrated from the CO_2 recycling loop and thus a carbon sink can be created. O_2 from RPM production can be used for combusting RPM and facilitate CO_2 recycling.

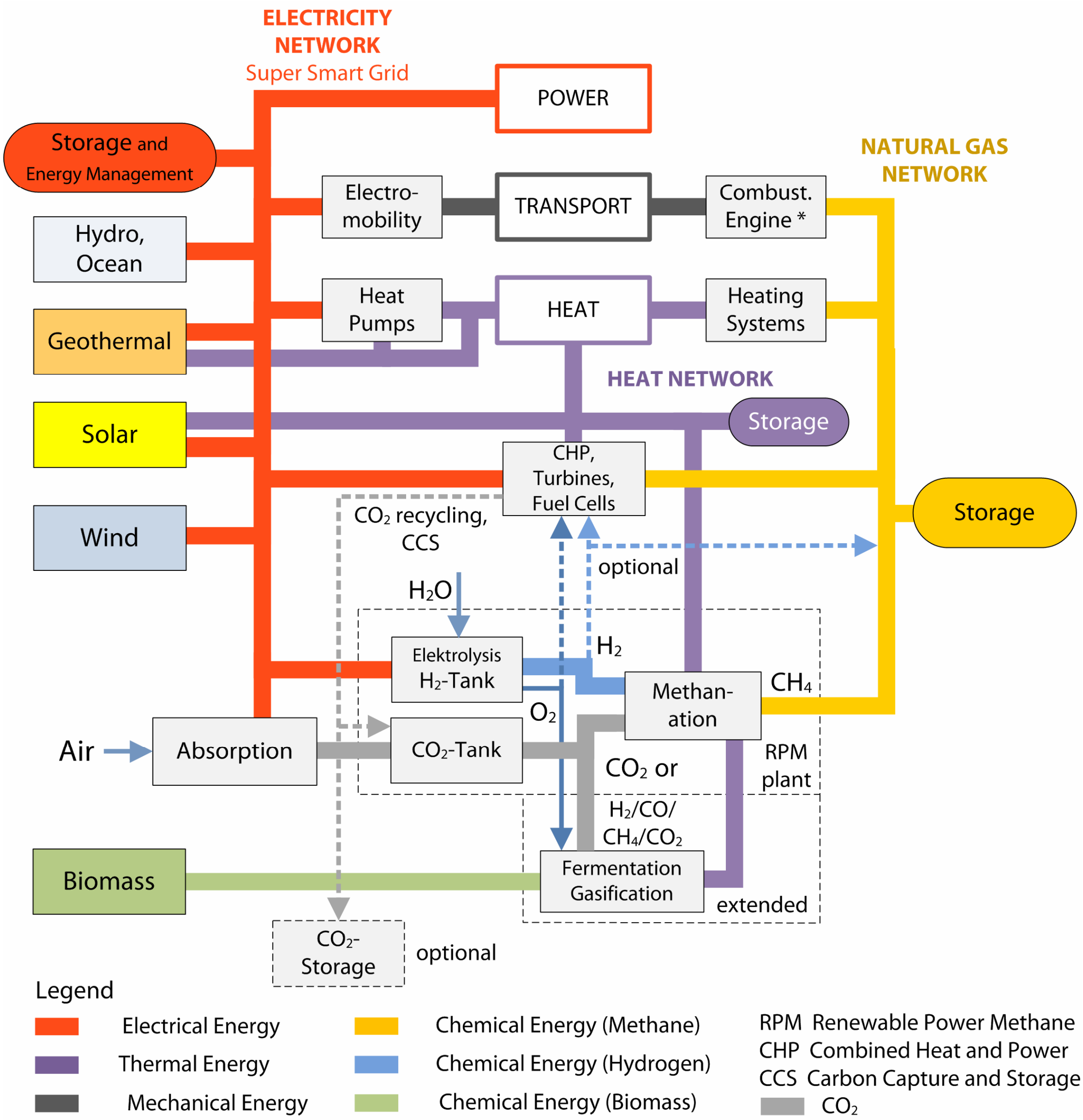

Figure 5.3-5: Blueprint of a sustainable energy supply structure in industrialized regions and nations. Based on the interconnection of electrical, thermal and chemical energy networks with information networks, energy management (supply and demand side) and storage capacities, (fluctuating) renewable energy supply can be matched to the fluctuating energy demand. A part of the CO_2 is recycled via renewable power methane that is used as balancing power, for special transport segments (aviation, navigation, heavy-duty; * also via other renewable fuels derived from H_2 and CO_2) and heat supply. CO_2 is extracted from the atmosphere or from biomass, optionally withdrawn from the CO_2 recycling loop, and stored permanently. Biomass is converted into renewable power methane in an extended RPM plant. Passenger transportation is done via electromobility. Most of the heat supply is covered by CHP heat, geothermal and solar thermal energy, the rest (process heat) by RPM. Source: own compilation.

5.3.3 *Transforming the system by applying 100% renewables and energy efficiency in all energy sectors*

Variation 3 '100% carbon-free renewables with CCS-bioenergy from residues' is chosen as an example for the transformation of energy systems, with the modification of integrating traditional biomass use like it is done in variation 2. The transformation results are similar for variation 1 and 2. To avoid land-use competition on food and material use; energy crops and surplus forestry are excluded from the assumed bioenergy potential. Thus, only residues (a small sustainable technical potential of 10 EJ yr^{-1}) are used as bioenergy for biomethane in combination with CO_2 recycling and storage in the transformation towards sustainable energy systems. Traditional biomass (about 45 EJ yr^{-1}) is assumed to be replaced by 3-4 times more efficient modern bioenergy use (10 EJ yr^{-1}) and other renewable clean energy technologies. In a first approach, final energy demand is assumed to stay constant to illustrate the effect of energy efficiency and the transformation itself, i.e. energy savings in the power sector are estimated at 10%, in the heat sector at 20% and in passenger transportation at 10% by methods described in chapter 5.2.1. In addition, GHG emission reduction by CCS is not considered in this subchapter.

Power sector

The key elements in the transformation of the power sector are

- energy savings in industry, services and households (10%) (chapter 5.2.1)
- increase of combined heat and power generation (chapter 5.2.2)
- increase of direct renewable power generation (chapter 5.2.3)
- use of sustainable bioenergy (10 EJ yr^{-1} of residues) as biomethane / renewable power methane (chapter 3)
- renewable power balancing, energy storage and supply of process heat and special transport segments with renewable power methane concepts (chapter 4)
- intelligent, interconnected, integrated energy networks (previous chapter)

Grid operation stability and balancing power will be supplied by imported renewable power via the super grid and renewable power methane, flexible biomass like biomethane or biogas in gas turbines, combined cycle power plants, small and medium CHPs or fuel cells (see chapter 5.3.2). Grid stability is also supported by direct renewable power itself (wind, solar, hydro) via smart power electronics and well designed generators. Surplus renewable power that is not feasible to convert into renewable power methane is exported to high electricity demand regions or stored e.g. in pumped hydro power.

An increased power demand will arise from providing energy for transport (electromobility, chapter 5.2.4), for heat (heat pumps, chapter 5.2.5) and renewable power methane that is assumed to compensate the effect of energy savings and increase overall power demand due to power consumption in heat and transport.

Transforming the power sector towards sustainability has a large impact on energy efficiency and GHG reduction, as this sector causes the largest amount of GHG emissions among energy sectors and shows large efficiency potentials (Figure 5.3-6).

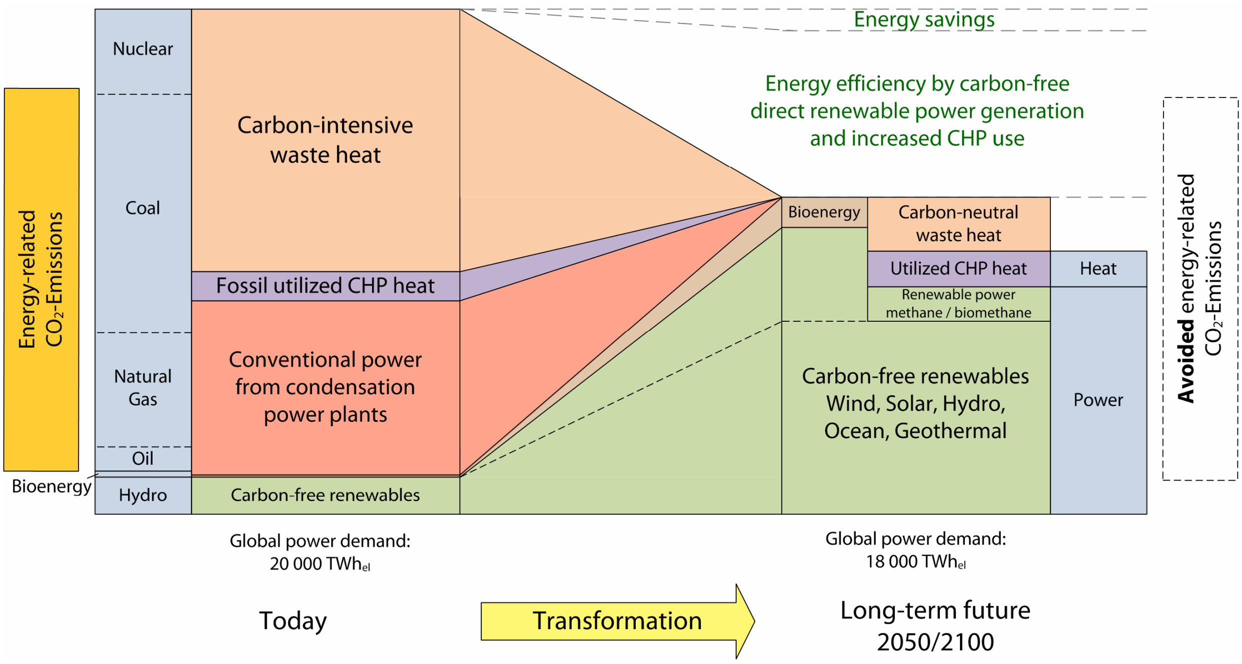

Figure 5.3-6: Transformation of the power sector, energy use for global power generation – increasing direct renewable power generation for direct use and renewable power methane production and energy savings can eliminate energy-related GHG emissions. Carbon neutral balancing power can be provided by renewable power methane and flexible biomass like biomethane from residues. Energy networks (power, gas, heat) will be interconnected and made ‚intelligent' by information exchange. Source: own compilation, based on today's data of (BP, 2009; REN21, 2008b; Teske et al., 2008).

A simulation of a 100% renewable power supply in 2050 with high temporal resolution (1h) for Germany is carried out in the outlook (chapter 6.2 and Annex A1), based on data from the 'lead scenario' on annually generated electricity (Nitsch, 2008). This simulation shows, that a full renewable power supply is possible and renewable power methane, flexible biomass plants and renewable power imported via the super grid can balance fluctuating generation and ensure grid stability and reliability of supply.

Heat supply

The key elements in the transformation of the heat supply system are

- energy savings in industry, services and households (chapter 5.2.1)
- increase of combined heat and power generation (chapter 5.2.2)
- increase of geothermal energy (direct, CHP heat and heat pumps) (chapter 5.2.3)
- increase of solar thermal energy

- renewable power methane for the rest of heat supply (e.g. process heat), that cannot be covered otherwise with renewable power methane concepts (chapter 4)
- overcoming traditional biomass (chapter 3.2.2) by clean renewables and sustainable bioenergy heat (10 EJ yr^{-1})

Solar thermal energy is an important element in the transformation of the heat sector. Solar thermal systems are integrated into heating systems and widely used for hot water supply. They are also increasingly used for process heat (Schmitt et al., 2008). Heat pump systems have interfaces for demand side management and store surplus renewable power as thermal energy. Furthermore, other devices like small CHP and integrated power heaters can serve for the energy management (Sievers et al., 2007). In addition, geothermal heat is used directly and as CHP heat from geothermal power generation. The development of district heat networks enables an amplified use of CHP heat. A further option for sustainable heat supply is the use of renewable power or renewable power methane for process heat.

Fossil fuels in heat applications are assumed to be used with an efficiency of 90%. The combination of these key elements and networks enables an efficient and almost emission-free heat supply (Figure 5.3-7).

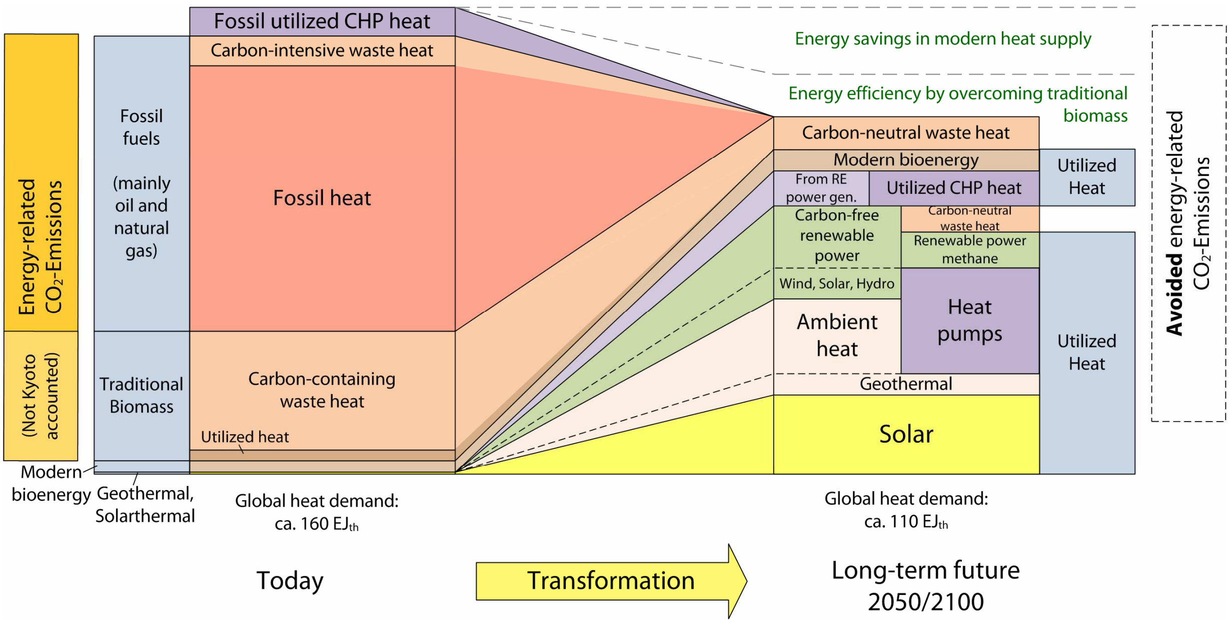

Figure 5.3-7: Transformation of the heat sector, energy use for global heat supply – combining CHP heat networks, geothermal and solar energy with energy savings lowers the primary energy demand and replaces finite fossil fuels, avoiding GHG emissions. Traditional biomass with an efficiency of 8% is replaced by modern bioenergy with 40% efficiency and other clean renewables. Source: own compilation, based on today's data of (BP, 2009; REN21, 2008b; Teske et al., 2008)

Transport sector

The key elements in the transformation of the transport sector are

- energy savings (chapter 5.2.1)

- (renewable) electromobility (chapter 4.2.4)
- hydrocarbons from renewable power, e.g. renewable power methane (chapter 4)

Oil is the predominant fuel in transportation. Most of the energy currently used for mobility is left to the atmosphere in the form of waste heat.

In the medium term, energy savings show the largest efficiency and GHG reduction potential as dependency on fossil fuels is rather high. Passenger transportation (cars, busses, tram, trains) will be done predominantly by electromobility, which is powered increasingly with renewable energy and thus becomes more and more emission-free. Electromobility is assumed to cover 60% of transport energy demand, predominately passengers traffic but also trucks. Nevertheless, electric hybrid vehicles will have range extenders, which are assumed to require 10% of the total transport energy demand. This demand for a transport fuel with high energy density will be covered by renewable power methane and other renewable fuels derived from H_2 and CO_2.

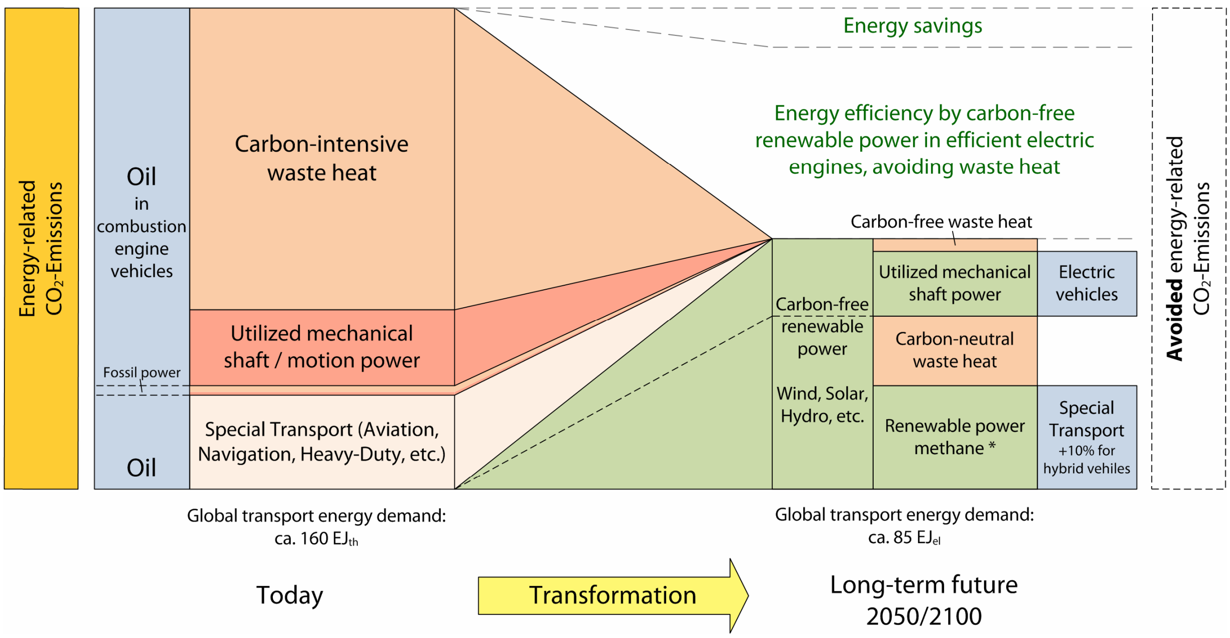

Figure 5.3-8: Transformation of the transport sector – energy savings, electromobility and renewable power methane enable carbon-neutral mobility. Long distances (aviation, navigation) and heavy-duty task (special transport segments) are covered by renewable power methane (RPM) * plus other renewable fuels derived from H_2 and CO_2 or as supplement to a small extent by sustainable biofuels from residues and waste in conventional engines. RPM serves also as range extender in hybrid vehicles. Source: own compilation, based on today's data of (BP, 2009; REN21, 2008b; Teske et al., 2008).

Beside electromobility as core element in the transition, special transport segments like aviation, navigation and heavy-duty tasks are powered by renewable power hydrocarbons, e.g. methane, ethanol, methanol, kerosene, DME from wind and solar power. As supplement, sustainable biofuels like Fischer-Tropsch kerosene from residues can also serve for these functions. The special segments are assumed to require 30% of the transport energy demand. The transformation of the transport sector enables an emission-free mobility (Figure 5.3-8).

Future energy mix – efficient and GHG emission-free – cumulated values

The global primary energy demand can be met by renewable energy sources in all energy sectors. If current developments continue, wind could be the predominant source.

More than 50% or 250 EJ yr^{-1} of today's global primary energy supply is not used and waste heat; i.e. half of global primary energy causes significant costs and CO_2 emissions without any benefit or use.

This large inefficiency due to thermochemical conversion 'losses' can be overcome by the large scale deployment of carbon-free renewable energy. Direct renewable power generation from wind, solar, hydro, and ocean energy is avoiding these thermodynamic conversion 'losses'. After the transformation, only 22% of total primary energy is waste heat, mainly from converting renewable power to methane or other renewable fuels (Figure 5.3-9).

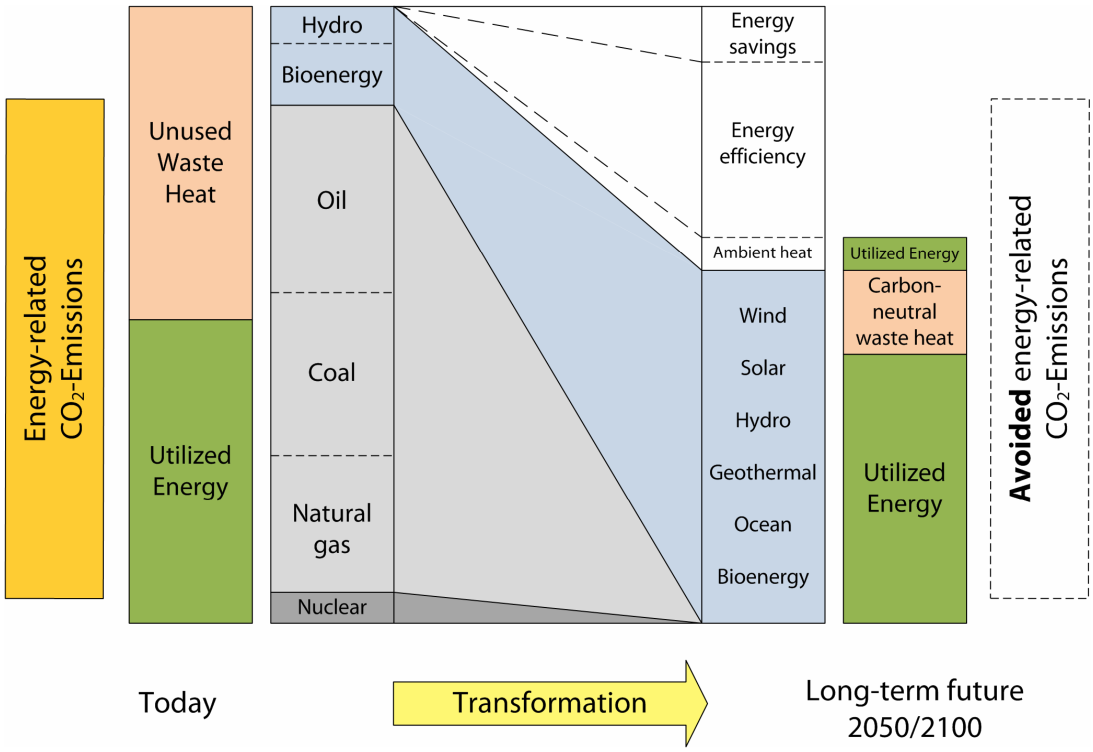

Figure 5.3-9: Transformation of global energy systems – by tapping the full potential of energy efficiency measures, global energy demand can be reduced significantly and energy-related GHG emissions avoided. Main efficiency measures are energy savings, direct renewable power generation, electromobility, heat pumps for using ambient heat, other renewables, renewable storage capacities, renewable power methane, CHP application, interconnection of intelligent energy networks, etc. The smallest contribution in renewable energy supply is coming from sustainable bioenergy, using only residues of 20 EJ yr^{-1} for biomethane and modern bioheat applications like improved cooking stoves. Source: own compilation, based on today's data of (BP, 2009; REN21, 2008b; Teske et al., 2008).

Sensitivity of energy demand assumptions

The assumption of constant energy demand is very optimistic regarding historic energy demand increases (BP, 2009). The power demand is likely to increase due to a shift towards electricity in heat and transport sectors, which is now indicated in the respective Figure 5.3-7 and Figure 5.3-8. The heat demand is likely to be reduced by global warming, because less space heating energy is required. However, the cooling demand will increase. In temporal regions like Central Europe, the net effect is likely to be dominated by energy savings from lower heating demands (Petrick et al., 2009).

Once a 100% renewable energy system is implemented, increasing energy demands to not cause harm to the climate, as the energy supply is almost emissions-free.

Costs of transformation

The initial costs for this transformation are immense at first, but feasible in the long run as external costs of fossil and nuclear fuels are avoided. Hydro and wind power are already competitive with fossil fuels. Other renewable sources like solar, geothermal, bioenergy or ocean energy are likely to become competitive with economy-of-scale effects and rising fossil fuel prices. Experience curves show declined costs of wind and solar power with increased cumulative production. In the last decades, these costs where reduced on average by 20% each time the production doubled (Staffhorst, 2007; Durstewitz et al., 2008). As growth rates of wind and solar are expected to be very steep for the next decades, large cost reductions can be expected. At the same time, fossil fuels are getting scare and CCS plus and CO_2 certificates are causing additional costs. These trends increase the costs of fossil energy. Therefore, considering both trends, it is only a matter of time until renewable energy technologies break even.

Time scale

The necessary time for this transformation process determines the carbon emitted. The transformation may take up to 2050 or 2100. The faster it happens, the sooner the climate system can be stabilized. The time scale is relevant for the speed with which energy-related emissions are reduced. The time scale is rather irrelevant for the necessity of the transformation in the long run, as fossil fuels are finite. Consequently, the transformation has to happen anyway. Once the energy system is 100% renewable, higher energy demands do not harm the climate.

5.3.4 Possible emission reductions - keeping the 2°C climate target without nuclear energy and carbon capture and storage by a transformation until 2050

As shown in Figure 5.3-9 for a global scale and Figure 6.2-1 in a case study for Germany, a stable 100% renewable energy supply without endangering supply security is possible. After the transformation, energy-related GHG emissions result merely from small amounts of sustainable bioenergy (20 EJ yr^{-1}) and renewable power methane.

These emissions are carbon-neutral. Compared to that, GHG emissions from solar, wind, hydro power and other renewables only result from their upstream production processes and are negligible, once most of the production is done with carbon-free or carbon-neutral energy.

Thus, it is technically possible to reduce energy-related emissions to ‘zero’ (i.e. more than 95%) without applying fossil carbon capture and storage (CCS) or nuclear energy.

Meeting the 2°C target – sample calculation and discussion of climate mitigation options

Energy-related emissions with minor shares of industry CO_2 account for about 67% (or 33 Gt $CO_{2\text{-eq.}}$) of total current GHG emissions, which are about 49 Gt $CO_{2\text{-eq.}}$. 33% (or 16 Gt $CO_{2\text{-eq.}}$) are from land-use, land-use changes and forestry (LULUCF), i.e. agriculture and forestry.

Current research results indicate that CO_2 is the most crucial GHG as it is mainly fossil and has the longest lifetime in the atmosphere compared to other GHG like methane or N_2O from mainly agriculture and forestry (Allen, 2009; Meinshausen et al., 2009).

In the following sample calculation, GHG emissions from these sectors are assumed to remain constant, as land-use competition is expected to continually cause emission-intensive land-use change. Annual GHG emissions from LULUCF (16 Gt $CO_{2\text{-eq.}}$) will then cumulate to 640 Gt $CO_{2\text{-eq.}}$ between 2010 and 2049.

To keep the 2°C target with a probability of 66%, a cumulated maximum of 1,700 Gt $CO_{2\text{-eq.}}$ are allowed to be emitted until 2050, i.e. the atmosphere cannot take up more CO_2 waste (Meinshausen et al., 2009). About 400 Gt $CO_{2\text{-eq.}}$ have been emitted between 2000 and 2009, assuming an annual emission rate of 44 Gt $CO_{2\text{-eq.}}$. Thus, a budget of 1,300 Gt $CO_{2\text{-eq.}}$ remains until 2050, which is reduced by 640 from GHG emissions of LULUCF down to 660 Gt $CO_{2\text{-eq.}}$ for energy-related GHG emissions.

If the transformation of energy systems starts in 2010 and is extrapolated on a linear time scale until 2049, total energy-related GHG emission will amount to 660 Gt $CO_{2\text{-eq.}}$.

In total, the GHG emission budget will then just not exceed the 1,700 Gt $CO_{2\text{-eq.}}$ limit. This means, completing the transformation of energy systems by 2050 at constant LULUCF emissions, global warming can be limited to 2°C relative to pre-industrial temperatures with a two-thirds probability.

In other words, if the outlined transformation does not happen until 2050, it will not be possible to stabilize the climate system and avoid larger damages by climate change.

Moreover, the scenario assumptions are optimistic, as a linear transformation and a constant energy demand is assumed. As drawback option, CCS can be used optionally in the system to balance higher energy demands or a slower transformation of energy systems. A further option is the reduction of LULUCF emissions by introducing sustainable land-use practices and avoiding climate harming land-use changes.

However, the easiest way to mitigate climate change will remain the application of energy savings and carbon-free renewable energy. LULUCF emissions are difficult to reduce as global population is growing. Clean fossil fuel technologies like CCS are not yet established, no single plant is operating commercially so far, and it takes years to decades until CCS technology is ready-to-use and possible storage sites are tested and authorized. Geoengineering is still at its infancy. Bioenergy can both benefit and harm the climate and is limited by land-use competition. Nuclear energy is a limited resource, contains high operation risks and unsolved problems like proliferation of nuclear weapons and waste disposal. Besides, doubling nuclear energy use reduces the most 4% of today's global GHG emissions in ideal case (see chapter 1.2.3).

In conclusion, the first choice in GHG reduction is the ample use of carbon-free renewables like wind energy, solar energy, hydro power, geothermal energy and ocean energy. Most of these technologies are available, functioning and some (wind, hydro) already competitive on the energy market. Energy savings are the second best choice, since they are quickly compensated by higher energy demands and only profitable for energy customers, not for energy providers, who have been the driving forces in the energy system so far. CCS might become a draw-back option if the development of other mitigation option fails but only half of fossil CO_2 emissions can be captured technically, as the other half are diffuse and mobile emissions. Therefore, CO_2 recovery from the atmosphere might become a necessity and can be integrated a 100% renewable energy supply which acts like a carbon sink (see chapter 5.3.2). In such a way, 'negative emissions' could be created but are hopefully not necessary as renewable energy technologies and energy savings perform sufficient emission reductions.

Sensitivity of total GHG emission results

The sensitivity analysis is done using the 2°C check tool of (Meinshausen et al., 2009).

If the outlined transformation of the energy system was delayed linearly until 2100, energy-related emissions would amount to 1,500 Gt $CO_{2\text{-eq.}}$ plus 1,440 Gt $CO_{2\text{-eq.}}$ of LULUCF emissions in the period of 2010 to 2100. This would cause a dangerous global warming, exceeding the 2°C limit with a 60% high probability.

Increasing the probability of limiting global warming to 75% leaves a budget of 1,500 Gt $CO_{2\text{-eq.}}$ or 1,100 Gt $CO_{2\text{-eq.}}$ for the period of 2010-2049. Subtracting constant LULUCF emissions in this period results in a budget of 460 Gt $CO_{2\text{-eq.}}$ for the energy sector. Then, the outlined transformation of energy systems has to be completed by 2037, which is rather unrealistic.

A reduction of 0.5% of annual GHG emissions in agriculture and forestry sectors by introducing sustainable land-use and avoiding climate harming land-use changes could be realistic. Annual GHG emissions from LULUCF will then be at 13 $CO_{2\text{-eq.}}$ in 2050 and the cumulated value between 2010 and 2049 at 580 $CO_{2\text{-eq.}}$. To keep then the goal of limiting global warming to 2°C with a two-thirds probability, the (linear) transformation of energy systems would have to happen until 2051. These are only 2 years more than without assuming improvements in the land-use sector, where emission reductions are not as simple as in the energy sector.

After all, transforming the energy sector remains the key instrument in mitigating climate change.

6. Summary and outlook

The four main objectives of this thesis were (i) to identify the strategic role of bioenergy in future sustainable energy systems and its potential in climate mitigation; and (ii) to develop new concepts for storing and integrating renewable power generation, and (iii) to design integrated and stable 100% renewable energy systems with emission-free energy sources, and (iv), to analyze the importance and role of the transformation towards 100% renewable energy systems in limiting global warming to 2°C.

6.1 Summary of new scientific results obtained by this thesis

Limiting global warming is possible by the transformation towards 100% renewable energy systems without applying CCS, nuclear energy or geoengineering

A full renewable energy supply of all energy sectors at very low GHG emissions is possible without using nuclear energy and carbon capture and storage (CCS) technology. Applying the described transformation of the energy system can reduce GHG emissions of the energy sector by almost 100%. If CCS is applied in a 100% carbon-free renewable energy supply via renewable power methane, the energy sector can become even a carbon sink by extracting and storing CO_2 from the atmosphere.

Thus, the target of limiting global warming to 2°C can be met by 2050 with a probability of 66%, assuming constant GHG emissions from agriculture and forestry. Delaying the necessary transformation to 2100 can cause severe damages by a non-restricted climate change. The major climate mitigation options are carbon-free renewables and energy efficiency. Using the newly introduced 100% renewable energy supply structures ensures technical supply security and reduces national dependences on energy imports. Further, crude oil is released for material use in industry.

New ‚renewable power methane' concepts enable stable renewable power supply and the use of wind, solar, hydro for long-distance transport and process heat

A key element for the integration of renewable energy into existing supply structures is the 'renewable power methane' concept, which has been developed in this thesis. Carbon-neutral methane ('real natural' gas or renewable fuels) can be produced by using renewable power, water and CO_2 from the atmosphere or other CO_2-neutral sources like industry and biomass. The main conversion steps are hydrogen production by renewable powered electrolysis of water, CO_2 recovery by a combined absorption and electrodialysis, and methanation of CO_2. Renewable power methane (RPM) allows the transfer and storage of renewable power in(to) a natural gas network and the flexible use of RPM in all energy sectors. In the power sector it can be used as balancing power, in the heat supply for process heat and in transportation as a range extender for electric hybrid vehicles or as liquefied renewable power methane and renewable fuels from H_2

and CO_2 (ethanol, DME, kerosene) respectively in combustion engines and turbines for aviation, navigation, long-distance traffic and heavy-duty task. RPM is a carbon-neutral substitute for natural gas that can be produced almost anywhere in the world. In this way, energy demand in industry nations and industrialized regions can be covered 100% by renewable energy sources.

New synergetic concepts have been developed in this work for the integration of renewable power methane plants in biogas plants, biomass gasification plants, coal power plants and natural gas sites, CO_2 intensive industry, landfills and sewage plants. Using concentrated CO_2 from fossil fuels, biomass, waste or industry processes is more efficient than extracting CO_2 from the atmosphere. Nevertheless, atmospheric CO_2 recovery offers the advantages of stand-alone concepts, avoiding long-distance CO_2 transportation.

Competition on underground storage sites by CCS, compressed air storage, hydrogen, geothermal energy, and natural gas can be diminished by using CO_2 from carbon capture for renewable power methane production and its storage in natural gas networks and storage facilities.

Renewable power methane and energy network integration are key elements of 100% renewable energy supply structures

Energy network integration is another key element of sustainable energy structures. Linking heat, electricity, natural gas and information networks enables an efficient, almost emission-free and coordinated use of energy and creates synergy and supply security. Energy management and energy storage facilities (especially long-term energy storage like RPM) will be important elements of future 100% renewable energy structures along with strong energy transmission capacities.

Major further components of renewable energy structures are efficient end user devices, direct power and heat generation from renewable sources, renewable electromobility, heat pumps and combined heat and power generation.

The major role in GHG reduction will be played by carbon-free renewables like solar energy, wind energy and hydro power and energy efficiency measures. Nuclear power plays only a minor role as nuclear fuels are depleting. Doubling the global installed capacity of nuclear power generation in 20 years doubles associated risks like proliferation, nuclear accidents and waste disposals but reduces at the most 4% of today's global GHG emissions given that carbon-free nuclear energy is being used.

Strategic use of sustainable bioenergy for overcoming traditional biomass and climate-friendly energy / material supply avoiding land-use competition and emissions

Bioenergy plays a major role in overcoming inefficient, harmful traditional biomass use that is still the predominating form of global bioenergy use. Modern bioenergy is a key element of sustainable energy supply in rural regions in developing countries as efficiency improvements and GHG reductions can be realized by simple technology at very low cost. Approximately 0.1 to 0.9 Gt $CO_{2\text{-eq.}}$ yr^{-1} can be avoided in this way.

The global sustainable technical bioenergy potential is estimated at 300 EJ yr^{-1}, the economic potential at 150 EJ yr^{-1}. Residues and surplus forestry show similar potentials like energy crops and are less volatile. However, the global bioenergy potential is neither sufficient to fulfill the task of balancing power in a 100% renewable energy supply nor to totally substitute fossil fuels in the transport sector.

There are potential win-win solutions for energy crops in the challenge of land-use competition with food, materials, water and biodiversity. Planting perennials like sweet sorghum or short rotation coppice on marginal or degraded land can have an overall positive effect on carbon stocks, and soil and water quality, and avoids emission-intensive direct and indirect land-use changes as well as displacement risks.

Another way of mitigating land-use competition is the cascade use of biomass: first for material purposes, later for energy purposes. Similar, residues avoid land-use competition and associated GHG emissions, and show therefore better GHG balances and GHG mitigation costs. Therefore, residues are the preferable bioenergy resource.

Bioenergy can accelerate or slow down climate change. On one side, exploring the full sustainable bioenergy potential in combination with low-emission bioenergy pathways, an overall GHG reduction potential of 2.5 to 16 Gt $CO_{2\text{-eq.}}$ per year (5-33% of today's emissions) by bioenergy can be seen. On the other side, bioenergy can amplify emissions from land-use and land-use changes.

The highest GHG reductions can be obtained by bioenergy in CHP applications, especially in substituting coal by co-firing biomass and by using biomethane when storing the separated CO_2. Large biomass heating systems in combination with district heating networks show the lowest (negative) GHG reduction costs. Improved cooking stoves and small biogas digesters enable GHG mitigation at 2-20 EUR t $CO_{2\text{-eq.}}^{-1}$. Direct combustion of biomass and co-fermenting manure shows the highest GHG reduction potentials at highest conversion efficiencies.

Electromobility is the most efficient and most climate friendly form of bioenergy use in transport as long as power and heat sectors are not emission-free or Bio-CCS is necessary. All positive effects of stationary energy conversion come into effect with electromobility, powered by biomass: (i) higher conversion rates are achieved by full-load operation, (ii) waste heat can be used, (iii) by-products like bagasse can be used and (iv) the possibility of future CO_2-sequestration is given. Biofuels in conventional combustion engines are merely suitable for special transport segments like aviation, navigation and heavy-duty tasks like machinery for agriculture, forestry and construction, where electromobility hardly can substitute fossil fuels and energy carriers with high energy densities are required. Oil fruits can be used in this way. All other biomass feedstocks are converted most efficiently to biomethane via gasification and fermentation that can be used flexibly like renewable power methane.

The most suitable parameter for evaluating GHG reduction potentials of bioenergy is the new developed absolute parameter linking GHG reduction to the chemical energy content of raw biomass. Percentual parameters do not reflect the amount of biomass or area used for generating one energy unit to substitute one fossil energy unit. Area-specific GHG reduction indicators have the drawback that hectare yields and heating values of energy crops differ widely, and these indicators can hardly cover the other main biomass source: residues and waste.

Bioenergy and renewable power methane are important elements of future sustainable energy supply. Eventually, the most important strategic function of biomass in the future is the supply of carbon for industry purposes like chemical products (biomaterials) at the time fossil fuels are gone. Energy supply is not bound to carbon and can be derived by other means, especially by renewable power as direct power and as natural gas substitute in form of renewable power methane.

6.2 Outlook on follow-up research topics

This work contributed to the further understanding of possible future sustainable energy systems and solutions for the integration of (fluctuating) renewable energy and sustainable bioenergy.

Simulation, integration and demonstration of renewable power methane concepts

The renewable power methane (RPM) concepts developed in this work require further research. In the methanation of CO_2, optimum catalyst and process parameters (pressures, temperatures, operation times) are to be identified. Costs need further investigation and RPM needs to be benchmarked with other long-term storage options, network expansion and other possibilities of decarbonizing the transport sector. The potential of renewable fuel for transportation from surplus power is to be explored. The demand for balancing power is to be simulated to derive the demand for RPM and optimum operation scheduling for RPM plants needs to be examined. First pilot plants are necessary to receive practical results that can be fed back to simulations.

First simulations are done in this work as an outlook on future research challenges. A possible power mix based on the RPM concept was simulated for Germany in 2050. For this purpose, scenario assumptions of the German lead study 2008 on the 'strategy to increase the use of renewable energy' (Nitsch, 2008) and our Fraunhofer IWES SimEE model introduced in (Saint-Drenan et al., 2009) were used. The model uses for example time series for wind and solar derived from meteorological and hydrological data; in this case 2007 data.

Figure 6.2-1 illustrates the power mix with a 1 h high-temporal resolution for the month of December. The RPM plants were simulated with an installed capacity of 5.4 GW_{el}, operating at least 5400 full-load hours (average 6020 FLh) and minimum 8 h operation for each start up (dark yellow shaded area). RPM is re-converted into power in combined cycle power plants with a 60% conversion efficiency (light yellow) with a installed capacity of gas power plants of about 50 GW_{el}. These high capacities are necessary to provide back-up power and system stability in the high voltage grid.

Balancing power is provided by RPM plants and gas power plants / CHPs with RPM as described in chapter 4.4, flexible biomass plants and renewable power imports via the super grid (mainly from concentrated solar thermal power plants). In this way, power system stability is ensured and a stable 100% renewable power supply is possible.

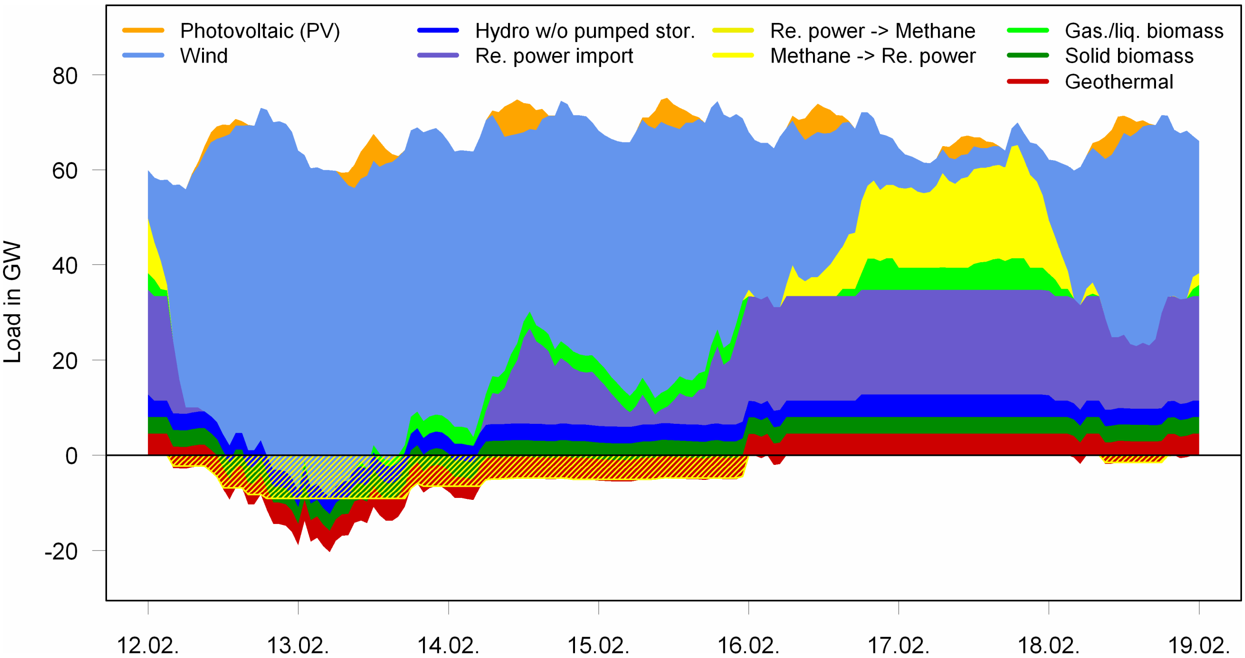

Figure 6.2-1: Time series of 100% renewable power supply of Germany for one week in February 2050 with high temporal resolution (1h). Surplus renewable power (mainly wind) is converted into renewable power methane (RPM) in the first part of the week (hatched dark yellow area below the zero line), stored in the natural gas grid and reconverted into power in the second part of the week where there is only little wind power (bright yellow area). using the IWES SimEE model (Saint-Drenan et al., 2009) based on the assumptions on electricity generation in the year 2050, made in the 'lead scenario' of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Nitsch, 2008), upscaled by factor 1.2 to replace fossil fuels; with 5.38 GW_{el} RPM plants operating at least 5400 full-load hours (economic constrain) per year minimum 8h per ramp up (technical constrain) for generating methane (60% power-to-methane efficiency) and re-conversion to electricity in combined cycle power plants (60% methane-to-power efficiency) with a high installed capacity of 50 GW_{el}, connected at the high voltage grid to ensure grid stability and supply security. Source: own compilation.

Negative loads indicate the surplus renewable power available for storage. It was not simulated which plants are shut down at times of surplus power, as no operation scheduling has been included so far. However, it is assumed that solar, wind and hydro power are prioritized and imported renewable power via the super grid is more economic than operating geothermal with high investment costs or biomass power plants, which have biomass feedstock costs. Surplus renewable power that is not converted into renewable power methane can be exported via the electricity network.

Annex A1 includes the simulations of the year 2050, an example residual load simulation for the month of January, a short description of the Fraunhofer IWES SimEE model, ideas for an economic operation of gas power plants in back-up mode and further modeling assumptions.

Beyond necessary power system simulations, the RPM concept needs to be included in energy system modeling (power, heat, transport) and technology forecasting.

Improvement of GHG balances and integration of emissions from land-use changes

GHG balances for bioenergy pathways show still a wide range of results and are very sensitive to assumptions on land-use change and fossil reference systems. The agricultural side of bioenergy, the cultivation of biomass, is the most effectant parameter on GHG balances. Thus, more attention should be paid on aspects like direct and indirect land-use changes, which are strongly related to agricultural rather than to energy conversion technology. On the technology side, an interesting research question is whether the fuel switch (e.g. fossil diesel to biodiesel or coal to pellets) or the technology switch (e.g. conventional combustion engines vs. electromobility) has larger impacts and relevancy for GHG balancing.

Further development of system modeling and stimulation of system transformation

Climate change mitigation imposes an ample industrial transformation into a post-fossil economy. This system change requires more than a working GHG emission trading system, which has to internalize external costs of fossil energy use. Large investments in infrastructure (transport, energy supply) are necessary, which are not stimulated by increased fossil fuel prices. Power networks provide the public service of supply security, which is a key infrastructure like road networks. Thus, also concepts of public power grids with guaranteed access and good maintenance can be beneficial for the transformation. The income of emission trading certificates should be used for this transition process and to support low-income developing countries, which suffer most of climate change, in adaptation and their transition.

The industrialized countries will not convince developing countries of climate mitigation, if they are not taking strong actions first. This applies as well for standards for sustainable bioenergy. One possible solution for implementing clean sustainable energy technologies in the world's economy is to link economic development with climate mitigation. The optimal instruments for this are yet to be identified. For shure, the proven example of a country 'after transformation' showing that a carbon-free or carbon-neutral 'way-of-life' does not hinder but enforce economic prosperity and social welfare will be a inviting and attractive leader towards sustainability.

7. References

7.1 Publications resulting from this work

The following publication list provides an overview of patents, book contributions, peer-reviewed papers and conference contributions that result from this work done in the past two and a half years.

Patents

Specht, M.; Sterner, M.; Stuermer, B.; Frick, V.; Hahn, B. (09.04.2009): Renewable Power Methane - Stromspeicherung durch Kopplung von Strom- und Gasnetz - Wind/PV-to-SNG. Registered on 09.04.2009. Patent pending No: 10 2009 018 126.1

Book contributions

Sterner, M. (2009): Nachhaltige Weltenergiesysteme. Wege in eine kohlenstoffarme Energiezukunft. In: Debiel, T.; Messner, D.; Nuscheler, F.; Ulbert, M. (Ed.): Globale Trends 2010. Frankfurt am Main: Fischer Taschenburg Verlag (to be published in December 2009)

Sterner, M.; Schmid, J. (2009): WBGU Gutachten - zukunftsfähige Bioenergie und nachhaltige Landnutzung. In: Faulstich, M.; Mocker, M. (Ed.): Biomasse & Abfall. Emissionen mindern und Rückstände nutzen. Sulzbach-Rosenberg: Dorner PrintConcept GmbH (Verfahren & Werkstoffe für die Energietechnik, 5), p. 23–38 (presentation and book contribution)

WBGU (2009): World in Transition - Future Bioenergy and Sustainable Land Use. Flagship Report 2008. Berlin: WBGU. (main contributions to chapter 4 'Bioenergie, Landnutzung und Energiesysteme: Status Quo und Trends' (p.35-60), chapter 7 'Anbau und energetische Nutzung von Biomasse' (p.139-196), chapter 8 'Optimale Einbindung und Nutzung der Bioenergie in Energiesystemen' (p.197-216), chapter 9 'Nachhaltige Produktion von Biomasse und Nutzung von Bioenergie: Synthese' (p.217-226) and further contributions to chapters 2, 5, 6, 10, 11, 12).

Peer-reviewed papers

Sterner, M.; Schmid, J.; Wickert, M. (2008c): Effizienzgewinn durch erneuerbare Energien - der Primärenergiebeitrag von erneuerbaren Energien. In: Brennstoff Wärme Kraft - Springer VDI Verlag, Jg. 06/2008, H. 60 (paper)

Sterner, M.; Schmid, J. (2008b): Electromobility - an efficient alternative to conventional biofuels to put biomass on the road. In: Proceedings of the International Conference '16th European Biomass Conference & Exhibition' of EUBIA in Valencia (presentation and paper)

Conference presentations and papers

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A Annex

A1 Simulation of 100% renewable power supply

The description of the simulation is continued from the outlook in chapter 6.

The IWES SimEE model (Saint-Drenan et al., 2009) is used to simulate the hourly generation of renewable power. It uses the 2005 time series for the total load, wind power and solar power penetration. The model is based on the following assumptions:

- the total load is the vertical bulk load plus decentral generation and the open source time series are taken from the German power transmission companies. The total load is directly extrapolated to the year 2050 using the power demand of the 'lead scenario' without the hydrogen generation demand (total 510 TWh_{el}).
- time series for solar power (PV) generation are generated by using meteorological data and PV models. Time series with 15min resolution for solar irradiation and ambient ground temperatures are taken from satellite measurement data for 120 distributed reference points. These meteorological parameters are converted into the tilted irradiance (direct, diffuse, ground) which enter a software model of the PV array and the PV inverter, which gives the power generated by PV for a high temporal and spatial resolution.
- meteorological data for wind power generation are taken from the German Meteorological Service (DWD). The time series are generated using the model applied in (Ernst et al., 2004) and the follow up grid integration study for onshore and offshore wind power generation in 2020. Wind power peaks are not dumped and thus all overshoots are shown in the simulation.
- imported renewable power via the super grid is assumed to be flexibly available both temporarily and spatially
- gaseous and liquid biomass power generation is assumed to be 100% flexible (30% are flexible for one day, 70% are flexible for three days). The flexible power plants (biogas, sewage gas, landfill gas CHP and plant oil CHP) are assumed to have double generation capacity to supply balancing power. The flexibility of variable biopower generation is limited to one or three days by the capacity of gas storage on one hand and by the buffering of CHP heat in heat storage devices on the other hand. The operation of CHPs depends also on the heat demand (e.g. in winter). Further details on biomass power generation are given in (Saint-Drenan et al., 2009).
- geothermal power generation and solid biomass power generation like wood chips steam power plants are assumed to run in continuous operation and are available throughout the year. Both can be operated flexibly in general. Further modeling will include heat and power controlled modes.

- run-of-river hydro power generation is assumed to be 80% constant and 20% flexible
- pumped hydro storage, ocean energy and power from waste heat was not include in the simulation

Further details on the IWES SimEE model can be taken from (Saint-Drenan et al., 2009).The model is fed with the 'lead scenario 2008' assumptions on power generation capacities and annual power generation for the year 2050. Table A1-1 summarizes these assumed values plus further details on data inputs (Nitsch, 2008).

Table A1-1: Values taken from the 'lead scenario' 2050 (Nitsch, 2008) for the simulation of residual load (given 'lead scenario') and 100% renewable power supply (upscaled 'lead scenario' by factor 1.2). [A] the ratio between on- and offshore wind power is taken from the 'lead scenario'; [B] liquid and gaseous biomass includes 'landfill and sewage gas', 'biogas' and 'liquid biofuels for power'; [C] solid biomass includes 'solid biomass' and 'organic waste' [D]; load without power demand for hydrogen production – load is not upscaled by factor 1.2; [E] no installed capacity given; therefore, a mean installed capacity was derived by assuming full time operation dividing generated electricity by 8760 full-load hours; [F] time series are matched to the assumed generated electricity, not to the given installed capacity, resulting in slightly different installed capacities in the simulation (given in brackets) than in the 'lead scenario' due to different assumptions on power generation efficiency. Source: own compilation, based on (Nitsch, 2008).

Scenario	Energy source	PV	Wind (on- and offshore)[A]	Hydro (run-of-river)	Ren. power import	Liquid + gaseous biomass[B]	Solid Biomass[C]	Geo-thermal	Load[D]
‚lead scenario' 2050	Installed capacity in GW	29 (20.8)[F]	71.0 (67.0)[F]	5.2 (4.4)[F]	20.0 (20.0)[F]	(6.0)[E F]	(3.1)[E F]	5.1 (4.1)[E F]	-
	Generated electricity in TWh	27.7	209.4	24.8	121.0	26.3	27.5	35.7	510.0[D]
‚lead scenario' 2050; ren. power times 1.2	Maximum power in GW	(25.0)[F]	(80.4)[F]	(5.2)[F]	(24.0)[F]	(7.2)[F]	(3.8)[F]	(4.9)[F]	-
	Theoretically generated electricity in TWh	33.2	251.1	29.8	145.9	32.9	33.0	42.8	510.0[D]

The residual load is calculated for January 2050 in Figure A1-1. Conventional fossil or nuclear base load power plants are not required any more. Suitable power plant types to meet this residual load are flexible natural gas power plants that can be operated with renewable power methane. To ensure stability of network operation, about 20-50 GW gas power plants are required as back-up power. Another option for distributed balancing power is to use RPM in numerous decentral CHP and control them from one single point (swarm power principle) (see chapter 4.4.2).

As the large gas power plants will only have few operating hours, new economic concepts and business plans will be required; e.g. a capacity market for gas power plants – similar to today's balancing power market. In this way, these plants receive income for providing back-up capacity (capacity price) and compensate the low income from low electricity sales due to few full-load hours operation (energy price).

The renewable power generation shares in the 2050 'lead scenario' are upscaled by factor 1.2, since the scenario is not a 100% renewable power scenario.

The renewable power methane (RPM) plants are modeled for charging with at least 5400 full-load hours (economic constrain) and 8h constant operation per start up (technical constrain). These constrains result in a maximum capacity of 5.38 GW_{el} that can be operated for 5400 FLh. Together with longer operating capacities, RPM plants can convert 32.4 TWh of surplus power to methane at average 6020 full-load hours per year. Combined cycle power plants simulate the methane-to-power conversion with an efficiency of 60% without flexibility or capacity constrains. The overall power storage efficiency is assumed at 36%.

Operating the RPM plants with lower full-load hours (e.g. 2,000 or 4,000 h) increases the share of renewable power that can be stored and also increases the installed capacity of RPM plants. The optimum operation conditions are to be identified yet.

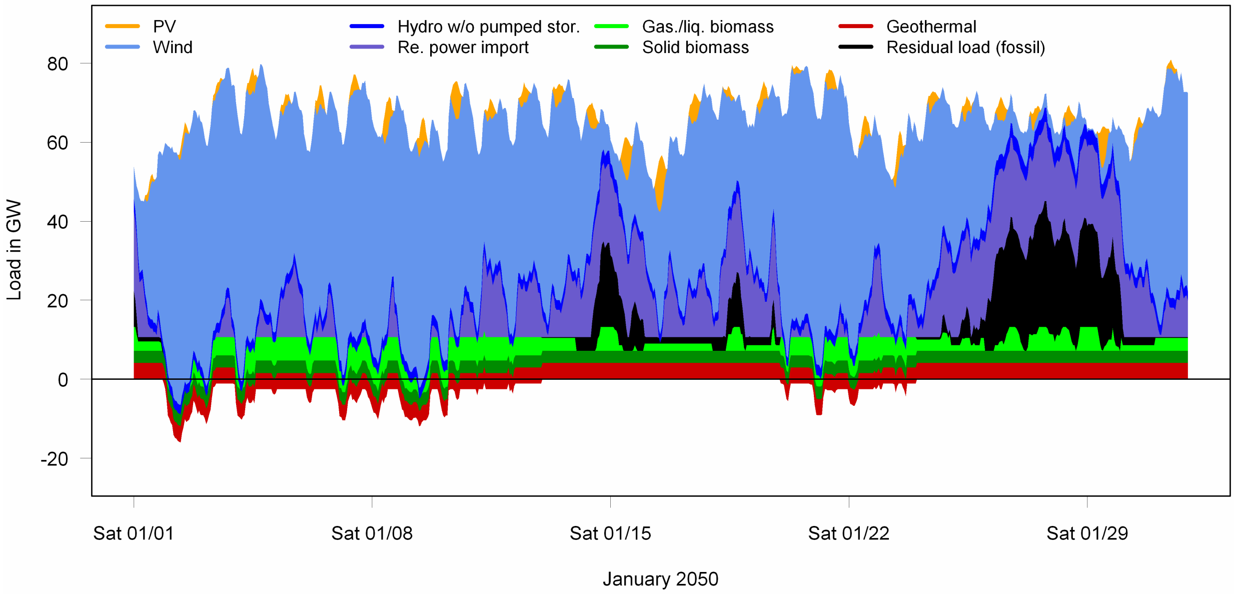

Figure A1-1: January 2050 - Simulation of the power supply with the IWES SimEE model (Saint-Drenan et al., 2009) according to the 'lead scenario' for 2050 taken from (Nitsch, 2008). The residual load is assumed to be covered by natural gas power generation. Source: own compilation.

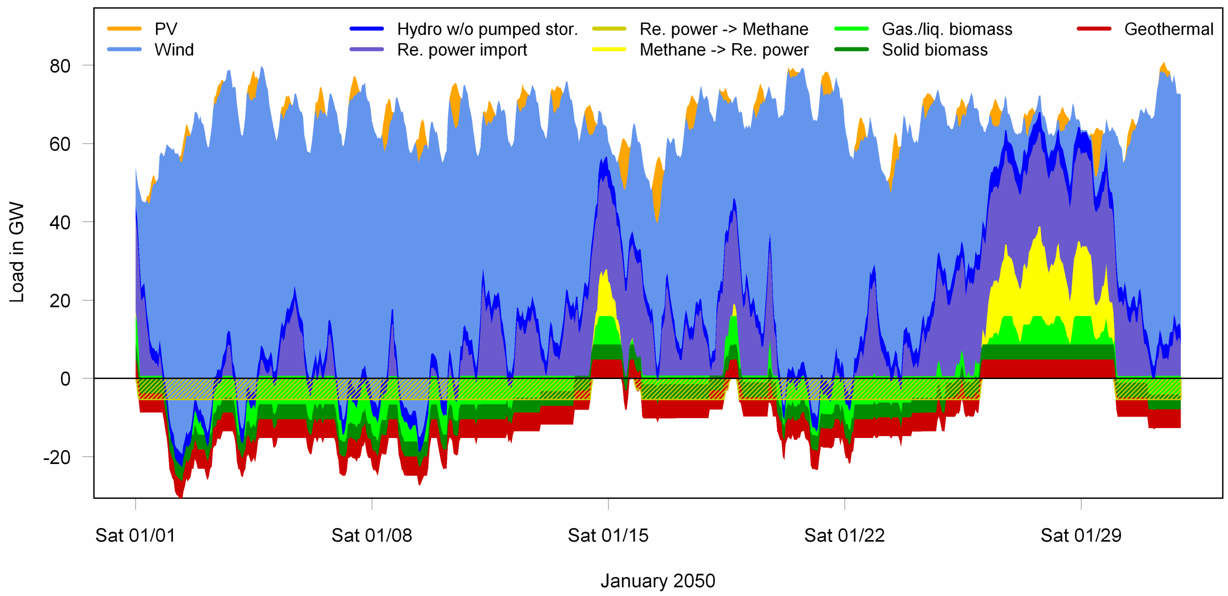

Figure A1-2: January 2050 - Simulation of 100% renewable power supply with the IWES SimEE model (Saint-Drenan et al., 2009) based on the 'lead scenario' for Germany (Nitsch, 2008), upscaled by factor 1.2; with 5.38 GW_{el} RPM plants, operating at least 5400 full-load hours. Source: own compilation.

One week in February is shown in Figure 6.2-1 in chapter 6. The year 2050 are illustrated in the following from Figure A1-2 to Figure A1-4.

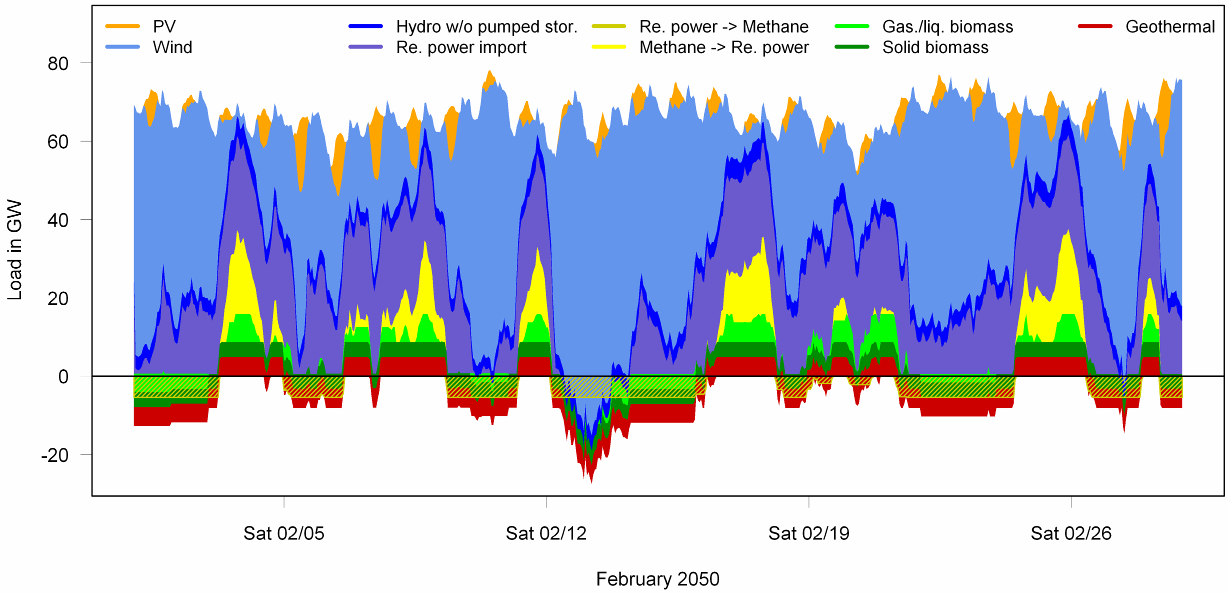

Figure A1-3: February 2050 - Simulation of 100% renewable power supply with the IWES SimEE model (Saint-Drenan et al., 2009) based on the 'lead scenario' for Germany (Nitsch, 2008), upscaled by factor 1.2; with 5.38 GW_{el} RPM plants, operating at least 5400 full-load hours. Source: own compilation.

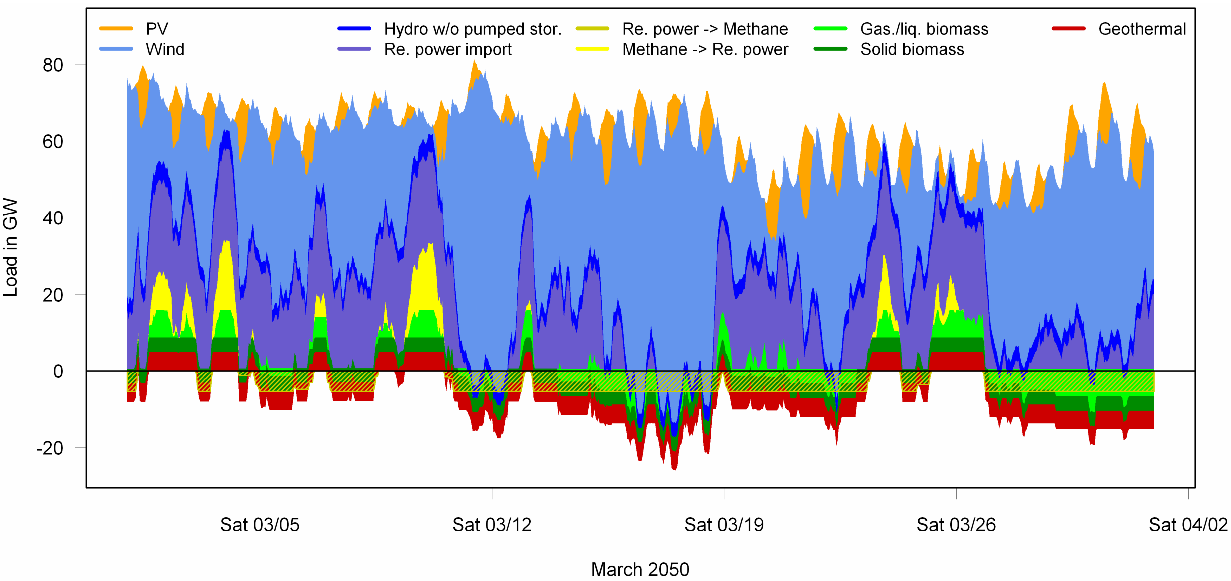

Figure A1-4: March 2050 - Simulation of 100% renewable power supply with the IWES SimEE model (Saint-Drenan et al., 2009) based on the 'lead scenario' for Germany (Nitsch, 2008), upscaled by factor 1.2; with 5.38 GW_{el} RPM plants, operating at least 5400 full-load hours. Source: own compilation.

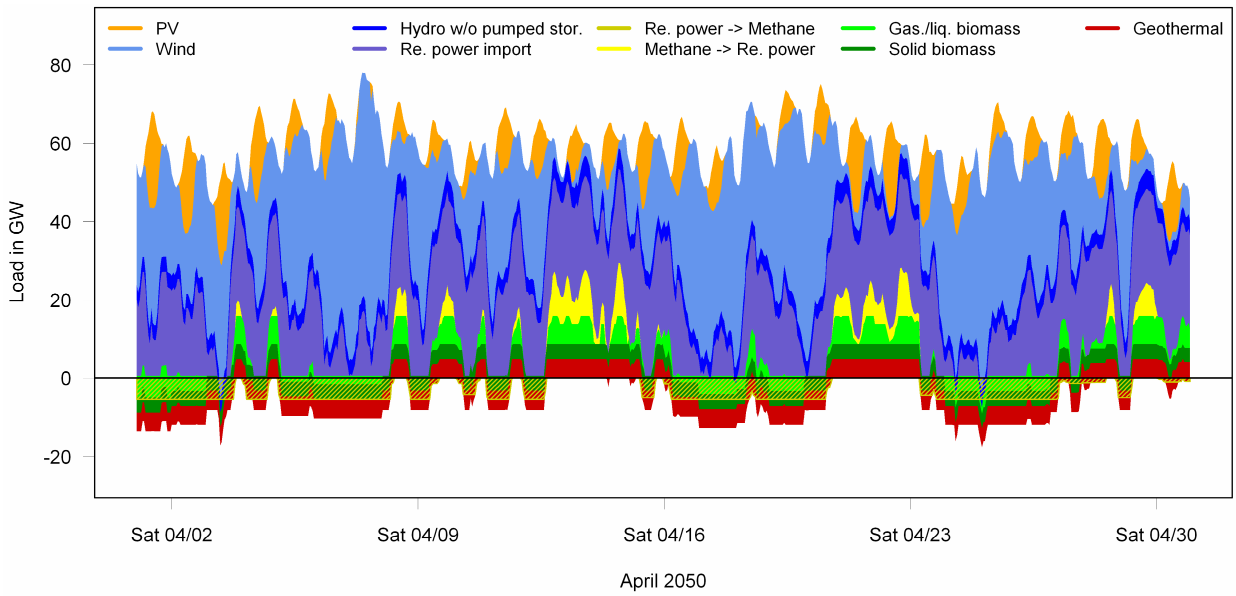

Figure A1-5: April 2050 - Simulation of 100% renewable power supply with the IWES SimEE model (Saint-Drenan et al., 2009) based on the 'lead scenario' for Germany (Nitsch, 2008), upscaled by factor 1.2; with 5.38 GW_{el} RPM plants, operating at least 5400 full-load hours. Source: own compilation.

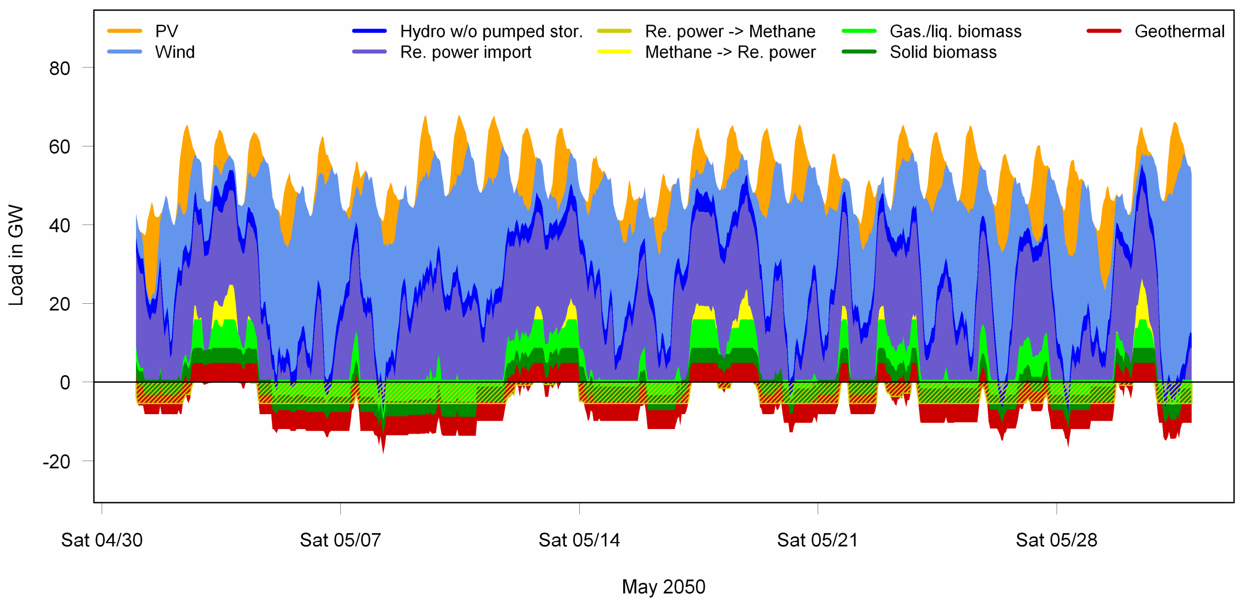

Figure A1-6: May 2050 - Simulation of 100% renewable power supply with the IWES SimEE model (Saint-Drenan et al., 2009) based on the 'lead scenario' for Germany (Nitsch, 2008), upscaled by factor 1.2; with 5.38 GW_{el} RPM plants, operating at least 5400 full-load hours. Source: own compilation.

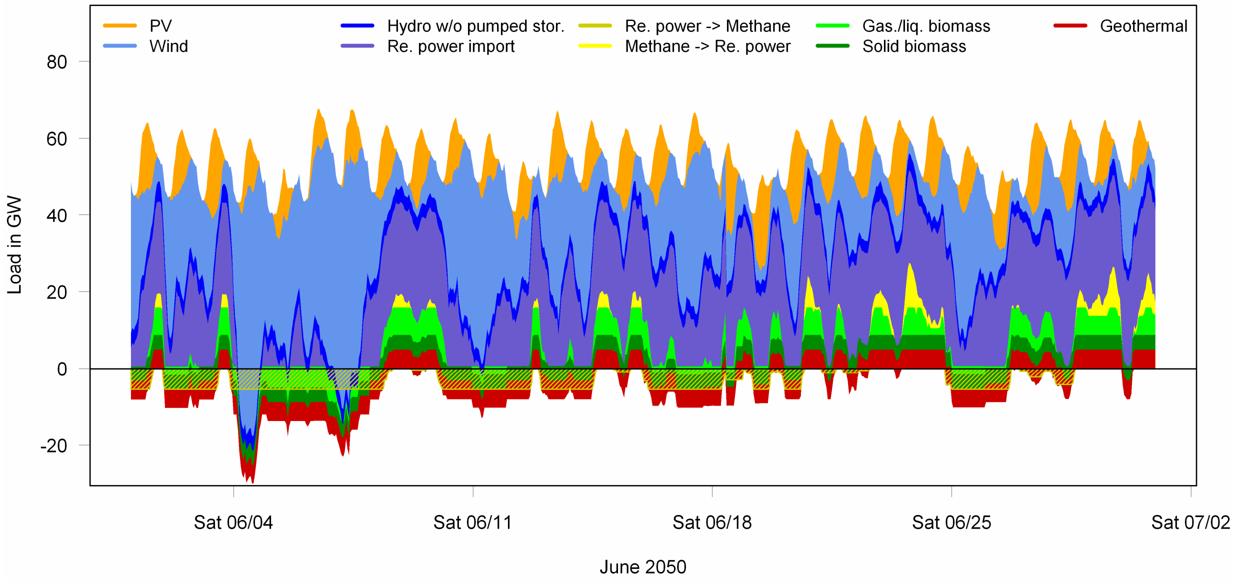

Figure A1-7: June 2050 - Simulation of 100% renewable power supply with the IWES SimEE model (Saint-Drenan et al., 2009) based on the 'lead scenario' for Germany (Nitsch, 2008), upscaled by factor 1.2; with 5.38 GW_{el} RPM plants, operating at least 5400 full-load hours. Source: own compilation.

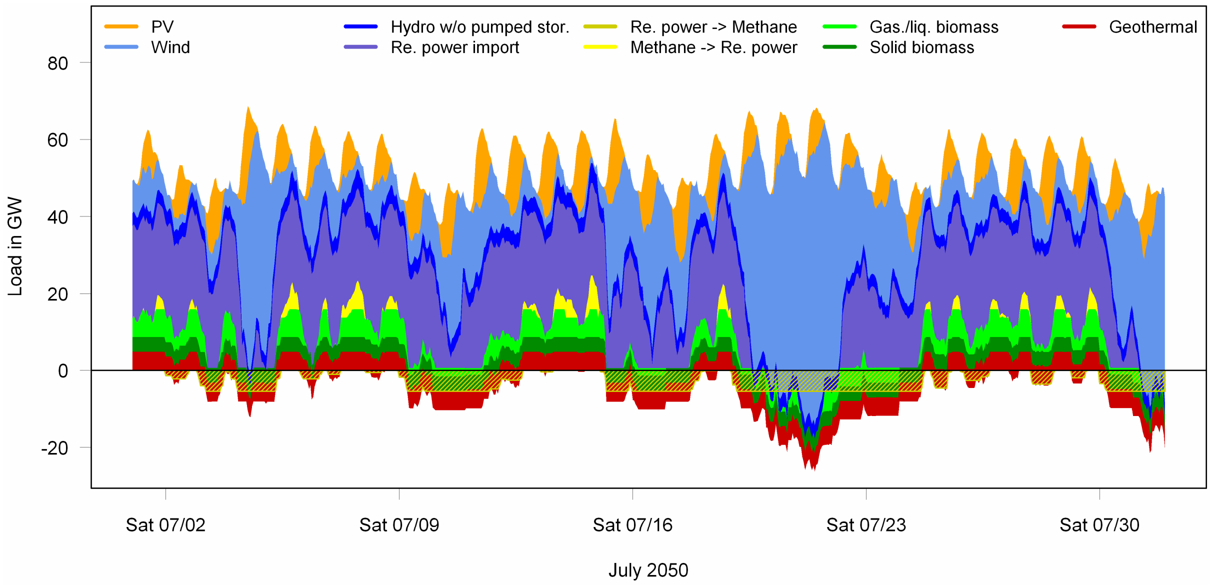

Figure A1-8: July 2050 - Simulation of 100% renewable power supply with the IWES SimEE model (Saint-Drenan et al., 2009) based on the 'lead scenario' for Germany (Nitsch, 2008), upscaled by factor 1.2; with 5.38 GW_{el} RPM plants, operating at least 5400 full-load hours. Source: own compilation.

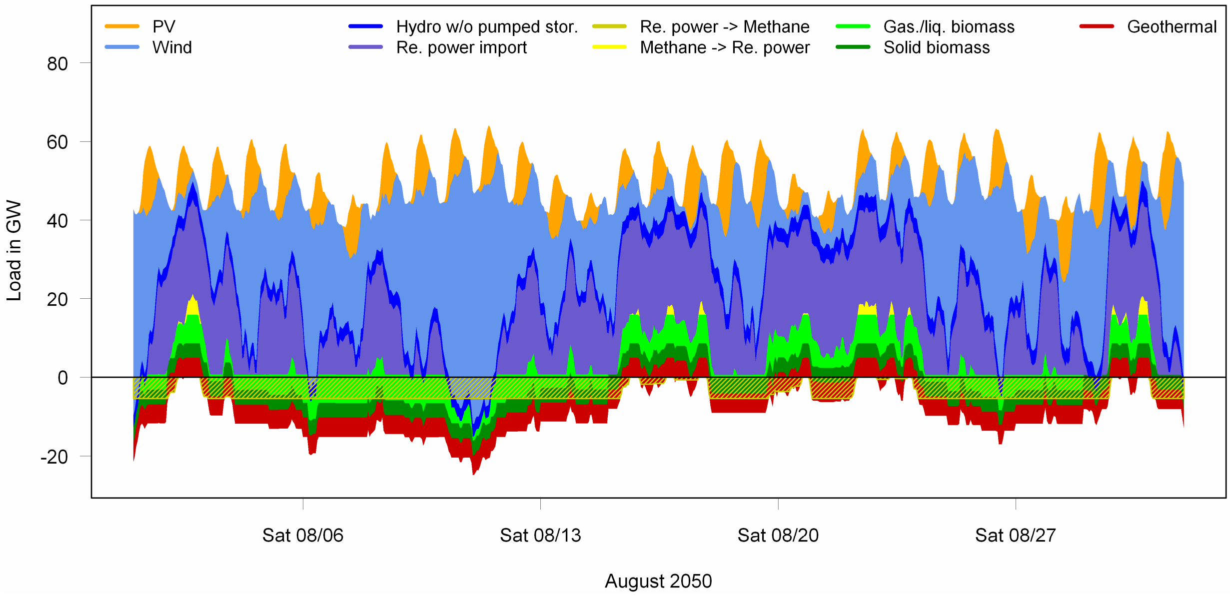

Figure A1-9: August 2050 - Simulation of 100% renewable power supply with the IWES SimEE model (Saint-Drenan et al., 2009) based on the 'lead scenario' for Germany (Nitsch, 2008), upscaled by factor 1.2; with 5.38 GW_{el} RPM plants, operating at least 5400 full-load hours. Source: own compilation.

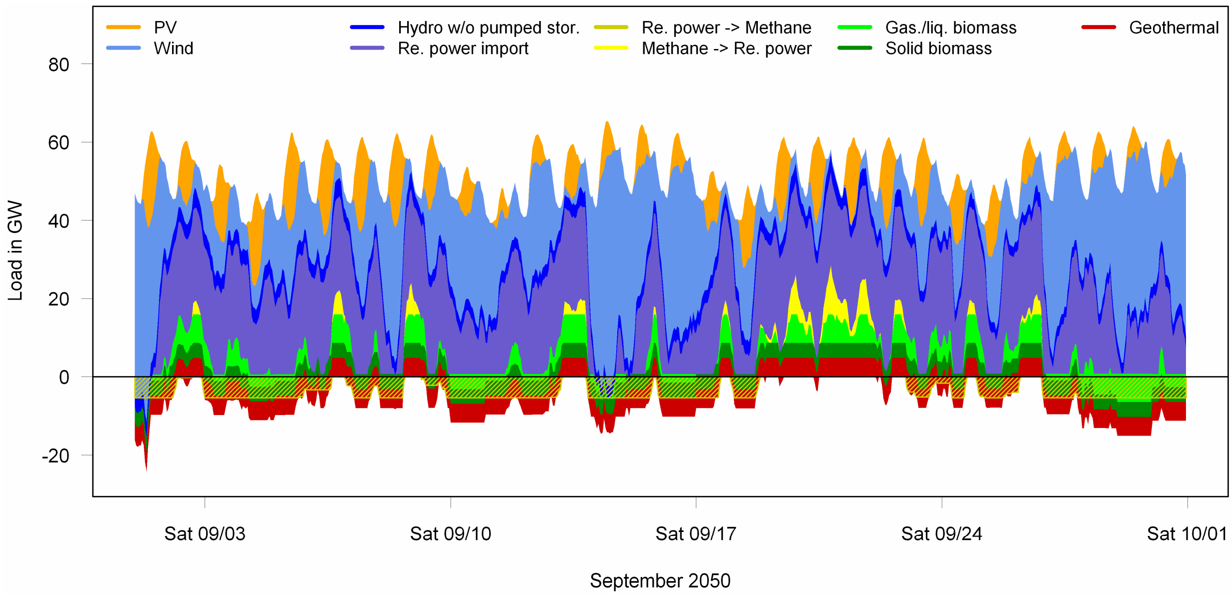

Figure A1-10: September 2050 - Simulation of 100% renewable power supply with the IWES SimEE model (Saint-Drenan et al., 2009) based on the 'lead scenario' for Germany (Nitsch, 2008), upscaled by factor 1.2; with 5.38 GW_{el} RPM plants, operating at least 5400 full-load hours. Source: own compilation.

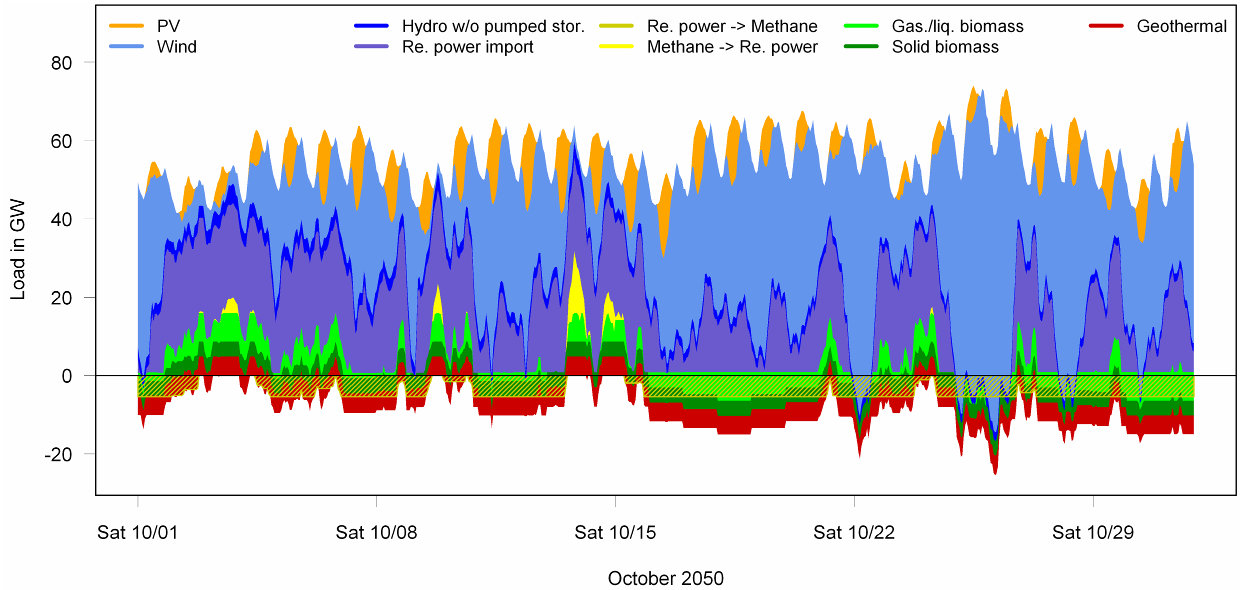

Figure A1-11: October 2050 - Simulation of 100% renewable power supply with the IWES SimEE model (Saint-Drenan et al., 2009) based on the 'lead scenario' for Germany (Nitsch, 2008), upscaled by factor 1.2; with 5.38 GW_{el} RPM plants, operating at least 5400 full-load hours. Source: own compilation.

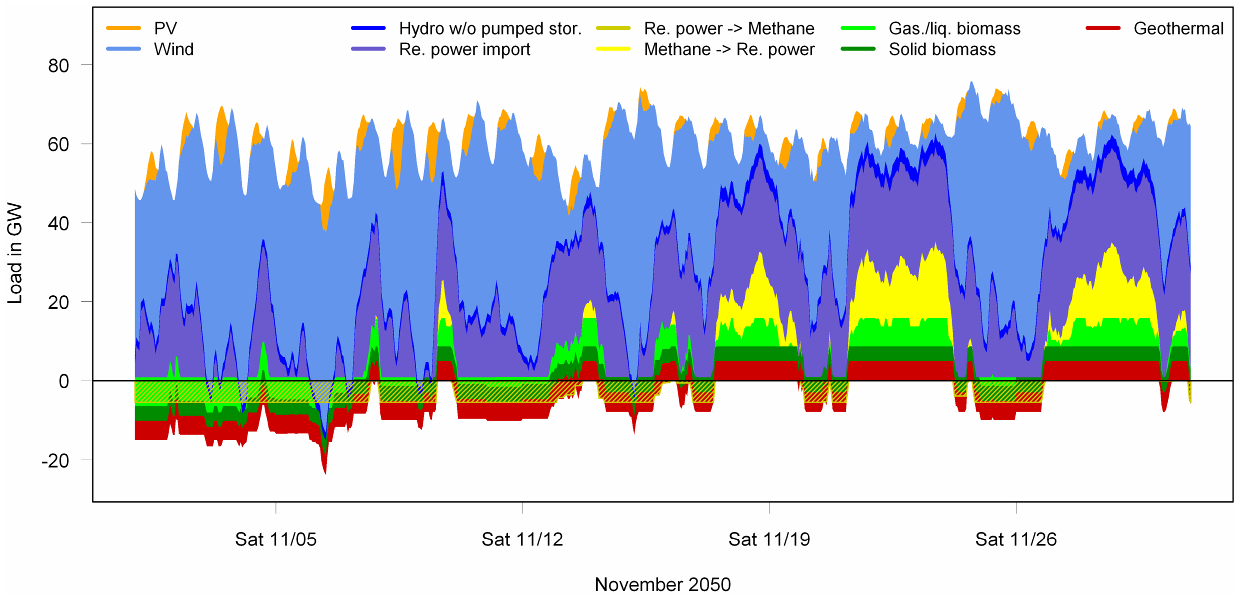

Figure A1-12: November 2050 - Simulation of 100% renewable power supply with the IWES SimEE model (Saint-Drenan et al., 2009) based on the 'lead scenario' for Germany (Nitsch, 2008), upscaled by factor 1.2; with 5.38 GW_{el} RPM plants, operating at least 5400 full-load hours. Source: own compilation.

A2 Relevant definitions

Definitions are taken from the Food and Agricultural Organisation of the United Nations (FAO), from the Global Bioenergy Partnership (GBEP), from the German Advisory Council on Global Change (WBGU) and other sources.

Agricultural land – (FAOSTAT, 2009a)

The definition of agricultural land composes of the following sub-categories:

(a) *arable land* – "land under temporary crops (double-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years)." The abandoned land resulting from shifting cultivation is not included in 'arable land'. Arable land figures do not to indicate the amount of land that is potentially cultivable.

(b) *permanent crops* – "land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as cocoa, coffee and rubber; this category includes land under flowering shrubs, fruit trees, nut trees and vines, but excludes land under trees grown for wood or timber; and"

(c) *permanent pastures* – "land used permanently (five years or more) for herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land)".

Balancing power

Balancing power is the necessary (control) power to ensure grid stability at high variable generation from wind and solar power. Simultaneously, this term is used for 'control power', and 'balancing energy' to indicate the power generation that covers the 'residual load'.

Barren land

Please see 'degraded land'.

Biomass - (WBGU, 2009; Kaltschmitt et al., 2003)

In principle, biomass is stored solar energy.

Solar energy powers photosynthesis that converts CO_2 and water into organic matter. In this way, solar energy is converted into chemical energy with an efficiency of about 1-2%. Biomass consists basically of carbon (C), oxygen (O) and hydrogen (H). More general, all organic matter can be named 'biomass', including plants and animals, their residues (e.g. straw, manure), dead and decaying plants and animals and residues from processing 'plants and animals' (e.g. black liquor, paper, animal fat).

Biomass resources are distinguished in energy crops and residues (see classification of bioenergy in chapter 1.2.1.3).

Bioenergy - (GBEP, 2008)

Energy derived from biomass.

Bioenergy use is distinguished in modern bioenergy and traditional biomass (see classification of bioenergy in chapter 1.2.1.3).

Biofuels (liquid and gaseous) - (WBGU, 2009)

Biofuels are liquid or gaseous fuels derived from biomass. They are mainly used in transportation but also for heat and power generation.

Biofuels can be classified in first and second generation biofuels. However, there is no clear and common definition on the classification criteria. Some studies distinguish, whether only parts of the energy crop are used (first generation) or the whole plant (second generation). Other studies classify biofuels according to their availability on the market (first generation) and 'paper and research' biofuels (second generation).

In this work, a technical distinction is used: First generation biofuels like biodiesel, bioethanol or biogas are derived from established physical-chemical conversion processes (pressing, extraction, transesterification) or bio-chemical conversion processes (alcoholic or anaerobic fermentation).

Second generation biofuels like Fischer-Tropsch-Diesel (BTL), Dimethylether (DME), Bio-SNG (biomethane from gasification) or bio-hydrogen (hydrogen from gasification) are derived from gasification processes. Biomethane from anaerobic fermentation is also defined as 'second generation biofuel'.

Biogas - (FNR, 2006b)

Biogas is a mixture of approximately 2/3 methane (CH_4) and 1/3 CO_2 and produced by anaerobic fermentation of biomass (e.g. grass silage and animal manure). Main trace gases are hydrogen, hydrogen sulfide and ammonia.

Biomethane - (WBGU, 2009; Hofbauer, 2009)

Biomethane is a substitute for natural gas. It is produced in two major pathways: (i) via biogas from anaerobic fermentation of biogas by cleaning biogas and upgrading biogas, i.e. separating CO_2 from the gas mixture to obtain 95% pure methane. (ii) via gasification of solid and liquid biomass to rawgas, that is clean and conditioned (syngas) and converted into methane via methanation.

Crude oil - (Campbell, 2003; Schindler et al., 2008)

(a) *conventional oil* is crude oil with a viscosity above 17°API gravity

(b) *unconventional oil* is (i) heavy oil between 10-17°API gravity, (ii) extra heavy oil below 10°API gravity (tar sands belong to this category), (iii) deep-sea oil below 500 meter water depth, (iv) oil shale, (v) polar oil north or south of the arctic/antarctic circle and (vi) condensateas crude oil having a viscosity above 17°API gravity.

Coal

Coal is used as one term for both lignite (brown coal) and hard coal. The specific term is used when only one item is referred to.

Degraded land - (WBGU, 2009; Fritsche et al., 2008a; FAO, 2008b)

"Degraded land comprises former suitable used land that has been turned in unsuitable land by a degradation process". Degraded land is not anymore used for agriculture or other economic human activities (Fritsche et al., 2008a). Marginal and degraded lands are areas with low yields and are characterized by low soil fertility and lack of water, constraining both plant growth and nutrient availability (FAO, 2008b). Set-aside land, waste land, fallow lands are other terms for these low-productive areas.

"Marginal land is used as an umbrella term for (1) areas with little capacity for fulfilling a production or regulation function, and also for (2) areas that have lost their production and regulation function, sometimes to a significant extent. (1) includes areas whose productivity for agriculture or forestry is considered low. Also in this category are arid and semi-arid grasslands, desert fringes and areas of steep ground and structurally weak or erosion-prone soils, particularly in mountainous regions. (2) covers formerly productive areas; they may have lost their yield potential as a result of human-induced soil degradation (e.g. overused, degraded and therefore unproductive land, including both forests and pasture and arable land), or the land may have been deliberately taken out of production (e.g. set-aside land in central Europe that has been taken out of production for economic or political reasons). Marginal areas are generally highly susceptible to soil degradation" (WBGU, 2009).

Direct generation (renewable power) - (Sterner et al., 2008c)

Direct generation of electricity is done by renewable power sources like wind, solar, hydro and ocean power. These sources do neither cause fuel costs nor greenhouse gas emissions during operation. Power conversion efficiency is much higher than in conventional Carnot cycle power generation with fossil, nuclear or biomass resources. All power generation processes that to not have waste heat 'losses' larger than 5%, and are CO_2 emission-free and not reluctant on fossil, nuclear or biomass feedstocks are called 'direct generation'.

Energy efficiency and energy saving - (Sterner et al., 2008c)

Energy efficiency and energy savings are two sides of the same coin. An improvement of energy efficiency of a device brings energy savings as it is applied and replacing another inefficient device. Energy efficiency can be achieved on the demand side, like better building insulation or improved cooking stoves in developing countries and as well on the supply side: e.g. using the waste heat of thermal power plants, improving generator efficiencies, minimizing power transmission losses, enhancing fermentation processes in biomass conversion to biogas, etc.

Energy saving

Please see 'energy efficiency'.

Forest and woodland – (FAOSTAT, 2009a)

"Land under natural or planted stands of trees, whether productive or not. This category includes land from which forests have been cleared but that will be reforested in the foreseeable future, but it excludes woodland or forest used only for recreation purposes."

Genset

A genset composes of a small kW-scale combustion motor coupled with a small generator for producing electricity. It is applied mostly in rural electrification.

Land-cover

The 'observed physical and biological cover of the earth's land as vegetation or man-made features'. Example terms are cropland, pasture, rangeland, built-up land, forest (Klein Goldewijk et al., 2004; IPCC, 2001).

Land-use

The purpose or intent for which land is being used (e.g. grazing, food and fodder production, timber extraction, conservation) and also to the human actions on a certain land (land management). Examples are 'cultivation, tilling, fertilization, irrigation' and all other arrangements and inputs on a certain land-cover type (Klein Goldewijk et al., 2004; IPCC, 2001).

Marginal land

Please see 'degraded land'.

Net primary production (NPP)

NPP is the 'net amount of carbon assimilated in a given period by vegetation' (Haberl et al., 2007); i.e. the rate at which plants in ecosystems produces net useful chemical energy by photosynthesis. The gross primary production includes NPP plus the energy necessary for plant respiration, i.e. the 'own consumption' of a plant. Both magnitudes are given in mass of carbon per unit area per year (g C m^{-2} yr^{-1}).

Oil

Please see *'Crude oil'*.

Polygeneration

Polygeneration is the combined generation of heat, power and a chemical energy carrier like methane or Fischer-Tropsch diesel.

Raw biomass

Raw biomass is used as a synonym for ‘dry matter’ or ‘dry mass’ and indicates the chemical energy content of untreated, harvested biomass on a dry matter, low water content basis.

Residual load

Residual load results from the total load (power demand) minus renewable power generation.

Renewable power methane

Renewable power methane is a substitute for natural gas. It can be produced by methanation of CO_2 with hydrogen. Hydrogen is generated by electrolysis of water, powered by direct generation renewable power sources like wind, solar, hydro and ocean power. These sources do neither cause fuel costs nor greenhouse gas emissions during operation. CO_2 can be extracted from air or from flue gas of processing biomass, fossil fuels or other carbon-containing materials.

Traditional biomass

The term ‚traditional biomass’ refers to simple heating and lighting by combustion of solid biomass like fuel wood with very simple technologies like the traditional biomass fired-stove. It is the main form of energy use in developing countries.

Waste land

Please see ‘degraded land’.

A3 *Effect of methodologies in primary energy balances and global potential of renewable energy sources*

Crucial differences in calculating the primary energy share of renewable energy

There are two main methods to calculate the share of renewable energy in total primary energy supply. The 'substitution method' calculates or accounts power from fossil and non-fossil sources equally, for example, 1 kWh wind power substitutes the equivalent primary energy input to produce 1 kWh coal power. The 'efficiency method' 'accounts' only one third of power from wind, solar and hydro as primary energy and thus undervalues the contribution of renewables to total primary energy supply.

2.78 kWh primary energy are required to generate 1 kWh power in conventional fossil power plants (conversion efficiency 36%, global average according to REN21, 2008b). Two-thirds of the primary energy input cannot be converted into power due to Carnot efficiency creating about 1.78 kWh of unused waste heat. Directly generated renewable power from wind, solar, hydro, ocean, etc. is avoiding these huge thermal losses (conversion efficiency 100%). Therefore, 1 kWh renewable power corresponds 'only' to 1 kWh primary energy (efficiency method), but replaces 2.73 kWh fossil and nuclear primary energy (substitution method). In other words, the efficiency method accounts the power output of renewables as primary energy and the power input of fossil and nuclear fuels as primary energy, which is distorting total primary energy shares of renewable energy (Sterner et al., 2008c; REN21, 2008b).

The 'efficiency method' calculates 1 kWh renewable electrical energy equal 1 kWh fossil (chemical) energy equal 1 kWh thermal energy, which is not conform with the 2nd law of thermodynamics and thus physically incorrect. Thermodynamic 'energy losses' cannot be avoided in Carnot cycles in condensation power plants.

Therefore, the 'efficiency method' undervalues the primary energy share of renewables. Figure A3-1 illustrates these facts with an example: The assumed 100 kWh are produced in year 0 by 100% fossil/nuclear sources and in year 100 by 100% renewables (wind, solar, hydro). The transition in between is linear. In the year 50, the power mix composes of 50% renewables and 50% fossil/nuclear power. The 'efficiency method' results in a distorted primary energy mix of 28% renewables and 72% fossil/nuclear primary energy share. Only the 'substitution method' reflects the actual contributions in the correct 50/50 ratio. The only benefit of using the 'efficiency method' is a smaller total primary energy demand in a 100% renewable energy system compared to a fossil energy system.

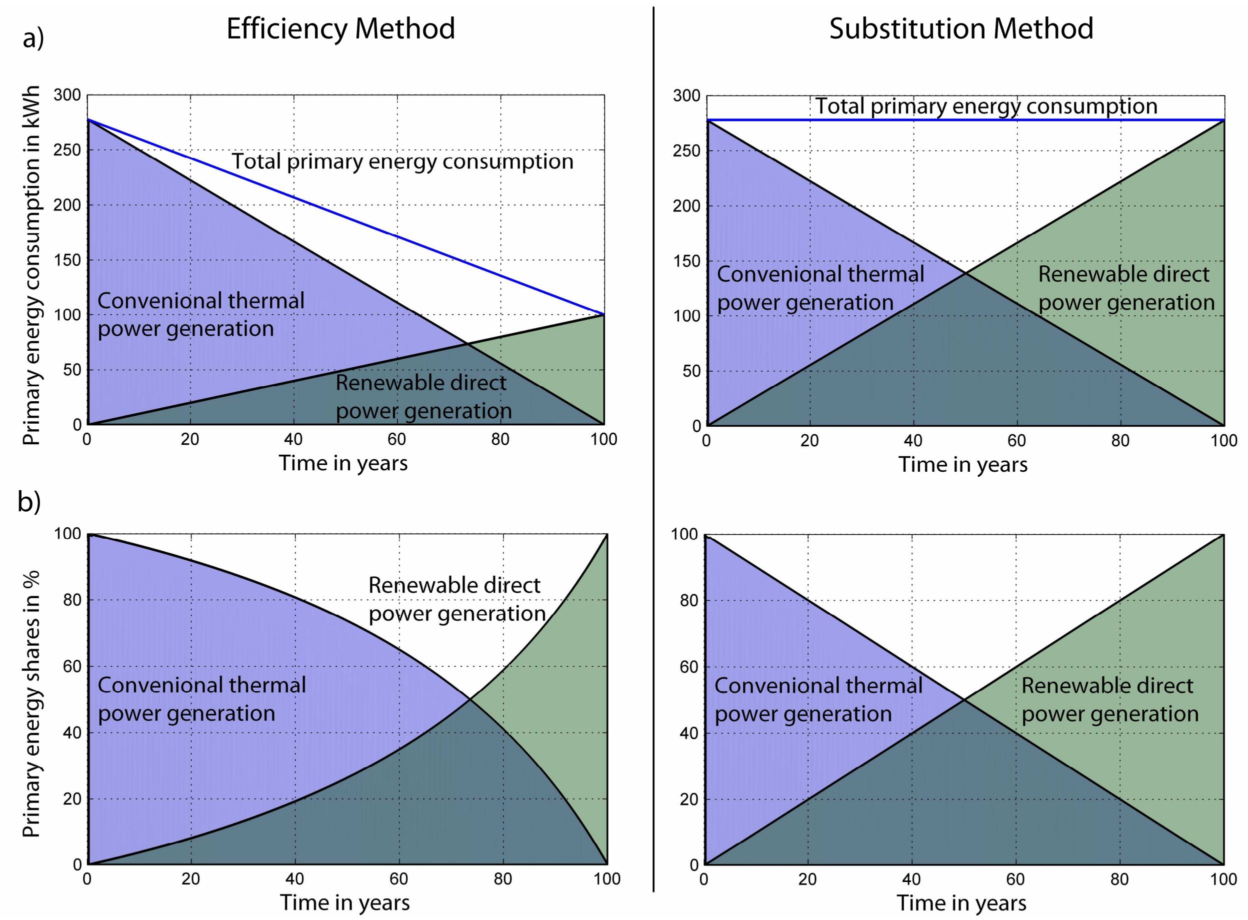

Figure A3-1: Illustrative example of the differences between methods for primary energy balancing. A linear power demand of 100 kWh is assumed which is provided 100% by conventional thermal power generation in year 0 and 100% by renewable direct power generation in year 100 and a linear transition in between. (a) Accounting of primary energy consumption in the two different methods and (b) shares of primary energy accordingly. The 'efficiency method' is distorting primary energy shares of renewables which is avoided in the 'substitution method'. Source: own compilation.

These differences become also apparent in counting the primary energy contribution of nuclear and hydro power. Both sources generated similar amounts of electricity (about 3,000 TWh) in 2006. However, according to the distorting 'efficiency method', applied by the IEA, nuclear power contributed 30,5 EJ or 6.2% and hydro power only 11.2 EJ or 2.2% primary energy (IEA et al., 2008). According to the 'substitution method', applied by BP, UNDP, REN21 and others, the share of nuclear (26.6 EJ or 5.2%) and hydro power (28.8 EJ or 5.7%) are in the same order of magnitude (BP, 2009; REN21, 2008b).

A third method 'final energy' is avoiding these ambiguities by only evaluating the final energy of each sector. The drawback in this method is that the energy of the three energy sectors power, heat, and transport cannot be summed up to one primary energy figure, as 1 kWh electricity and 1 kWh heat or fuel are thermodynamically not the same.

Since 'primary energy' is a political and economic magnitude and often used, the choice of the balancing method imprints on policy targets set by decision makers.

Primary energy shares, availability of energy resources and technical potential of renewables

Applying the ‘substitution method’, Table A3-1 gives the 2006 shares of energy sources, growth rates, their availability and the global potential for renewable energy. Latest studies indicate especially high potentials for wind power. Globally, and estimated 840-1,300 PWh_{el}, equal to 40-65 times of current global power consumption, are available (Lu et al., 2009). In Europe, the potential is estimated to 41.8-70 PWh_{el} that corresponds to 10-20 times of Europe’s expected power consumption, taking all environmental aspects into account (EEA, 2009).

Table A3-1: Potentials, primary energy shares and growth rates of fossil, nuclear and renewable energy sources and their challenges. Source: own compilation, based on data from [P](BP, 2009; REN21, 2008b), [A] all related to energy, except [B], related to installed capacity; (IEA et al., 2008; GBEP, 2008; GWEC, 2008), [u](Goldemberg, 2000), P.168, [i](IPCC, 2007d), P.264.; [K](Lu et al., 2009), P.4, using the ‘substitution method’.

	Energy source	2006 share in global primary energy supply	2006 primary energy equivalent 2006 in EJ	Growth rate [A] in the decade 1997-2007	Reserve / Production ratio in years	Challenge / Danger	Available fossil and nuclear resources in EJ and technical potential of renewables in EJ per year
Fossil	Crude oil	32.0%	163.7	15.1%[P]	42	GHG emissions Supply security Geopolitical / military conflicts Competition with chemical industry	21,300 EJ[u] - 45,000 EJ[i]
	Coal	24.9%	127.4	37.4%[P]	133		132,000 EJ[i] - 179,000 EJ[u]
	Natural gas	20.9%	107.1	30.2%[P]	60		32,500 EJ[i] - 34,900 EJ[u]
Nuclear	Uranium	5.5%	28.1	5.7%[P]	30-70	Nuclear weapons Terrorism Nuclear accident Waste disposal	7,400 EJ[i]
Renewable	Hydro (large / small)	6.0% (5.5% / 0.5%)	30.8	5.8%[P]	∞	Large hydro: water stress and settlements	50-62 EJ[i]
	Biomass (trad. / modern)	10.0% (8.6% / 1.4%)	51.4	18.0% GBEP/IEA for 1996-2006	Depending on land-use competition	Land-use competition (food, water, biodiv.)	275-600 EJ[i]
	Wind	0.3%	1.55	1235.1% GWEC [B]	∞	Grid integration	250-640 EJ [I] 8400-13,000 EJ[K]
	Geothermal (heat / power)	0.2% (0.08% / 0.12%)	1.04	heat 217% power 18.8% REN21 2000-2006 [B]	∞	-	5000
	Solar (heat / power)	0.1% (0.06% / 0.04%)	0.51	heat 92.5% REN21 2003-2007 [B] power 916% REN21 1997-2007[B]	∞	Grid integration, cost reduction, recycling	1575-1650i
	Tidal and wave energy	0.0005%	0.0025		∞	-	7i

A4 Basic biomass conversion technologies

A4.1 Thermo-chemical conversion processes

Direct combustion - cofiring

All bioenergy pathways end up with the combustion of a solid, liquid or gaseous 'biofuel' to yield thermal, electrical or mechanical energy. Thus, combustion is the core process of all bioenergy pathways.

Combustion is a sequence of exothermic chemical reactions, whereby the combusted fuel is completely oxidized (perfect combustion) and heat is released. Carbon (C) or hydrogen (H) is reacting with an oxidant (usually oxygen (O_2)) resulting in CO_2 or steam (H_2O). The standard enthalpy change of reaction ΔH_R (released energy in a chemical reaction) for the combustion of C to CO_2 is -394 kJ/mol and for the combustion of H to H_2O 242 kJ/mol. The process combustion of a solid fuel consists of different phases: pyrolysis, gasification and oxidation of gaseous components. In a complete combustion, all reactants are completely oxidized (CO_2, NO_2, SO_2, etc.). This is as well called stoichiometric combustion (Kaltschmitt et al., 2003).

Direct combustion of biomass is the most common form of using solid biofuels. Woody biomass like wood chips are burnt in boilers to generate heat for heating systems or power via a steam cycle process. This process is similar to the standard power generation process using conventional fossil fuels like coal.

Biomass can as well be combusted with fossil fuels in conventional power plants. The so called 'co-firing' of biomass with coal is a standard cost-efficient technology and state-of-the-art. The clear advantage is the use of existing power plant technology and a high combustion efficiency of the process itself. Another example of integrating renewable with fossil energy use is the combination of biomass for local heat networks, applying biomass for basic load and oil or gas for peak loads (GBEP, 2008).

Direct combustion of biomass for heat supply is the most common process of energy supply in developing countries (Mande et al., 2007).

Gasification

Gasification is a thermo-chemical conversation process, converting a gasification media (solid or liquid biomass feedstock) into a gaseous fuel. Biomass is gasified with a gasification agent (air, oxygen, CO_2, water vapor, etc.) under sub-stoichiometric conditions ($\lambda < 1$) in a high temperature, low oxygen content environment. The oxygen provided in the process is limited to avoid complete combustion (partial combustion) so that not all energy is converted into heat but also to chemical energy in form of a gaseous biofuel. In this way, an energy-rich raw gas is produced, which can be cleaned and upgraded to synthetic gas for transport fuel synthesis and, used in a internal combustion engine / turbine for heat and power generation or used directly for heat applications. Heat has to be supplied in the basically endothermic process (Kaltschmitt et al., 2003), p.272ff. The process can be split into four different sub-processes. First, biomass is heated and dried at temperatures up to 200°C (drying). Second, the dry biomass is decomposed to gaseous hydrocarbons, pyrolysis oil and pyrolysis char at temperatures in the range of 200-500°C (pyrolysis). Third, pyrolysis products are partially oxidized at temperatures up to 2,000°C and split into molecules (CO, H_2, CH_4, H_2O) and traces of other gases. This exothermal reaction supplies the heat for an allothermal gasification (oxidation). Fourth, in a final step, most of the combustible components are formed by the 'reduction' of CO_2 (C reacts with CO_2 to CO – Bourdouard reaction) and H_2O (C reacts with H_2O_{vapour} to CO and H_2 – heterogeneous water-gas-shift reaction). In addition, also the homogeneous water-gas-shift reaction (CO reacts with H_2O_{vapour} to CO_2 and H_2) and the methane reaction (C and H_2 react to CH_4) take place.

The so formed raw gas composes mainly of carbon monoxide, hydrogen (main components), carbon dioxide, methane, water vapor and nitrogen. The raw gas composition depends much on the method of gasification and gasifier design, the gasification agent (type and quantity) and on the basic gasification parameters temperature and pressure. Using air as gasification agent is inexpensive and simple, but the drawback is a high share of inert gas in raw gas. Therefore, usually oxygen or water vapor are applied for synthetic biofuel production (Fischer-Tropsch Diesel, Biomethane, etc.) (Sterner, 2007; Kaltschmitt et al., 2003).

Besides the main products, the raw gas contains also diverse impurities (tars; particles; alkali, sulphuric, nitrogen, halide components) which have to be separated from the raw gas stream by (sophisticated) gas cleaning methods. This is the bottleneck for market implementation of small scale decentral gasifiers in industrialized countries (Kaltschmitt et al., 2003; Knoeff, 2005).

Raw gas can be applied directly in boilers or burners for heat provision (large stoves, bakeries, industry). Gas cleaning is necessary for power generation as raw gas impurities would damage and foul the engine or turbine. The cleaned gas can be applied in multiple ways: (i) cofiring as substitute diesel in a diesel engine, (ii) combusting pure clean gas in a gas engine or turbine or (iii) use clean gas in a fuel cell. The use of solid-oxide fuel cells (SOFC) seems the most promising fuel cell type for clean gas from biomass gasification (Dasappa, 2009; Vogel, 2007; Aravind et al.).

Gasification is the core conversion process of producing second generation biofuels. Biomass feedstock is dried and when necessary chopped. Two common gasification technologies are the entrained flow gasifier and circulating fluidized bed gasifier. Clean gas can be upgraded to synthesis gas (syngas) by adopting the H_2/CO ratio and converted basically to any hydrocarbon desired. It can be methanized (biomethane) or converted into other gaseous fuels (dimethylether, hydrogen) or liquefied and upgraded to Fischer-Tropsch diesel, ethanol, or methanol. These synthetic fuels can be also used for heat and power generation (Vogel, 2006; Sterner, 2007).

Gasifiers for heat and power services are very common in the emerging nations of India and China. The operation conditions and requirements on emissions (off gas and waste water) of gasification plants are usually tougher in industrialized countries like Germany or Austria than in emerging countries. Their construction and operation is sophisticated, resulting in high production costs. Due to these technical and economic challenges, only very few gasification plants for heat and power generation are found in Europe (Vogel, 2007).

While gasification for heat and power is standard technology in Asia, it is still at a demonstration scale in Europe. Commercial second generation biofuel plants can be expected in 2020 or only in 2030. The most promising concepts show a high process integration, which ensures maximum fuel utilization and high efficiencies (Sterner, 2007). One Austrian example is the polygeneration concept using a circulating fluidized double bed gasifier for heat, power and biomethane generation (TU Vienna, 2005). Another Swedish example integrates an efficient production of biofuel (methanol, dimethylether), power and heat or biorefinery products in a pulp and paper mill (Lindblom et al., 2007).

Pyrolysis

Pyrolysis is a thermochemical process that decomposes biomass into mainly liquid products at oxygen abundant conditions. The goal of the process is to maximize the share of liquid product output (pyrolysis oil) and use solid and gaseous pyrolysis products in the process internally. Flash-pyrolysis is done by heating biomass up to 450°C at very steep ramp rates (1,000 °C/s) and short retention times. The gaseous products are condensed and the product oil can be used for second generation biofuel production or power and heat (Kaltschmitt et al., 2003), 477ff. The main benefit is an up to 10-fold higher energy density of bio-pyrolysis oil (slurry) compared to raw products like wheat straw. However, only few demonstration pyrolysis plants are set up in Europe (Sterner, 2007).

A4.2 Physical-chemical conversion processes

Extraction

Biofuels can be produced by pressing and extracting oil rich crops like rape seeds, soybeans, sunflower or tropical fruits like jatropha, palm or coconut. The process technology is basically the same as for vegetable oil production. Also residues like animal fat from meat processing or fishing industries or cooking oil from restaurants serve as biofuels. Leftovers like press cake can be used energetically (e.g. direct combustion) or as fodder substitute (e.g. instead of maize or soy). The pressing technology is available both small scale (e.g. for agriculture use) and industrial scale. Alternatively, oil can be extracted chemically by using a solvent (e.g. hexane). The solvent is separated from the extracted oil via distillation and recycled. The extracted oils can be used as 'straight vegetable oil' in diesel engines or CHPs for transport, mechanical power, electrical power or heat. In temperate climate regions, diesel engines have to be adopted to fit pure vegetable oil as the oil's viscosity is too high for direct motor application. A unit for pre-heating the oil is necessary (FNR, 2005; GBEP, 2008). Instead of adopting the engine to the fuel, the fuel can also be adopted to the engine. This is done via transesterification of vegetable oil to biodiesel.

Transesterification

Vegetable oil or waste grease can be converted into biodiesel with the help of an alcohol and a catalyst. The mix of 80-90% oil, 10-20% alcohol and the catalyst is heated to produce biodiesel. This conversion to FAME (Fatty Acid Methyl Ester) has an efficiency of 5-10% (Dreier et al., 2000). Transesterification is state-of-the-art technology. Biodiesel has almost the same and even better fuel properties like fossil diesel, which enables blending (e.g. 5% equals B5). In the blend, biodiesel improves combustion properties, fuel lubricity and the cetane number. It is used also purely as B100. Biodiesel is used commonly in diesel cars but can be also combusted in stationary compression ignition engines (CHP). However, it is more efficient to use directly vegetable oil in CHPs than to convert the oil first into biodiesel (FNR, 2005, FNR, 2006a; GBEP, 2008).

A4.3 Biochemical conversion processes

The biochemical conversion of biomass into bioenergy carriers is done by microorganisms.

Anaerobic digestion - fermentation

Fermentation is the break down of biogenic material by micro-bacteria in the absence of oxygen. The organic matter that is used here can be organic waste, manure or energy crops like maize or grass. The final product of this fermentation is a combustible mixed gas that comprises of methane (50–70%) and carbon dioxide (25–40%). The conversion process can be classified into four stages: (1) Hydrolysis, (2) Acidogenesis, (3) Acetogenesis and (4) Methanogenesis.

In hydrolysis, the complex large organic polymers (e.g. carbohydrates, fats, proteins) are broken down in smaller simpler monomers like sugars, fatty acids and amino acids. The acetate and hydrogen released in hydrolysis can be used directly in methanogenesis and can be converted into methane. The other intermediate molecules are further cracked down by acidogenic bacteria into shorter fatty acids (acetic-, propionic- and butanoic acid), carbon dioxide and hydrogen. Further products are low amounts of alcohols, ammonia and lactic acid. In acetogenesis, these products are digested and converted into acetic acid, hydrogen and carbon dioxide as pre-biogas products. Finally, all intermediate products are converted into methane via methanogenesis. A simple example of the overall chemical reaction is the conversion of $C_6H_{12}O_6$ to three CO_2 and three CH_4 (FNR, 2006b; BayLfU, 2004).

These processes run in one single or several fermenters, which are the core device of each biogas plant. To obtain high methane yields, the fermenter temperature has to be in the range of 35 to 37°C, which is comfortable for the working bacteria. In many cases waste heat of the power generation engine is used for fermenter heating. Some organic waste has to pass a sanitation stage first before entering the fermenter. The digestates are deposited in a post-fermenter and conventionally used as fertilizer. Unwanted methane and N_2O emission by leakage affect the overall GHG balance negatively, which is why post-fermenters are supposed to be covered and closed (Zah et al., 2007).

Biogas can be applied as heat and light source (mainly in developing countries) or for heat and power generation in CHPs or micro gasturbines (mainly done in industrialized countries). It can be also upgraded to biomethane and fed into the natural gas grid as substitute natural gas. The main advantage of this upgrading process is the use of the natural gas grid as storage medium. In this way, biogas can be collected decentrally, distributed easily and used centrally or decentrally for power and heat generation or in transport as vehicle fuel. This increased flexibility and storability is the main advantage of biomethane, which can also be produced via gasification of non-digestable biomass like woody biomass. Another core advantage of producing biomethane is the fact that the CO_2 has to be separated from the biogas or syngas. The first step of carbon capture and storage is thereby implemented. If the captured CO_2 can be stored adequately, biomethane production offers a practical way of decarbonizing the atmosphere: CO_2 is absorbed by the plant. The plant is gasified or digested into biomethane, whereby the CO_2 is separated and stored and thus permanently withdrawn from the atmosphere. The flexibility of biomethane on both the biomass feedstock side and the energy system side and the ability of decarbonization are turning biomethane into a strategic option in (bio)energy and climate policy (WBGU, 2009).

Industrial biogas plants have become very popular in Europe within the last decade (IE, 2008). In many parts of Asia small biogas digesters have been quite common since the 1960s. Today, about 25 million households worldwide use biogas for lighting and cooking (REN21, 2008b). The fermenters can be operated in sub-tropical and tropical conditions without extra heat supply. Low maintenance effort, simple installation and simple handling of the plants are the basis of this success.

Composting

Composting or aerobic digestion is the break down of biogenic material by micro-bacteria in the presence of oxygen. Usually organic waste like food waste or road side vegetation is used for composting. The process releases heat, which could theoretically be used as bioenergy for heat supply via heat pumps. In reality, however, waste heat of composting is not used and if energy production is intended, the anaerobic digestion of biodegradable materials to biogas is preferred (FNR, 2005).

Ethanol fermentation

Ethanol can be produced from sugar-containing, starchy or cellulosic organic matter by the help of yeast and bacteria and purified by distillation and rectification respectively. Starchy and cellulosic materials have to be converted into glucose first. Then, glucose is converted into ethanol and carbon dioxide.

Ethanol fermentation is state-of-the-art and applied in bakeries and alcoholic beverages. The main bioethanol feedstocks are sugar cane (Brazil) and maize (USA). Bioethanol can be applied as transport fuel vehicles and airplanes or for heat and power generation in CHPs. It can be blended with fossil gasoline up to 5% for usage in conventional cars (E5) and blended up to 85% and used in 'flexible fuel' vehicles (E85) (FNR, 2005; REN21, 2008a). The volumetric content cannot be replaced one-to-one, since the energy content of bioethanol equals only 65% of fossil petrol. Producing bioethanol from lignocellulosic feedstocks via fermentation is done in a first stage in pilot scale (Igelspacher et al., 2006). Bioethanol from woody biomass via gasification is theoretically also possible (Sterner, 2007). The benefit of lignocellulosic bioethanol is a broader biomass feedstock that can be utilized.

A5 Definition of conversion efficiency and system boundaries

To compare different process technologies, the definition of efficiency is a fundamental part of technical assessment.

The German industry guideline VDI 4661 serves for the purpose of comparing bioenergy applications for power, heat and transport. It enables the necessary cross-sectoral evaluation. In general, the efficiency of a system is defined as the quotient of the power output (benefit) and the power input (effort). The definition of benefit and effort depends on the application itself and its energy supply task.

The target power is the benefit of the system. It is the form of power aimed at in the energy-conversion process (VDI, 2003; Stiens, 2000). In this work, target power is defined as mechanical, electrical and thermal energy, i.e. useful heat. The supply task of bioenergy is therefore the provision of mobility (shaft power), electricity and useful heat.

All energy balances must include the core conversion of all forms of bioenergy: the combustion of the bio-energy carrier. Consequently, the energy balance for transport is not limited to biofuel as energy carrier, but also encloses its combustion in the car's mobile combustion engine.

This definition is similar to the efficiency definition of CHP plants, where thermal and electrical power are considered equally as target power. The definition can be called 'polygeneration' method, as all forms of power outputs are considered equal and compared on a neutral exergy basis.

The efficiency of bioenergy pathways is calculated according to VDI 4661 as the fraction of the target power referred to the sum of the fuel power of the raw-biomass, the auxiliary power for feedstock cultivation and provision, transport and thermal and electrical power reduced by the fuel power or accounted power of by-products (Equation A5-1).

$$\eta_{ex/en} = \frac{P_{out}(benefit)}{P_{in}(effort)} = \frac{P_{net\_electr\_power} + P_{mech\_power} + P_{Heat} \cdot \eta_{Carnot}}{P_{Raw\_Biomass} + P_{AP\_Cultivation} + \sum P_{AP\_Trans.} + P_{AP\_therm.} + P_{AP\_electr.} - P_{By\_products}}$$

Equation A5-1: Calculation of exergetic and energetic conversion efficiency. In exergetic efficiency, heat is weighted with the Carnot efficiency. The calculation of energetic efficiency is done in the same way but without applying the Carnot efficiency factor, i.e. not temperature-dependent. AP means Auxiliary Power.

Accounting of auxiliary power and by-products

The main power input to a system is the raw-biomass input. Besides main and target power, additional power can be accounted as auxiliary power or by-product power (Figure A5-1).

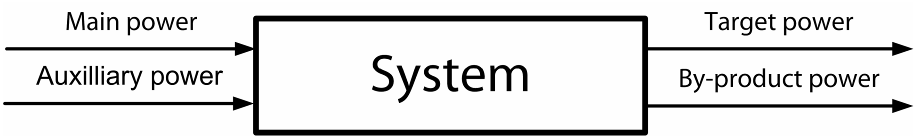

Figure A5-1: Definition of auxiliary power and by-product power integration. Source: own compilation.

Conventionally, auxiliary power is considered as additional effort and therefore added to the main power input. Examples of auxiliary power are machine employment for growing and harvesting biomass, transport raw-biomass and bioenergy carrier and electricity and heat in the biomass conversion process itself. If auxiliary power is of the same form of energy as one target power, it can be subtracted from the output (VDI, 2000b).

Therefore, a necessary electrical power input is subtracted from the electrical power output, resulting in a net electrical power output. In reality, this may not be the case due to economic reasons if power can be sold with a higher price than it is purchased. This accounting does not apply in the same way for auxiliary thermal power, which can only be subtracted from target thermal power if it is integrated into the process. In most cases, the temperature level of surplus heat is lower than the required auxiliary process heat. In steam power plants, auxiliary power like thermal process power is as well added to the effort and not subtracted from the benefit (Strauß, 2006; Bolhár-Nordenkampf, 2004). Thus, all forms of auxiliary power are added to the 'effort', except the internal electricity consumption of a plant if the plant itself is producing electricity. If the internal electricity demand is smaller than the production, it is subtracted from the 'benefit' and otherwise added to the 'effort'.

Besides target power, bioenergy pathways can have many by-products of energetic and material value ($P_{by\text{-}products}$ in Equation A5-1). As 'by-products' are not the main target of a bioenergy pathway and rather substituting fossil fuel based products, they are not added to the 'benefit' but subtracted from the 'effort'. In this work, by-products are integrated into efficiency calculations by accounting a certain percentage of their energetic value.

This percentage is determined by qualitative and quantitative estimations. Pure energetic by-products like heat and power are accounted 100%. For all other by-products, the following assumptions are made: Chemical by-products like naphtha (raw-petrol) and glycerine (for biogas plant or chemical industry), that can be used directly for energetic purposes, are accounted 90%, assuming a high thermal combustion efficiency for naphtha and digestion efficiency for glycerine. Sugar cane bagasse from bioethanol production is usually used in boilers for internal heat (and power) supply of the ethanol plant but has to be dried first and is therefore accounted 70%.

The press cake and leftovers from jatropha and palm oil production are not suitable as fodder but can be applied as well for energy purposes (biogas plants, combustion), however they need to be upgraded (e.g. drying) and are therefore calculated or 'accounted' as 70%. Press cake from rape seed oil production or DDGS (Dried Distillers Grains with Solubles) from ethanol production are conventionally used as animal fodder and replace conventional fodder, i.e. fossil energy in form of mineral fertilizer, machine diesel, etc. These by-products are accounted as 50%, as their upgrading usually is energy-intensive.

The energetic value of digestates from biogas plants can be calculated by comparing the fossil energy amount used for mineral fertilizer, which is replaced by biogas digestates. The percentage that can be accounted depends strongly on the feedstock of the biogas plant, i.e. the nitrogen, potassium and phosphor content of the digestate.

A rough estimate of (Gutser, 25.01.08) gives a mineral fertilizer-equivalent of energy crops digestate between 40 and 60% and for cofermentation of manure with residues and waste a range of 50 to 70%. For a conventional 500kW plant, about 280 ha of maize are used and 7,000 t of digestate are left over per year, which can replace mineral fertilizer of about 32 t nitrogen, 60 t potassium and 20 t phosphor, which is equivalent to about 3400 GJ fossil fuel. The digestate itself contains about 8,000 GJ chemical energy. Thus, about 45% of the energy content of digestate can be accounted. The same amount is accounted for organic waste. The nutrient content of other feedstock's digestate is even higher. For manure digestate, 70% can be accounted and for grass silage digestate, about 50% (KTBL, 2009; Scholwin, 2007).

These assumptions for the use of by-products are of a theoretical nature. The real utilization rates of by-products depends on (i) economics, (ii) conversion technologies, and (iii) the plant site itself and possible synergies with other industrial processes.

System boundaries

Each efficiency definition is related to a system boundary definition. The system boundary for all pathways is covering energy crop cultivation, residues provision, feedstock transport, conversion of raw-biomass to a bioenergy carrier / 'product' like biofuels or biopower and product conversion to target and final energy heat, electricity and mechanical shaft power. By-products and auxiliary power are integrated into the described way (Figure A5-2).

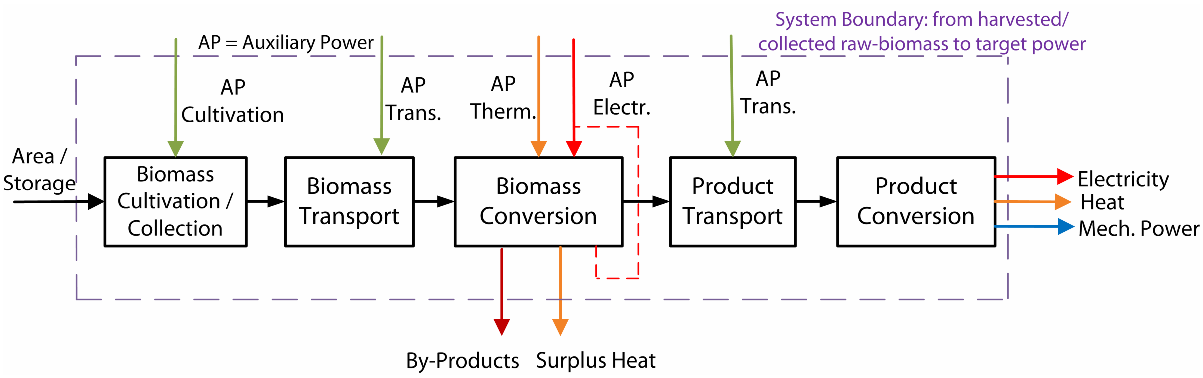

Figure A5-2: System boundaries for efficiency calculations. All energy fluxes along the pathway are integrated: raw biomass as main power input and electrical, mechanical and thermal energy as main power output as well as all auxiliary power forms and by-products like surplus heat, press cakes, naphtha, bagasse, glycerine and digestates. Source: own compilation.

Data basis, utilization rates (full-load hours) and other assumptions

The data basis for efficiency and cost calculations are given in (Müller-Langer, 2008; Sterner, 2007; WBA, 2007; Fritsche et al., 2008b). The 'utilization rate' or 'full-load hours' (FLh) of all CHP applications were set to 8,000 full-load hours (FLh), except for industrial solid oxide fuel cells (7,000 FLh) and co-firing of pellets in coal power plants (6,000 FLh). All mobility provisions chains, mainly biofuel production plants, are set to 8,000 FLh. The full-load hours of the 15kW pellet heating system was assumed to 1600 FLh and the larger 400kW wood chips heating system to 2600 FLh. The auxiliary energy effort for transporting raw-biomass is set to a distance of 50 km and for distribution of bioenergy carriers like biofuels at a distance of 300 km.

Exergy of heat

One energy unit of thermal energy is not of the same ‚value' as one energy unit of electricity/work. According to the second law of thermodynamics, „it is impossible to convert heat completely into work in a cyclic process"(Baehr et al., 2006). Only part of the heat can be converted into mechanical and electrical power. This share is called exergy and depends on the temperature level of the heat. It can be determined by Carnot efficiency in Equation A5-2. Vice versa, mechanical or electrical energy can be converted 100% into heat. The exergy of heat is the equivalent to mechanical and electrical energy. The anergy of heat is the part, which cannot be converted into this 'high quality' energy form. Energy is always the sum of exergy and anergy (Baehr, 1965; Baehr et al., 2006).

In the efficiency calculations, the exergy of heat is determined by Equation A5-2 at an ambient temperature T_L = 293K (20°C) and the heat temperatures at different levels. The temperature level of the CHP by-product heat is assumed to be 110°C of all concepts larger than 10 MW. For all other concepts, the temperature level is assumed to be 90°C with the exception of 70°C for small heating applications, like e.g. pellet heating, traditional biomass-fired stoves, improved cooking stoves, and biogas stoves.

$$E_{ex} = E_{th} \cdot \eta_c = E_{th} \cdot \left(1 - \frac{T_L}{T_U}\right)$$

Equation A5-2: Calculation of the exergy of heat.

Parameters and efficiency of cars in applied mobility pathways

The investigated mobility pathways contain the combustion of biomass and therefore as well the car technology. Characteristic data of average middle vehicle class are used that were calculated according to the NEDC (New European Driving Cycle), which represents the typical use of a car (including urban and over-land drive cycles) (Müller-Langer, 2008; Zimmer, 2009). The vehicle efficiencies and ranges are listed in Table A5-1.

Table A5-1: Characteristic data of selected vehicle types applied in mobility pathways. MJ_Input corresponds to the 'tanked' energy, i.e. one MJ chemical energy in form of fuel and one MJ electricity. The efficiency of methane in combustion engines is usually higher than for gasoline and the given vehicle efficiency for all vehicle types is rather high. Nevertheless, the available source was used. Source: (Müller-Langer, 2008; WBGU, 2009; Zimmer, 2009).

Vehicle type - Drive unit	**Time frame**	**Range** in km per MJ_{input}	**Vehicle efficiency tank-to-wheel** in $MJ_{mech\_shaft\_power}$ per MJ_{input}
Otto internal combustion engine for gasoline and methane	2005	0.37	0.26
	2030	0.48	0.29
Diesel internal combustion engine for diesel and plant oil	2005	0.43	0.29
	2030	0.53	0.32
Electric engine	2030	1.11	0.78
PEM-Hydrogen-Fuelcell-car with an electric engine	2030	0.71	0.39

Allocation method for economic and ecologic calculations

The allocation method described in chapter A7 is used to integrate all by-products and target energy outputs in a comparable manner in cost and GHG balance calculations.

A6 Framework for production cost analysis

The following framework is applied for all bioenergy conversion plants, except for two wood chips heating systems, which are given in (WBA, 2007).

The expected useful life is set to 15 years. The inflation rate for all payments is assumed as 1.5%. Possible taxes or subsidies are not calculated.

Capital-related costs include annual payments for the total investment costs and maintenance costs as 1.5% of the total investment costs. The investment costs are covered by a 20% equity with a 15% interest rate and an 80% loan capital with an 8% interest rate.

The conversion chain parts included in investment costs differ by energy sector:

- Mobility: biofuel / biopower production plant and auxiliary devices
- Heat: boiler and heat distribution system
- Heat and power: biopower production plant and auxiliary devices; for co-firing in coal power plants, only extra costs for additional devices for a 10% co-firing of biomass are considered as 'investment cost'.

Operation-related costs include e.g. personnel costs, administration costs, insurance costs, maintenance costs and waste disposal costs.

Consumption-related costs consist of biomass provision costs (except for organic waste, whose disposal gives revenues), auxiliary energy costs (e.g. heat and power) and auxiliary material costs (e.g. chemicals, water).

The sum of capital-related, operation-related, consumption-related costs and revenues from by-products gives the annuity of total annual payments. Production costs are calculated as the annuity divided by annual energy yields.

A7 Methodology of greenhouse gas balances and mitigation costs

The applied method for GHG balancing shall conform to the ISO 14000 environmental management standards, in particular to the ISO 14040 series on life-cycle assessments. Inputs (fossil fuels, raw materials) and outputs (GHG, pollutants) along the production chain are accounted and analyzed according to their environmental impacts.

This includes the assessment of raw material production, conversion, distribution, use and disposal. A life-cycle assessment evaluates the impact of products in a holistic way, i.e. impacts on global warming, eutrophication, acidification, air pollutants, land use, and many other parameters. The single GHG balancing applied in this thesis is rather a life-cycle inventory than a full life-cycle assessment, as only one of the many possible parameters is evaluated. GHG (in particular CO_2, CH_4 and N_2O) are thus accounted according to their global warming potential for a period of 100 years (Kyoto protocol and IPCC standard) (IPCC, 2007f).

Like any balancing method, the ISO norms offer room for interpretation and thus results are sensitive to system definitions like system boundaries and the chosen 'functional unit' on which all values are related. It is of fundamental difference in bioenergy GHG balancing, whether this unit is kWh_{th} chemical energy of heat, biofuels or raw biomass (dry matter). This come into effect in accounting by-products such as straw, press cakes, bagasse or CHP waste heat and so on. The life-cycle assessment software GEMIS 4.5 has been applied for all GHG balance calculations (Fritsche et al., 2008b).

Allocation of by-products

In bioenergy provision, by-products are generated in agriculture and energy conversion. The used resources (energy, area, water, materials) and the caused emissions have to be split between main products (bioenergy) and by-products.

ISO 14040 norms suggest to deal with by-products in the following priority: (i) avoiding allocation by extension of system boundaries, (ii) credits for by-products, or (iii) allocation of by-products according to their price, mass, or energy content. For bioenergy GHG balances, the allocation of emissions between main and co-products via heating values has been proven to be the most favorable methodology option, as the extension of system boundaries is difficult due to missing data and credits for by-products depend strongly on current prices and are thus highly volatile (IFEU, 2007).

For example growing rape on one hectare produces rape straw, rape seed press cake and rape seed oil. Rape straw is ploughed in, but the press cake is used as animal fodder, replacing other fodder like maize, which reduces the required area. Therefore, the area used for energy (plant oil) and fodder (press cake) is split and emissions are allocated accordingly (WBGU, 2009).

In this thesis, all energetic and material by-products are allocated along the pathway according to their lower heating values by allocation factors (AF). These factors determine which share of area / emissions / energy is assigned to the main product (e.g. plant oil) and to the by-product (e.g. press cake). The larger the factor, the higher the allocated share of input energy / material / emissions / etc. on the product.

$$AF = \frac{m_{MP} \cdot LHV_{MP}}{m_{MP} \cdot LHV_{MP} + \sum\left(m_{BP,n} \cdot LHV_{BP,n}\right) + E_{el} \cdot F_{el-eq.} + E_{th} \cdot F_{th-eq.}}$$

Equation A7-1: Calculation of energetic allocation factors (AF). m_{MP} – mass of main product; m_{BP} – mass of by-product; LHV_{MP} – lower heating value of main product; LHV_{BP} – lower heating value of by-product; E_{el} – electricity as by-product; E_{th} – heat as by-product; F_{el} – 'heating value' of electricity (2.5 kWh_{th} / kWh_{el}); F_{th} – 'heating value' of heat (1 kWh_{th}). Source: adopted from (WBGU, 2009; Müller-Langer, 2008).

Some bioenergy conversion processes require auxiliary energy like electricity and heat. It is assumed that electricity is generated by a 50/50 mix of natural gas combined cycle power plants (electrical efficiency 60%) and coal power plants (electrical efficiency 44%). For heat provision, a natural gas condensing boiler with a thermal efficiency of 95% serves as assumption. Electrical energy is allocated with a 'heating value' of $F_{el\text{-}eq.}$ = 2.5 kWh_{th} per kWh_{el}, which corresponds to a electrical conversion efficiency of 40% and balances thus the thermodynamically high exergetic value of electricity (Fritsche et al., 2008c). Equation A7-1 illustrates the calculation of allocation factors.

In CHP pathways, the main product is electricity and the by-product heat accordingly. The allocation factors for CHP electricity and heat are built by relating the electrical and thermal conversion efficiency combined with the energetic values of electricity (2.5) and heat (1) (Equation A7-2).

$$AF_{el-CHP} = \frac{2{,}5 \cdot \eta_{el}}{(2.5 \cdot \eta_{el} + \eta_{th})} \quad AF_{th-CHP} = \frac{\eta_{th}}{(2.5 \cdot \eta_{el} + \eta_{th})}$$

Equation A7-2: Allocation factors (AF) of electricity and heat from CHP plants. η_{el} – electrical CHP efficiency; η_{th} – thermal CHP efficiency. Source: adopted from (WBGU, 2009; Müller-Langer, 2008).

Table A7-1 illustrates the assumed efficiencies and calculated allocation factors for CHP plants. High electrical efficiencies result in high allocation factors due to the high 'energetic value' of electricity. Therefore, the largest share of GHG emissions from bioenergy CHPs is allocated to electricity and the avoided fossil emissions from CHP heat use are not accounted. This is one major drawback of the allocation by 'heating values'. A simple solution is not present. Any applied GHG balancing method has more or less drawbacks.

Table A7-1: Efficiencies and allocation factors for electricity from CHP pathways. Source: modified and adopted from (WBGU, 2009; Müller-Langer, 2008).

Technology	Electrical efficiency	Thermal efficiency	Allocation factor for CHP electricity
CHP	38%	44%	0.68
SOFC	48%	23%	0.84
Steam turbine	23%	60%	0.49
Gas turbine	25%	55%	0.53
Coal power plant	45%	6%	0.95
Combined cycle power plant	43%	30%	0.78

Therefore, it is important to know the applied method when comparing GHG balancing and life-cycle assessment results of different studies. Especially the system boundary and the accounting of by-products are of importance.

Examples for varying parameters in bioenergy life-cycle assessments:

- different functional units: Energy output, energy input, product value
- different system boundaries: biofuels including the vehicle, without the vehicle
- different time frames are important for land-use change emissions: 10, 20 years
- different assumptions on land-use change emissions: with or without GHG emissions from direct / indirect land-use change

Calculation of greenhouse gas mitigation costs

Usually, the production costs of bioenergy are higher than the production costs of fossil fuels. The difference is the additional cost for bioenergy. The GHG mitigation costs are calculated as the fraction of additional costs and GHG reductions. The GHG reductions result from the net GHG emissions avoided by substituting fossil energy with bioenergy. In some cases, bioenergy does not result in net GHG reductions but in more GHG emissions than the fossil reference. In this case, no GHG mitigation costs can be calculated. Equation A7-3 illustrates the calculation of GHG mitigation costs.

$$C_{GHG\_mitigation} = \frac{C_{Bioenergy} - C_{Fossil\_reference}}{GHG_{Fossil\_ref} - GHG_{Bioenergy}} = \frac{\Delta C}{\Delta GHG} \qquad with \quad \Delta GHG > 0$$

Equation A7-3: Calculation of GHG mitigation costs ($C_{GHG\_mitigation}$ in EUR per t $CO_{2\text{-eq.}}$). $C_{Bioenergy}$ – specific production cost of bioenergy; $C_{Fossil\_reference}$ - specific production cost of fossil reference; ΔC – additional costs of bioenergy (All specific costs in EURCents per kWh_{el} or kWh_{th} or driven kilometer). $GHG_{Bioenergy}$ – GHG emissions of bioenergy; GHG_{Fossil_ref} – GHG emissions of fossil reference; ΔGHG – net GHG emissions avoided by substituting fossil fuels with bioenergy (All GHG emissions in t $CO_{2\text{-eq.}}$ per $TJ_{raw\_biomass}$). Source: adopted from (WBGU, 2009; Müller-Langer, 2008).

System boundary

The same system boundaries were applied for GHG balances as it is the case for energy balances (see chapter A5).

Sensitivity

Sensitivity in biomass pathways are inherent in:

- hectare yields of energy crops
- efficiency and scale of conversion plants
- own energy and material consumption of conversion plants
- costs of pathways (e.g. include / exclude costs of vehicles)
- conversion plant technology (e.g. cover of biogas co-fermenter or not)
- fossil reference system
- inclusion / exclusion of GHG emissions from direct / indirect land-use changes
- inclusion / exclusion of GHG emissions from soil respiration

In this thesis, average values for all input parameters have been used in GHG balance calculation. The basic cost of vehicles was excluded in costs calculations, except surplus cost of new technologies like electromobility. The fossil reference system is described and a sensitivity analysis conducted. Emissions caused by direct and indirect land-use changes have been accounted in GHG balances (see chapter 2.4).

A8 Figures

A9 Tables

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Herausgegeben von / Edited by
Prof. Dr.-Ing. Jürgen Schmid, Universität Kassel

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