The Energy System and Intergenerational Issues

Energy Substitution and Resource Economics

Master's Thesis

Institute of Electricity Economics and Energy Innovation
Graz University of Technology

Submitted by
Philipp Mattle, MSc

Supervised by
Univ.-Prof. DI Mag.rer.soc.oec. Dr. Heinrich Stigler
Ass.Prof. DI Dr. Udo Bachhiesl
DI Gernot Nischler

Head of Institute: Univ.-Prof. DI Mag.rer.soc.oec. Dr. Heinrich Stigler

A - 8010 Graz, Inffeldgasse 18-III
Tel.: (+43 316) 873 – 7900
Fax: (+43 316) 873 – 7910
http://www.iee.tugraz.at
http://www.tugraz.at

Graz / Juli 2011

Acknowledgements

I would like to express my appreciation to my supervisor Univ.-Prof. DI Mag.rer.soc.oec. Dr. Heinrich Stigler for supporting this thesis. In addition, special thanks are due to my advisors Ass.Prof. DI Dr. Udo Bachhiesl and DI Gernot Nischler. I also acknowledge with great appreciation the interesting and inspiring discussions with Univ.-Prof. DI Karl Rose from the University of Graz.

For proofreading and the friendship over all the years, I wish to thank my flatmate Michael.

My special gratitude goes to my family for their interest in my studies and the motivation they gave me. I also thank my grandparents for supporting me during the years of my studies.

Finally, my most heartfelt thanks go to my girlfriend Manu for her unconditional support, enduring patience, understanding and love.

STATUTORY DECLARATION

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

……………………………   ………………………………………………..

Date   (Signature)

Abstract

The energy system has emerged to one of the major issues for our society due to scarce resources and changing climate as a result of the anthropogenic greenhouse effect. The matter is how to transform the world's energy system that is by now mainly based on fossil fuels.

Within this work the transformation processes in the energy system are analyzed. For that purpose an assessment of the energy system based on the Primary Energy Substitution Model, which was introduced by Cesare Marchetti in 1977, is performed. The analysis of real world data shows disruptions of the long-time change processes of the energy system in the 1970s. Particular interesting changes are observed in the development path of coal. Additional examinations of the final consumption demonstrate that a large part of the fossil energy sources is not directly consumed in its original energy form but transformed into another form of energy before provided to the end user. Especially electric power gains importance, which is on the one hand related to changed usage of fossil fuels and on the other hand a consequence of increasing generation of electricity from renewable energy sources.

Today's energy system relies heavily on fossil energy sources. Since fossil fuels are exhaustible resources, which can be interpreted as only once available for all human generations, considerations on the development of the energy system need to take intergenerational issues into account. The question how prosperity for the present and future generations, which is related to consumption possibilities, can be attained under the constraint of a finite stock of natural resources is studied within the framework of resource economics. Consumption is always related to the allocation of resources. Therefore, it is discussed what is the optimal allocation of finite natural resources for all generations and whether a market economy is capable of allocating natural resources intergenerationally optimal.

Kurzfassung

Das Energiesystem hat sich speziell durch die Klimaproblematik und die knapper werdenden Ressourcen zu einem wichtigen Thema für unsere Gesellschaft entwickelt. Die Veränderung der Energiesystems, das zurzeit vor allem auf fossilen Energieträgern beruht, stellt eine besondere Herausforderung dar.

In dieser Arbeit werden Veränderungsprozesse im Energiesystem analysiert. Die Untersuchung der Vorgänge im Energiesystem basiert auf dem „Primary Energy Substitution Model“, das 1977 durch Cesare Marchetti vorgestellt wurde. Die Analyse von realen Daten zeigt grundsätzlich langfristige Veränderungsprozesse und deutet auf einen Systembruch in den 1970er Jahren hin. Besonders interessant erscheint der Verlauf des Marktanteils von Kohle. Zusätzliche Untersuchungen zum Endverbrauch weisen darauf hin, dass sich der Anteil der Primärenergieträger, der nicht in der ursprünglichen Energieform konsumiert wird sondern vor der Lieferung an den Endkonsumenten umgewandelt wird, erhöht. Elektrizität gewinnt dabei an Bedeutung, da einerseits fossile Energieträger in der Stromproduktion Verwendung finden und andererseits vermehrt erneuerbare Energiequellen durch Elektrizität nutzbar gemacht werden.

Aufgrund des großen Anteils von fossilen Energieträgern im aktuellen Energiesystem und der Tatsache, dass fossile Energieträger erschöpfliche Ressourcen sind, die nur in einer begrenzten Menge für alle Generation gemeinsam zur Verfügung stehen, ist die Berücksichtigung der Intergenerationenproblematik im Zusammenhang mit dem Energiesystem notwendig. Die Frage, wie Wohlstand für alle Generation, der mit Konsummöglichkeiten in Verbindung steht, trotz einem begrenzten Ressourcenvorrat erreicht werden kann, wird anhand von theoretischen Erkenntnissen der Ressourcenökonomie untersucht. Da Konsum mit der Bereitstellung von Ressourcen verbunden ist, ist zu klären, wie die optimale Bereitstellung von begrenzten Ressourcen für alle Generationen aussieht und ob eine Marktwirtschaft diese optimale Allokation erreichen kann.

Table of Contents

List of Abbreviations ... 1

1 Introduction ... 4

2 Primary Energy Substitution Model ... 6

2.1 Theoretical Basics and Historical Development ... 6

2.2 The original Primary Energy Substitution Model ... 11

2.3 Critical Appreciation ... 19

3 Analysis of the Energy System ... 24

3.1 Global Analysis ... 27

3.2 Regional Analysis ... 36

3.2.1 Europe ... 37

3.2.2 USA ... 41

3.2.3 China ... 46

3.3 Energy Substitution Concluded ... 50

4 Resource Economics and Intergenerational Issues ... 60

4.1 Concepts in Resource Economics ... 65

4.1.1 Classical Economics ... 65

4.1.2 Neoclassical Economics ... 73

4.2 Modern Resource Economics ... 90

4.2.1 Intergenerational Efficiency and Intergenerational Equity ... 91

4.2.2 Intergenerational Utilization of Nonrenewable Resources ... 98

4.2.3 Sustainability and Capital Stock ... 113

5 Conclusions for the Electricity Sector ... 116

6 Summary ... 126

List of Figures ... 129

List of Tables ... 131

Bibliography ... 132

List of Abbreviations

CHP …	Combined heat and power
EIA …	Energy Information Administration
FFF …	Fluid fossil fuels
RES …	Renewable Energy Sources
USA …	United States of America

AL …	Effective labor
A_t …	Technology at time t
$C(R_t)$…	Extraction costs at time t
$c(R_t)$ …	Marginal costs of extraction at time t
co …	Consumption per unit of effective labor
co^* …	Golden rule consumption per unit of effective labor
Co_t …	Consumption at time t
d…	Discount rate
D_t …	Demand function
F …	Fraction of the market
g …	Rate of technological progress
$h_j(t)$ …	Logarithm of the relative market share of technology j
$h_j'(t)$ …	First derivative of $hj(t)$
$h_j''(t)$ …	Second derivative of $hj(t)$
I_t …	Investment at time t
K …	Capital input
k …	Capital per unit of effective labor
k^* …	Golden rule capital stock per unit of effective labor

K_t …	Capital at time t
K_{t+1} …	Capital at time t+1 (in the next period)
L …	Labor input
L_0 …	Initial Population
L_t …	Labor at time t / Population at time t
MEC …	Marginal extraction costs
MEC_x …	Marginal extraction costs in period x
MEC^X…	Marginal extraction costs for deposit X
MWP_x …	Marginal willingness to pay in period x
N …	Biomass density of population
OC_x …	Opportunity costs of the extraction in period x
$\bar{\bar{p}}$ …	Constant price
p_0…	Price at time t=0
p_0^X …	Price at time t=0 for deposit X
p_0^x …	Price at time t=0 at discount rate x
p_M …	Maximum price
p_x …	Price x
r …	Rate of discount / interest rate
R …	Land input
$\bar{\bar{R}}$…	Total stock of the resource
R_t …	Extracted quantity of the resource at time t / Resource input at time t
ΔR_0^x …	Extraction quantity at time t=0 and discount rate x
ΔR_t …	Extraction quantity at time t
s …	Saving rate
SV_0 …	Shadow value at time t=0
T …	Time of depletion of the resource
t_0 …	Time at which F=1/2
T_x …	Time of resource depletion at discount rate x

$u(co)$ …	Utility of the actual consumption
$u(co^*)$ …	Utility of the golden rule consumption
$u'(co)$ …	Marginal utility of the actual consumption
$U_1 \ldots U_n$ …	Individual utilities or utilities of generation 1 … n
U_τ …	Utilities of generation τ
W …	Social welfare function
W_t …	Aggregate social welfare at time t
X_t …	Quantity X at time t
X_τ …	Quantity X at time τ
Y …	Net product
y …	Output per unit of effective labor
y^* …	Golden rule output per unit of effective labor
Y_t …	Output at time t
z …	Social rate of discount
α …	Fractional growth
$\underline{\alpha}, \underline{\beta}, \underline{\gamma}$ …	Marginal product of capital
β …	Constant parameter of the logistic curve
Γ, ξ …	Positive constants
δ …	Depreciation factor
κ …	Equilibrium density
λ …	Rate of population growth
π…	Profit

1 Introduction

The changing climate due to anthropogenic greenhouse effect and resource scarcity are two important topics that make the energy system to one of the major issues for our society. On the one hand the economic system relies on energy as a vital production factor and on the other hand the current energy system is strongly related to climate change as well as the ongoing shortage of resources. The challenge is to find a balance between these conflictive subjects.

The question how to enhance the energy system, which is currently mainly based on fossil fuels, is essential. Changes in an economic structure like the energy system are always connected to major investments. Especially in the case of the energy system investments are characterized by capital intensity and long-living assets. This longevity as well as the fact that the finite stock of fossil fuels is available only once, for now and for all following generations, makes clear that time is a key factor for considerations. Due to the long time periods, which need to be taken into account, the considerations have to cover more than one generation. Therefore, intergenerational issues need to be included.

The energy system and its development plus intergenerational issues in the context of resource economics are the main topics of this work. In the following the contents and the structure of the work are briefly described.

Description

At the beginning of this work the energy system with its different energy technologies and sources is the main topic. A model to describe changes in energy markets is introduced. This model is called Primary Energy Substitution Model and was established originally by Cesare Marchetti in the 1970s. It describes substitution processes among different energy technologies respectively among different primary energy sources. Thus, the life cycle of energy sources with growth and decline is represented within the model. The Primary Energy Substitution Model is discussed in chapter 2. After a discussion of previous results, derived from the Primary Energy Substitution Model, the development of the world's energy system after 1950 is analyzed based on this model. Here, the Primary Energy Substitution Model is employed to illustrate changes and trends in the energy market in graphical form in an easy recognizable and structured way.

The global energy market is examined in terms of market share of the most important primary energy sources. The analysis includes the temporal development of petroleum, coal, natural gas, renewable energy sources and nuclear energy. An assessment of long-time and recent trends in the global energy system is performed. The additional analysis of the regional energy markets of Europe, USA and China enables the identification of common changes in the different energy systems and allows evaluating if external effects like political decisions influence the course of the market share of the primary energy sources. Based on the study of regional and global development paths, the role of the primary energy sources in the energy system is investigated. A more detailed insight is gained through the examination of the final consumption at the end user facility. These analyses on the development of the energy system after 1950 are covered in chapter 3 of this work.

Due to the importance of fossil fuels in the current energy system, the question how to utilize exhaustible resources under consideration of intergenerational issues is discussed in the next part of this work. As introduction in the discussion the historic development of major theories in the field of resource economics is described. In the framework of resource economics, the question how prosperity for the present and all subsequent generations can be obtained with a finite stock of resources is analyzed. Prosperity and social welfare is commonly positively related to the possibility of consumption. Consumption in turn is linked to the production of commodities and resources are needed for the production process. For this reason the actual question is if a positive consumption level like in the present can be maintained also in the future when considering that the resources, which are used now, are finite and only once available for all generations. Consequently, it is discussed how finite natural resources are allocated optimally for all generations and if the market economy secures an optimal allocation.

In chapter 4 these questions related to intergenerational issues and resource economics are addressed. Conclusions and a discussion on the importance of electricity for the energy system is the content of chapter 5, which combines the studies of the previous chapters. A summary of the results in chapter 6 finalizes this work.

2 Primary Energy Substitution Model

As this work is based on the Primary Energy Substitution Model developed by C. Marchetti, his publication “Primary Energy Substitution Model: On the Interaction between Energy and Society”[1] serves as starting point.

C. Marchetti’s underlying idea for the Primary Energy Substitution Model is the hypothesis, that the different primary energy sources are commodities competing for a market. Consequently, the competition between the energy sources becomes comparable to other markets. Therefore it is assumed, that similar laws can be used for the description of this market.

The following section gives a brief introduction in substitution models in conjunction with a summary of their historical development and shows some basic principles used in the Primary Energy Substitution Model.

2.1 Theoretical Basics and Historical Development

In order to substitute one commodity in a competitive market another commodity has to grow in terms of market share. Accordingly growth processes are the crucial cause of substitution.

Logistic models are a common way to describe growth processes. The logistic equation was used initially to explain population growth. The English economist Thomas Robert Malthus (1766 - 1834) was the first who introduced logistic functions to exemplify growth processes in “Essay on the principle of Population”. Pierre Francois Verhulst (1804 - 1849) first used logistic curves as a model of population growth and formed equations. Equation (1) describes the population growth according to P. F. Verhulst. He also established the term logistic for these kind of function.[2,3]

---

[1] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

[2] Kucharavy, D. and Guio, R. de Logistic Substitution Model and Technological Forecasting, pp. 1–2, http://www.seecore.org/d/200811.pdf, January 2011.

[3] Kucharavy, D./ Schenk, E./Guio, R. de Long-Run Forecasting of Emerging Technologies with Logistic Models and Growth of Knowledge, p. 278, http://dspace.lib.cranfield.ac.uk/handle/1826/3730, January 2011.

(1)
$$\frac{dN}{dt} = \lambda N \cdot (1 - \frac{N}{\kappa})$$

N ... *Biomass density of population*
λ... *Growth rate*
κ ... *Equilibrium density*

The link between growth and competition was established by the independent works of Alfred J. Lotka (1880 - 1949) and Vito Volterra (1860 - 1940) in 1925 respectively 1926. The so called Lotka-Volterra or predator-prey equations describe the growth process of different species under competition. These equations extend the P. F. Verhulst model from a single-species to a two-species model. Correspondingly, the primary application area of these equations is ecological systems.[4]

Besides the usage of logistic functions in demographic science, Zvi Grillich and Edwin Mansfield employed the concept of logistic curves into the field of economics.[5] In particular, they analyzed technological diffusion. Both analyzed the way how industries adapt to innovations and observed that this introduction process conforms to a logistic function. A sample logistic growth process is shown in Figure 1[6,7]

A further advancement in the use of logistic curves goes back to John C. Fisher and Robert J. Pry and their transformation method of the S-shaped logistic curve. In “A Simple Substitution Model of Technological Change”[8] they developed a model for binary technological substitution.

The Fisher-Pry-Model is based on three assumptions:[9]

- In general technological innovations act as competitive substitution of one method for another.
- After a substitution process moved on to the extent of some percent, the substitution will continue

---

[4] Berryman, A. A. (1992): The Origins and Evolution of the Predator-Prey Theory, in: Ecology, Vol. 73, Issue 5, pp. 1530–1536.

[5] Kucharavy, D. and Guio, R. de Logistic Substitution Model and Technological Forecasting, p. 2, http://www.seecore.org/d/200811.pdf, January 2011.

[6] Mansfield, E. (1961): Technical Change and the Rate of Imitation, in: Econometrica, Vol. 29, Issue 4, pp. 741–766.

[7] Griliches, Z. (1980): Hybrid Corn Revisited: A Reply, in: Econometrica, Vol. 48, Issue 6, pp. 1463–1465.

[8] Fisher, J./Pry, R. (1971): A simple substitution model of technological change, in: Technological Forecasting and Social Change, Vol. 3, pp. 75–88.

[9] Fisher, J./Pry, R. (1971): A simple substitution model of technological change, in: Technological Forecasting and Social Change, Vol. 3, pp. 75–88.

- The fractional rate of the substitution of a new commodity for an old is proportional to the amount that is not yet substituted, which is equivalent to market not yet covered.

The underlying mind of the first assumption is that a new commodity entering a market is not as advanced as an old commodity that is already established. Therefore it is plausible that the new commodity has a higher potential for further development and consequently a higher potential for a reduction in cost, as the initial development will be continued. Furthermore, a commodity that achieved a market share of some percent proved its concept and will gain market share. As a consequence this new commodity will substitute the old one.[10]

J. C. Fisher and R. J. Pry state that substitutions are likely to follow a S-shaped path, as empirical analyses show. The easiest definition of an S-shaped curve is by the early growth rate and the time where the substitution process has half finished, each as a constant. The S-shaped growth path can be specified by equation (2), which is derived directly from the third assumption.

$$\frac{1}{F}\frac{dF}{dt} = \alpha \cdot (1 - F) \tag{2}$$

$F \ldots$ *Fraction of the market*
$\alpha \ldots$ *Fractional growth*

The description of population growth of P. F. Verhulst, as specified in equation (1), is the same logistic function as J. C. Fisher and R. J. Pry used for the “Simple Substitution Model” and as C. Marchetti subsequently incorporates in the Primery Energy Substitution Model given by equation (2).[11] Besides the fractional growth α the time t_0 at which the fraction of market F reached $F=1/2$ is used for the description of the logistic curve defined in equation (2) and the solution to this differential equation is given in equation (3).[12] A sample logistic curve is illustrated in Figure 1. The S-shaped growth path of the world’s air transport in billion passenger-kilometers per year is plotted.

---

[10] Fisher, J./Pry, R. (1971): A simple substitution model of technological change, in: Technological Forecasting and Social Change, Vol. 3, pp. 75–88.

[11] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

[12] Fisher, J./Pry, R. (1971): A simple substitution model of technological change, in: Technological Forecasting and Social Change, Vol. 3, pp. 75–88.

(3)
$$\mathrm{F} = \frac{1}{1 + e^{-\alpha(t-t_0)}}$$

t_0 … *Time at which* $F=1/2$

According to equation (3) the market share is based on an exponential function. Therefore, a graphical representation of equation (3) in the form of $F/(1\text{-}F)$ as a function of time results in straight line on a semilogarithmic plot. Accordingly substitution data can be approximated as straight lines in such a graph. Therefore the approximation task simplifies to a linear problem, as shown in Figure 2. The slope of the resulting linear function equals α.[13] This approach also denoted as Fisher-Pry transformation. Figure 2 shows the Fisher-Pry transformed version of the logistic curve plotted in Figure 1, whereas F is calculated as a fraction of an assumed saturation level κ.

(4)
$$\frac{F}{(1-F)} = e^{\alpha(t-t_0)}$$

The “Simple Substitution Model” of J. C. Fisher and R. J. Pry is used for binary technological substitution scenarios. Various markets consist of more than two commodities that are in competition. Accordingly a binary model is not sufficient.

In the case of several competing commodities within a single market, more than one single growth respectively shrinkage process happens at the same time. As a consequence, the transition between the period of growth and shrinkage has to be part of the model as well.

In order to cope with this kind of settings, the Fisher-Pry-Model has to be adapted. As the energy market is one of these settings with multiple commodities competing for one market, C. Marchetti extended the presented model for the Primary Energy Substitution Model, as described in the following section 2.2.

---

[13] Fisher, J./Pry, R. (1971): A simple substitution model of technological change, in: Technological Forecasting and Social Change, Vol. 3, pp. 75–88.

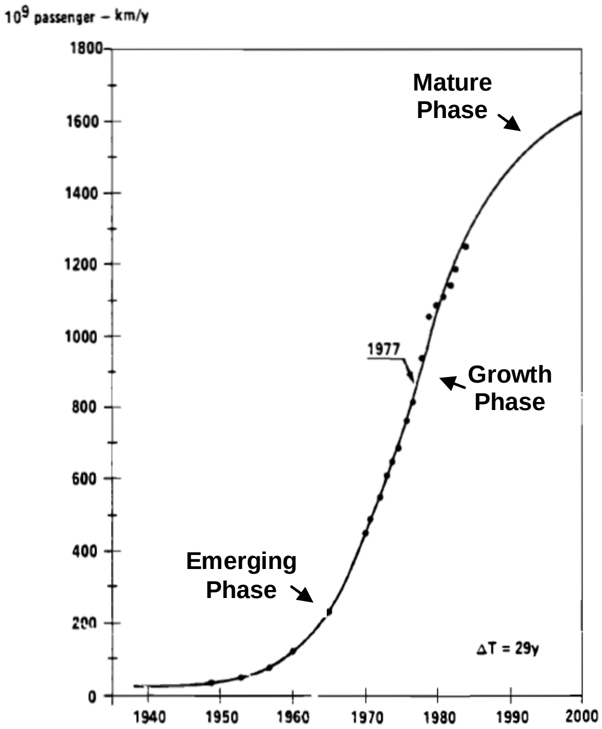


Figure 1: Sample logistic growth curve

Growth of the world's air transport in billion passenger-kilometers per year

Source: Based on Lee, T. and Nakićenović, N. (1990): Technology Lifecycles and Business Decisions in: *Life cycles and long waves*, ed. T. Vasko, Berlin, p. 5.

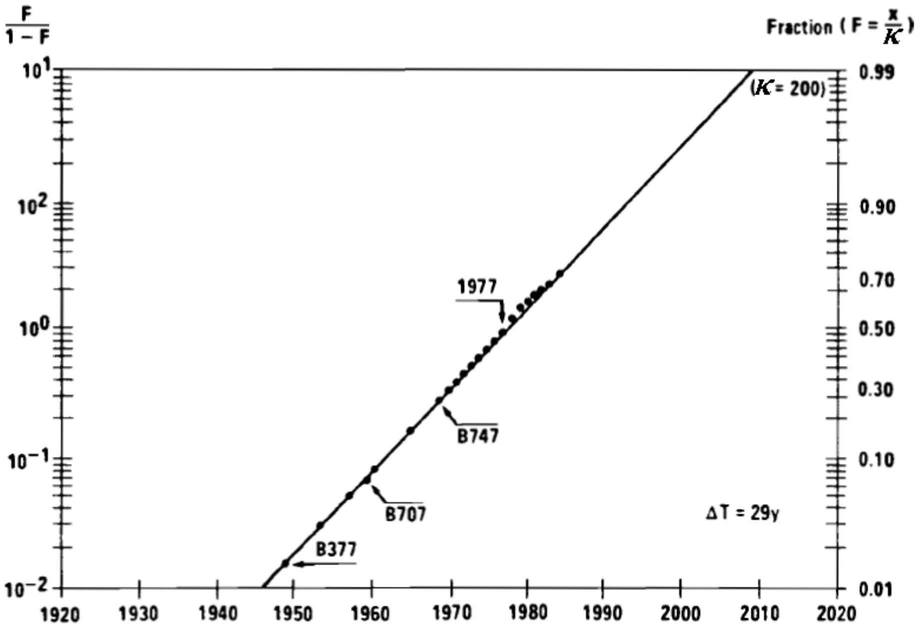


Figure 2: Transformed logistic curve with semilog y-axes

Growth of world's air transport with F as a fraction of an assumed saturation level κ.

Source: Based on Lee, T. and Nakićenović, N. (1990): Technology Lifecycles and Business Decisions in: *Life cycles and long waves*, ed. T. Vasko, Berlin, p. 6.

2.2 The original Primary Energy Substitution Model

Since primary energy sources are recognized as different technologies competing for a market, the same laws as for other competing products may apply. Accordingly, changes in the energy system comply with substitution processes, as described in the previous section 2.1, and follow logistic growth curves. Therefore, C. Marchetti's Primary Energy Substitution Model incorporates the rules of J. C. Fisher's and R. J. Pry's "Simple Substitution Model".[14] Consequently it is assumed, that the relative growth rate in market share of one technology penetrating the market is proportional to the market fraction of all other technologies, in accordance with equation (2).

As already stated, the market for primary energy sources usually consists of more than two major competitors.[15] To deal with the fact that multiple sources of primary energy are in competition for the energy market, C. Marchetti developed an approach to enhance the "Simple Substitution Model" introduced by J. C. Fisher and R. J. Pry.

For this reason the given mathematical model has to be adapted, since it is unlikely that the sum of individual market shares equals one. Therefore, the share of one technology is defined as the difference of the sum of the other technologies to 100%. Especially during phases of transition from growth to shrinkage this definition permits the composition of a continuous graph for the technologies and allows tracing the whole life-cycle.[16]

The course of the fraction that is determined using the specification given above follows approximately the logistic growth path of equation (4), as in the binary substitution model of J.C. Fisher and R. J. Pry, until a stage of saturation and a subsequent shrinkage period. In contrast to the binary case full substitution with hundred percent market share is never reached.

C. Marchetti proposed a change in coefficients in the mathematical representation, given in equation (4), after the saturation stage and logistic decline afterwards. As commodity respectively technology that is treated in that way, the oldest growing one is used. This corresponds to the principle often expressed as "first in – first out".[17]

---

[14] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

[15] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 1, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[16] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

[17] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

The shrinkage period of the oldest commodity with declining market shares shows logistic behavior as well as the growing process, because the new commodity entering the market and substituting the oldest one grows at logistic rates. Thus, the saturation stage as the transition from growth to decline is the only period with a non logistic path.[18]

When the oldest growing technology entered the shrinkage period, the next technology comes into saturation stage. This procedure is repeated for one technology after the other in the sequence as they enter the market. Consequently always only one technology stays in the saturation stage at one point in time.[19]

For the incorporation and the analytical treatment of real world data a finite number of technologies n is ordered chronologically in the sequence of their market entrance. Subsequently for every technology the parameters α and t_0 for the logistic curves according to equation (5) are estimated using historical data for a given period of time. It is not necessary that the historical data do overlap. Typically one has to deal with discrete time intervals, due to the availability of annual historical data. For the estimation of the parameters different methods can be used, including the ordinary least squares principle. The outputs of the estimation process are n equations in the form of equation (4) that describe the growth respectively the shrinkage of the different technologies.[20]

The next step is to describe the development of the technology in saturation. Therefore the oldest still growing technology j is selected to enter the saturation stage. Hence, the technological development is described by the following equations (5) and (6).[21]

$$\mathrm{F_i(t)} = \frac{1}{1 + e^{-\alpha_i(t - \mathrm{t_{0,i}})}} \tag{5}$$

$$\mathrm{F_j(t)} = 1 - \sum_{\mathrm{i \neq j}} \frac{1}{1 + e^{-\alpha_i(t - \mathrm{t_{0,i}})}} \tag{6}$$

As previously mentioned, the saturation stage respectively the transition from growing to shrinking market share ends up with the period of logistic decline. Hence, a logistic process results in a linear function in the case of applying the Fisher-Pry-Transformation according to

---

[18] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 4, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[19] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 4, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[20] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 5, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[21] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 5, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

equation (7). The entry into the stage of logistic decline can be observed by the curvature of $h_j(t)$.

(7)
$$\log\left(\frac{\mathrm{F_j(t)}}{1-F_j(t)}\right) = \alpha_j\,(\mathrm{t}-\mathrm{t_{0,j}} = \mathrm{h_j(t)}$$

$h_j(t)$ … Logarithm of the relative market share of technology j

The entry into the shrinkage stage is marked by the point of minimal rate of change of the slope of $h_j(t)$ as a linear function is characterized by zero change in the slope coefficient. This is applied to the time horizon after the initiation of the saturation phase which is mathematically represented by the additional condition that the slope has to be negative, shown in equation (8).[22]

(8)
$$\mathrm{h_j^{''}(t)/\,h_j^{'}(t)} \xrightarrow{\text{yields}} \mathrm{Min} \qquad \mathrm{h_j^{'}(t)} < 0$$

$h_j^{'}(t)$ … *First derivative of $y_j(t)$*
$h_j^{''}(t)$ … *Second derivative of $y_j(t)$*

The immediate progress following the point of minimal rate of change of the slope of $h_j(t)$ specifies the further course of technology *j* in the shrinkage stage. Thus the parameters of the logistic decline of technology *j* are derived using the first points after the condition, identified by equation (8), applies. Since technology *j* lasts in declining stage the next oldest growing technology is ready to enter saturation stage.[23]

C. Marchetti first published the Primary Energy Substitution Model applied to real world data on world level in 1977 in "*Primary Energy Substitution Model: On the Interaction between Energy and Society*", which is shown in Figure 1 with the thick lines as estimations of the model and the thin lines as the historical data.[24] This application of the presented model to the historical data of the different energy technologies (wood, coal, oil gas) showed a remarkable consistency with the modeled development, which led C. Marchetti to the suggestion that the whole destiny of an energy source is completely predetermined.[25]

---

[22] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 6, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[23] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 6, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[24] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

[25] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

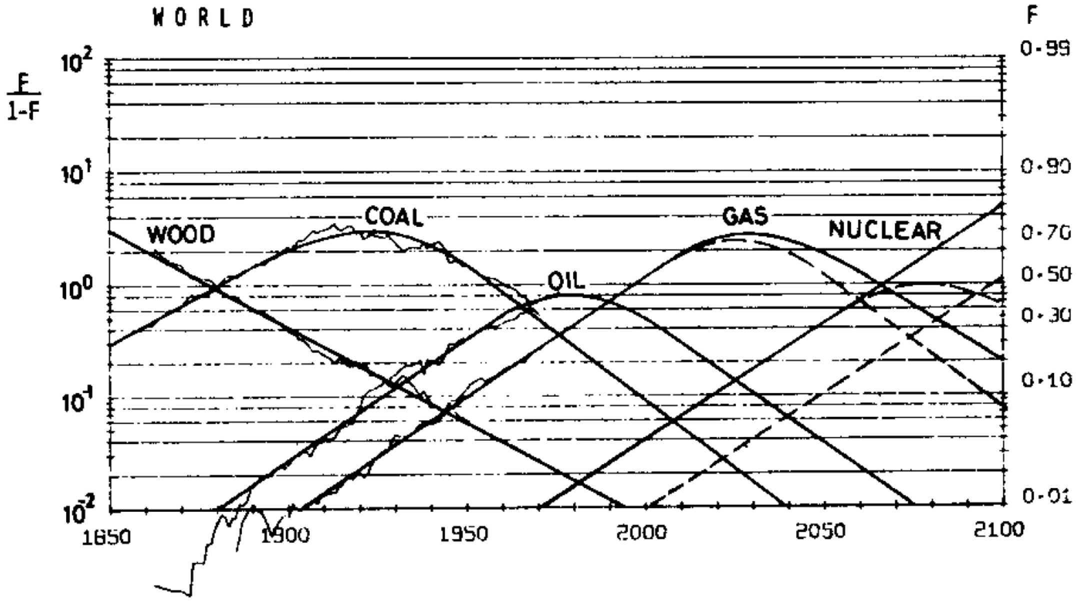


Figure 3: Historical evolution of the world primary energy mix

Source: Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

Resulting from the small deviation of the real world data from the estimated course of the different energy sources over almost one century, C. Marchetti derives that the predetermined evolution of the energy sources goes almost unchanged through wars, wild variations of energy prices and depressions or returns soon to the original trend. One of his further conclusions is that the total availability of an energy source does not affect its evolution and that the tendency towards a declining market share at world level can be observed long before depletion of the source.[26] This interpretation is based on the decreasing importance of wood and coal at a time when both had a capability of increasing market share.[27] Beyond that, it seems that the substitution process has internal dynamics that are mostly independent from external factors, according to C. Marchetti. [28]

Moreover, C. Marchetti and N. Nakićenović presume that "*the system has a schedule, a will and a clock.*"[29] This expresses C. Marchetti's attitude towards human interaction with the

---

[26] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

[27] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 8, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[28] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

[29] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 17, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

energy system, when he states that people are no decision makers, they are just optimizers.[30]

The fit of the Primary Energy Substitution Model to real world data, as shown in Figure 3, indicates that the introduction of a new energy technology is a long-time project, as roughly 100 years are required to become leading when starting from scratch. Beyond that, a remarkable stability in the evolution process of the different technologies can be observed.[31]

The logistic substitution model, as used in the Primary Energy Substitution Model, revealed a similar good fit to historical data in numerous other technological fields such as steel and coal production[32], means of transport and transport infrastructures[33] as well as music recording media[34] and further more.

The small deviations of the logistic substitution model from real world data creates the possibility of predicting the further course of a market based on a limited number of data points, which means a relatively small time frame for example 20 years of data.[35]

With these properties, the Primary Energy Substitution Model in conjunction with the previously mentioned assumptions seems to offer a notable foundation for forecasting. More precisely this means the prediction of the further development of already introduced energy technologies, since the introduction of new technologies is not covered by the model, as it cannot be foreseen. This implies a limitation in the forecasting time frame.

Furthermore the application of the model to a subset of the market shows a particular good agreement with real world dataset.[36] An example is shown in Figure 4 with wood excluded from the energy market and the historical dataset also included as thin lines. In addition to the application of the model to a subset of data, using a restricted set of historical data, which

---

[30] Marchetti, C. (1979): Energy systems—The broader context, in: Technological Forecasting and Social Change, Vol. 14, Issue 3, pp. 191–203.

[31] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 7, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[32] Grübler, A. (1990): Technology Diffusion in a Long-Wave Context: The Case of the Steel and Coal Industries in: *Life cycles and long waves*, ed. T. Vasko, Berlin, pp. 128–143.

[33] Grübler, A. (1990): *The rise and fall of infrastructures,* Heidelberg, pp. 71–181.

[34] Meyer, P. (1999): A Primer on Logistic Growth and Substitution The Mathematics of the Loglet Lab Software, in: Technological Forecasting and Social Change, Vol. 61, Issue 3, pp. 247–271.

[35] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

[36] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 21, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

considers differences in the available statistical data, yields to more or less the same outcome. [37]

All these substitution processes including the previously mentioned binary substitutions are social diffusion processes. One thing they have in common is a remarkable stability. Even the epidemic diffusion behaves in the same way. Accordingly the stability is suggested to be characteristic for the society. It is based on diffusion on cultural level. C. Marchetti referres to Mr. Hägerstrand in one of his speeches and declares that the reason behind this stability is the way how information is distributed in a verbal society.[38]

The diffusion is the propagation and verification of aggregated cultural information that sets paradigms for thoughts and actions on personal and social level. Therefore, it seems reasonable that the diffusion of technology shows the same characteristics since technology is one kind (a subset) of information. [39]

Hence technological diffusion can be viewed as a subset of information distribution. C. Marchetti states that "*Human actions are the consequence of the 'epidemic' diffusion of 'action paradigms'*"[40] and various examples demonstrate that this rule is independent from the hierarchical level of the action.

---

[37] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 19, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[38] Marchetti, C. (13.09.1991): *A Forecasting Model for Research and Innovation Activities in Selected Areas: A Support for Strategic Choices,* Venice, p. 4.

[39] Marchetti, C. (1991): Modelling Innvoation Diffusion in: *Forecasting technological innovation: [based on the lectures given during the Eurocourse on Forecasting Technological Innovation held at the Joint Research Centre Ispra, Italy, October 22 - 26, 1990]*, ed. Bernard M. Henry, Dordrecht, p. 55.

[40] Marchetti, C. (13.09.1991): *A Forecasting Model for Research and Innovation Activities in Selected Areas: A Support for Strategic Choices,* Venice, p. 2.

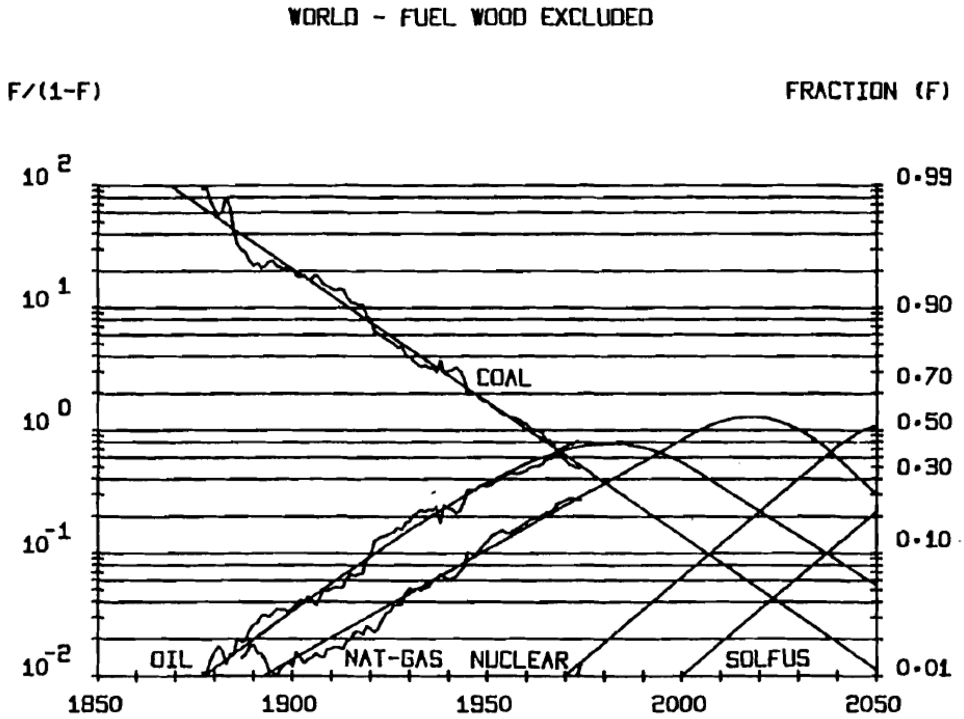


Figure 4: Historical evolution of the world primary energy mix excluding wood

Source: Marchetti, C. and Nakićenović, N. (07 / 1978): *The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part,* Laxenburg, p. 21, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

Some key insights of the historical evolution of the energy system, analyzed by the use of C. Marchetti’s Primary Energy Substitution Model in Figure 3, are to be mentioned in particular in the following paragraphs, with reference to the dataset presented by N. Nakićenović.[41]

Previous to 1860 only two energy sources, wood and coal, were present at mentionable shares. Coal was at that time the substitute of wood and hence the use of coal was advancing. By the year 1862 the first data concerning oil as energy source is known. The first time after introduction of a new technology it has to prove its feasibility. During this term the new technology requires resources and capital from the economic environment to utilize all its improvement potential. Due to this first investment, the technology usually experiences a fast growth. Generally this fast growth period is followed by a break at approximately 2 - 3%

---

[41] Nakićenović, N. (12/1979): Software Package for the Logistic Substitution Model, RR-79-12, pp. 22–26, http://www.iiasa.ac.at/Publications/Documents/RR-79-012.pdf, February 2010.

market share and a moderate growth rate subsequently, which equals the final rate of penetration.[42]

With the availability of historical data for natural gas in 1885, maybe one of the most important energy sources for the 21st century entered the market. Some fluctuations especially for coal and oil during the late 1930s and in the 1940s are influenced by the pre-war and war situation. A recurrence to a stable trend occurred throughout the subsequent years.[43] Data for nuclear energy is first available for the year 1962. Due to the small market penetration of nuclear energy, the estimation of an appropriate growth rate is not valid for a significant projection at this time. Therefore, the illustrated course of nuclear energy is based on the previously observed penetration rates and derived from the information on the construction of nuclear power plants.[44] With the analysis carried out till 1974 it is not possible to identify any impacts of the oil crisis within the early 1970s on the further course of the analyzed energy sources.

In the following some conclusions derived from this first application of the Primary Energy Substitution Model to historical data are summarized.

The primary fuels show a quite significant insensitivity to changes of newly emerging sources, which leads to the assumption that also the introduction of new energy technologies would not affect the course of decline significantly.[45] Based on the presented historical evolutions of the energy sources, the proposition that the market share of a single source is bounded to 60% - 70% seems plausible.[46]

From the standpoint of the 1970 it seems that natural gas will play an important role at least in the next 50 years.[47] Generally, a revival of coal appears rather improbable[48] but a pile out of nuclear energy by coal is at least a possible option.[49]

---

[42] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, pp. 6–7, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[43] Kwasnicki, W./Kwasnicka, H. (1996): Long-term diffusion factors of technological development: An evolutionary model and case study, in: Technological Forecasting and Social Change, Vol. 52, Issue 1, pp. 31–57.

[44] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 17, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[45] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 25, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[46] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 17, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[47] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, pp. 18–19, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

The most important properties derived from the so far described Primary Energy Substitution Model are the significant regularity and the slowness of the substitution processes in the energy market with approximately 100 years for the evolution from 1% to 50% of market share. Remarkable as well is the fact that the described processes contradict to the broadly sensed acceleration of times.[50,51]

As the 1970s, when the Primary Energy Substitution Model was initially developed, were an exciting decade concerning the energy system, it seems to be very interesting to follow the further course of the energy sources, which will be examined in the following section and more deeply in chapter 3.

2.3 Critical Appreciation

Right after the severe oil price increase in 1973, also known as oil crisis, it was assumed that this oil price shock did not have any significant implications on the substitution rates, apart from temporary fluctuations. This presumption was mainly based on the notion that previous variations of prices did not show medium- or long-term implications on the course of the energy sources.[52]

With the time advancing and a second significant rise in oil prices in 1979, more insight was gained and changed evolutions of coal and natural gas could be observed. The market share of coal did not fall in accordance with the previous trend. Instead, an almost constant share of coal could be observed, as shown in Figure 5. Furthermore a change in the market penetration rate of natural gas is identifiable. As oil is in transition to declining market share in the 1970s, it is difficult to determine its further trend based on the available dataset at this time, which is displayed in Figure 5.[53]

It turned out that the strong variations of the oil prices during the 1970s affected the further trends in the energy system more than previous events. The impact on the energy system can be observed in later updates of the first Primary Energy Substitution Model. Deviations of

---

[48] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

[49] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 25, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[50] Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

[51] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 17, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[52] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 8, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[53] Marchetti, C. (1985): Nuclear Plants and Nuclear Niches: On the Genertation of Nuclear Energy During the Last Twenty Years, in: Nuclear Science and Enginieering, Vol. 90, pp. 521–526.

the real-world energy data from the predicted evolution of the energy system by C. Marchetti and N. Nakićenović are indications for notable effects on the energy system due to the vast variations in oil prices in the 1970s.

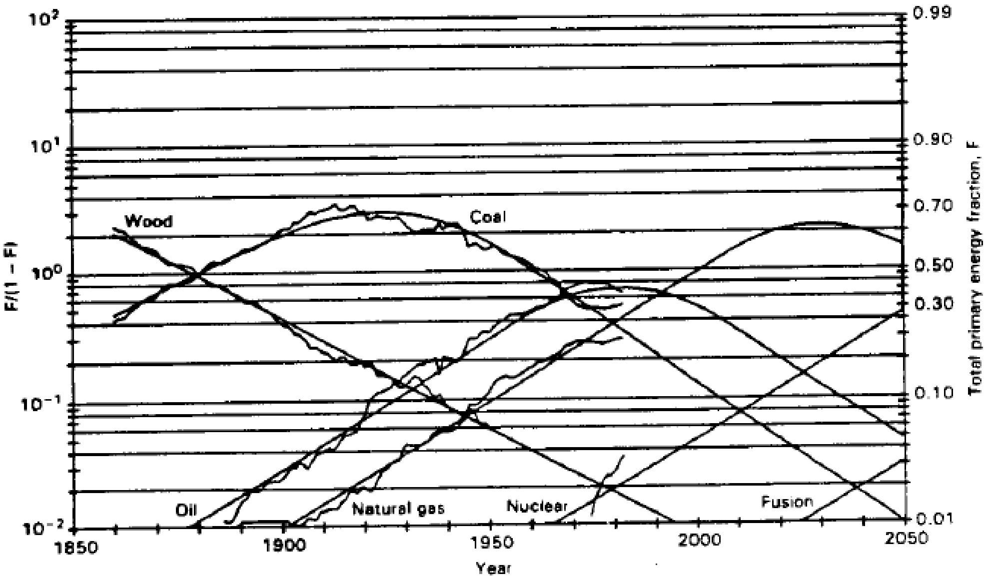


Figure 5: Historical Trends in Energy Substitution on world level 1985

Source: Marchetti, C. (1985): Nuclear Plants and Nuclear Niches: On the Genertation of Nuclear Energy During the Last Twenty Years, in: Nuclear Science and Enginieering, Vol. 90, pp. 521–526.

The Primary Energy Substitution Model including the predicted evolution trends of the different primary energy sources and the deviations towards historical real-world data are subject of discussion in publications by Vaclav Smil.[54,55]

V. Smil points out that C. Marchetti's projections of the future's energy system do not conform to the actual rates of the primary energy sources in the year 2000. According to V. Smil's dataset, crude oil has the highest market share in 2000 with about 37% and natural gas as well as coal supply about a quarter of the world's primary energy, which is shown in Figure 6. In comparison, Marchetti predicted 25% market share for crude oil, 52% for natural gas and 10% for coal for the year 2000, according to V. Smil.[56]

He ascribes the lower penetration rate of natural gas during the 1970s compared to the previous evolution of crude oil to the general superiority of oil over coal, which is not given for

---

[54] Smil, V. (1998): Future of Oil: Trends and Surprises, in: OPEC Review, Vol. 22, Issue 4, pp. 253–276.

[55] Smil, V. (2000): Perils of Long-Range Energy Forecasting Reflections on Looking Far Ahead, in: Technological Forecasting and Social Change, Vol. 65, Issue 3, pp. 251–264.

[56] Smil, V. (2000): Perils of Long-Range Energy Forecasting Reflections on Looking Far Ahead, in: Technological Forecasting and Social Change, Vol. 65, Issue 3, pp. 251–264.

natural gas, because it has lower energy density and is more expensive to transport than oil.[57]

In addition V. Smil does not share C. Marchetti's view that the energy system is not influenced by external factors. He considers that the energy system has been heavily influenced successive to the oil crisis in 1973. The changed paths of the market shares on global level lead V. Smil to the assumption that the energy system has evolved to a regime with almost constant market shares.[58]

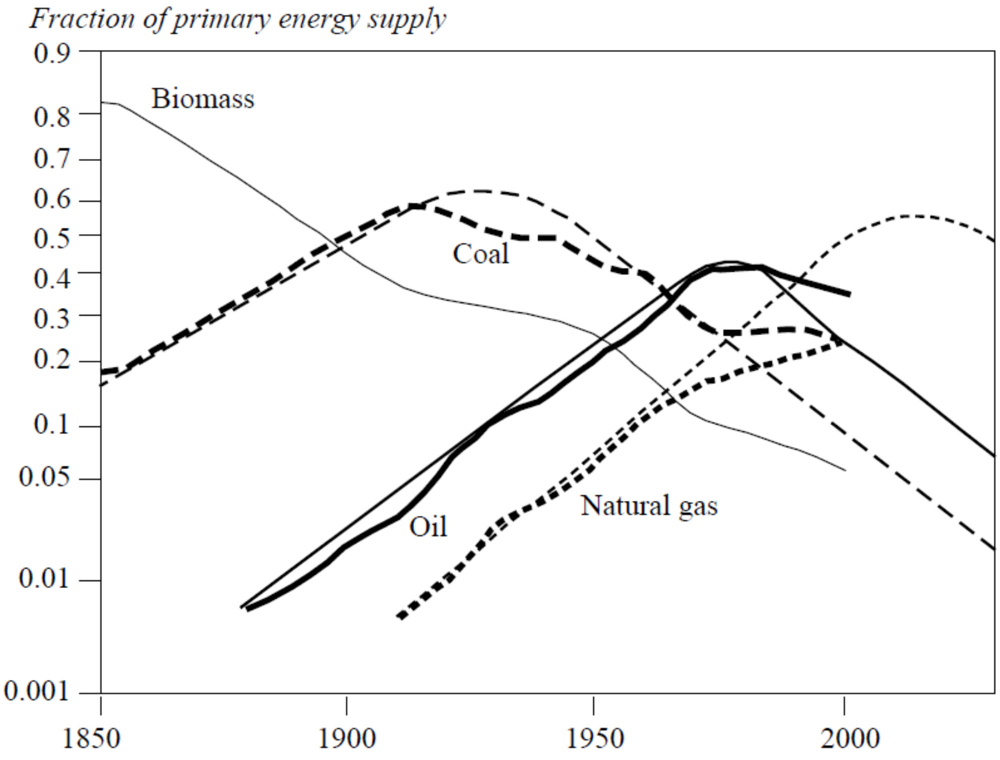


Figure 6: Global Primary Energy Substitution by V. Smil 2000

Source: Smil, V. (1998): Future of Oil: Trends and Surprises, in: OPEC Review, Vol. 22, Issue 4, pp. 253–276.

A different approach in analyzing the deviations of Marchetti's Primary Energy Substitution Model from the real-world historical data after 1970 is shown by Tessaleno Devezas et al. in the year 2008.[59]

---

[57] Smil, V. (1998): Future of Oil: Trends and Surprises, in: OPEC Review, Vol. 22, Issue 4, pp. 253–276.

[58] Smil, V. (2000): Perils of Long-Range Energy Forecasting Reflections on Looking Far Ahead, in: Technological Forecasting and Social Change, Vol. 65, Issue 3, pp. 251–264.

[59] Devezas, T./ Lepoire, D./Matias, J./Silva, A. (2008): Energy scenarios: Toward a new energy paradigm, in: Futures, Vol. 40, Issue 1, pp. 1–16.

In contrast to V. Smil, this approach assumes that the logistic substitution of the Primary Energy Substitution Model is also true for the energy system after 1970, but under different presumptions. The relative constancy of the energy market shares is supposed to be a transitory phenomenon, as this constellation is not maintainable forever ultimately, because of the finiteness of fossil fuels.[60]

This approach starts with a different selection of energy sources. Due to the short time difference between the time when crude oil had penetrated the energy market a few percent and when natural gas obtained the same, these energy sources are combined as a single primary source of energy named fluid fossil fuels (FFF). The authors argue that the combination of crude oil and natural gas results in a more regular evolution pattern. Besides, they consider this combination meaningful due to similar geological origins of crude oil and natural gas, related extraction technologies and frequently same commercial organizations involved. Apart from that, on the consumption side oil and natural gas do have different main fields of application. Nevertheless, the authors assume a coupled evolution of oil and gas by reason of a relatively constant rate between the market shares of these energy sources.[61]

Additionally, the proposed approach introduces energy efficiency, intrinsically assigned to the demand-side, as a substitute to energy sources on the supply side. The transformation from the demand side to the supply side is performed by assigning the amount of saved energy due to energy efficiency measures in relation to a specified base year to the virtual energy source “Efficiency”.

As efficiency is not a quantity that is easy to measure, the proposed approach uses the global energy intensity as measure for energy efficiency. Regional or national shifts in the economic structure like the change from a manufacturing to a service dominated economy influence the energy intensities of these units, but will compensate on world level. Hence, only a global analysis seems to be plausible.[62]

The evolution of the energy system on world level, based on the presumptions of T. Devezas et al., is shown in Figure 7.

---

[60] Devezas, T./ Lepoire, D./Matias, J./Silva, A. (2008): Energy scenarios: Toward a new energy paradigm, in: Futures, Vol. 40, Issue 1, p. 4.

[61] Devezas, T./ Lepoire, D./Matias, J./Silva, A. (2008): Energy scenarios: Toward a new energy paradigm, in: Futures, Vol. 40, Issue 1, p. 4.

[62] Devezas, T./ Lepoire, D./Matias, J./Silva, A. (2008): Energy scenarios: Toward a new energy paradigm, in: Futures, Vol. 40, Issue 1, p. 5.

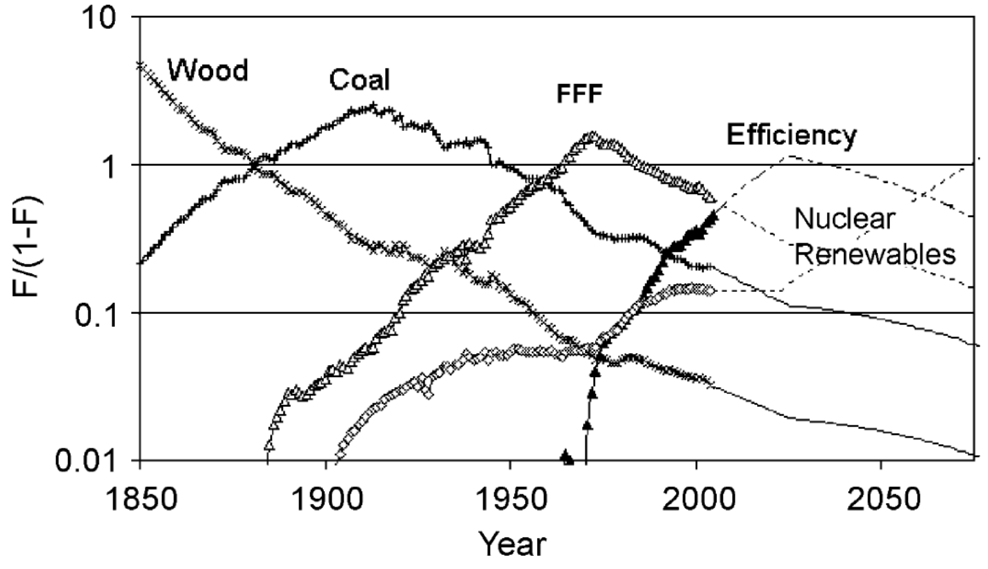


Figure 7: Historical energy trends for the world by T. Devezas 2008

Source: Devezas, T.; Lepoire, D.; Matias, J.; Silva, A. (2008): Energy scenarios: Toward a new energy paradigm, in: Futures, Vol. 40, Issue 1, p. 6.

In succession to the theoretical introduction into the Primary Energy Substitution Model and various interpretations as well as variations of the model with different perspectives in matters of time the following chapter presents an updated version of the model.

3 Analysis of the Energy System

The previous chapter already illustrated some changes of the development trends in the energy system after the 1970s. On the basis of an update of the Primary Energy Substitution Model, the evolution of the world's energy system from 1950 up to the recent years is analyzed. The aim of this analysis is to study past trends and deviations from trends in order to gain insights for future developments. The attempt is to find cause and effect relationships that represent past experiences which offer basic guidelines how far external interventions affect the further course of energy sources. Furthermore, the question arises whether there are interconnections between different energy sources, which is an important issue for decision makers or as C. Marchetti would say "optimizers".

This is another question that is investigated within this chapter, whether C. Marchetti's opinion that we are just optimizers and the system is making the decisions, is valid or is disproved by developments after his examinations in the 1970s and 1980s.[63]

The approach to analyze the developments of the world's energy system on the basis of the Primary Energy Substitution Model is organized in different levels of detail. At the beginning, the market conditions of the energy system are investigated and distinctive elements are examined in more detail starting in 1950.

The examination on world level does not provide deep insights regarding reasons behind events. This is improved by more detailed examinations on regional level. Three major world regions in terms of energy, that are Europe, USA and China for this work, are further analyzed. With this procedure global effects of various regional events as well as different local characteristics of the energy system can be analyzed.

Subsequent to the introduction in the approach of the analysis, the assumptions that lie behind the model and therefore apply for the analysis are defined as well as limitations related to the dataset, which have to be considered, are indicated.

Dataset issues

Preceding the global analysis, certain information concerning the datasets is given. As already identified in the previous chapter, transitions in the energy system are longtime

---

[63] Marchetti, C. (1979): Energy systems—The broader context, in: Technological Forecasting and Social Change, Vol. 14, Issue 3, pp. 191–203.

processes. For that reason it is necessary to examine the system in the long run, which implies the need of an almost complete dataset for a long time period. The time frame that is analyzed within this work is a period of about 60 years starting in the year 1950. Since most data sources do not cover the whole period, combinations of different sources are used. In order to avoid artificial changes of the system due to a changeover of different data sources, the constraints described below are introduced.

The analyses based on the Primary Energy Substitution Model rely on market shares. Correspondingly, an important issue concerning the dataset is to have correct ratios between the energy sources. Absolute values are not primarily important. This requirement is usually met by data sources that include all energy sources that are used as input for a given time frame. Hence, data sources that include all analyzed energy sources are preferred. In case that no such data source is available, a comparison of absolute values for the data points around the year of breakage is performed. If necessary, adjustments of this particular data points are made.

The world’s energy system in particular the course of five important energy sources from 1950 up to 2009 is the content of this chapter. The five energy sources coal, petroleum, natural gas, nuclear and renewable energy sources are central for all analysis. Out of this five energy sources the three major sources for the given time frame are fossil fuels. Fossil fuels are primarily burned during the process of energy consumption and the thermal energy used directly or indirectly. For that reason, energy measurement units related to thermal processes like British thermal unit [Btu] or tons of oil equivalent [toe] are used as common system of units for all calculations.

Conversions

In general the primary energy sources are no homogeneous goods. They differ from region to region and additionally show temporal changes. Especially coal is subject to highly different characteristics. They rank from hard coal (anthracite) to brown coal (lignite) with very different heat contents. For this work, the term coal refers to the sum of various coal types that are usually anthracite, bituminous coal, subbituminous coal and lignite. All data sources include at least the most important types, anthracite and lignite.

In order to be able to compare different energy sources, for data sources that specify coal data in units of weight a conversion to an energy measuring unit is necessary. This is done by considering the heat content per ton of coal. To account for local differences, the conversion to units of energy is based on heat content data on national level. The calculations of the heat contents are based on individual heat contents of anthracite, bituminous, and lignite.[64]

When data is given on a per day basis, which is common for petroleum and oil products, the annual data is calculated using 365 days per year. In particular for petroleum, some sources provide data in weight units whereas the heat content is given per barrel, which claims for a conversion from weight to volume units. The conversion factors from weight units to barrels also vary from region to region. Thus, conversion factors on national level are used.[65]

The term natural gas refers here to conventional natural gas. If natural gas data is provided in volume units also a conversion to energy units is performed.

Whenever the term renewable energy sources (RES) is used within this chapter it accounts for the sum of hydroelectric power, geothermal, biomass, solar, wind, wave action and tidal action that is used for electricity generation, if not otherwise specified. Due to a lack of data and inconsistencies between the data sources for differently used RES, they are generally not included for the analyses in this chapter.

There are different approaches to include energy sources that are not necessarily connected to a thermal process, which applies for some renewable energy sources such as hydro or wind power. The approaches differ in the amount of heat that is assigned to this kind of energy production. As this energy production is usually available as electricity, one can assign a heat content that equals the amount of thermal energy that can be converted from electric energy. Alternatively, it can be assumed that the electricity production, which is not related to a thermal process, replaces production from fuel fired power plants. Consequently, the heat content of one kWh of electricity from a non-thermal power plant is based on the heat that an average fuel fired power plant needs to produce one kWh. Following the primarily used data source (EIA[66,67]) the second approach is pursued.

Besides these general assumptions, some distinctive issues are mentioned within each section separately. In section 3.1 the energy system and its alteration on a global scale since 1950 is discussed. This first step leads directly to the more detailed analysis on regional level in section 3.2, where similarities and differences between the global evolution and local alterations are investigated.

---

[64] U.S. Energy Information Administration : International Energy Statistics, http://www.eia.gov/countries/data.cfm, 10.04.11.

[65] U.S. Energy Information Administration : International Energy Statistics, http://www.eia.gov/countries/data.cfm, 10.04.11.

[66] U.S. Energy Information Administration : Annual Energy Review 2009, DOE/EIA-0384(2009), http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.

[67] U.S. Energy Information Administration : International Energy Statistics, http://www.eia.gov/countries/data.cfm, 10.04.11.

3.1 Global Analysis

The 1970s were a decade with special events for world's energy. Prior to the 1970s, the course of the most important energy sources seems was relatively stable, as already discussed in the previous chapter. The question arises, whether the events of the 1970s had modified this mostly stable evolution or had just temporarily affected the long-term path of the system. In section 2.3 some indications for changed characteristics of the evolutionary pattern of the energy system as a result of these turbulent years have been already discussed. This analysis of the world's energy system, based on the Primary Energy Substitution Model, is intended to provide an easy to read visualization of the energy market in order to identify answers to these questions.

The energy market represented by the market shares of the most important energy sources during the past 60 years is shown in Figure 8, which is the central element for the further discussion.

The underlying dataset for Figure 8 are energy production data as specified in Table 1. To avoid artificial deviations resulting from the combination of different data sources overlaps in the different data series are exploited for adjustments of the absolute values, which is conducted because of partial incompleteness of data sources.

Unlike the original model, presented in section 2.2, Figure 8 does not show a continuous line as the modeled development of the energy sources, but provides trend lines for the most part as follows.

The trend lines are calculated by a minimum least squares regression. With regard to the question whether the events of the 1970s caused a break in the evolutionary pattern of the energy system or even led to a pullout of the logistic path of market penetration, the trend lines are separated in two parts. The first part of the trend lines apply for the years prior to 1970 and the second part to the data points after 1980. As petroleum is in the transition phase from growing to declining market share in the time frame 1970 to 1980, its fraction of the market would be calculated in the original Primary Energy Substitution Model as the difference of the sum of all other sources to 100 percent. This time frame is omitted for the calculation of the trend lines in Figure 8, as the actual evolution of the energy system shows some kind of transition not only for petroleum but in other energy sources as well. For the aim of a clearer recognition of the tendencies, the trend lines prior 1970 and past 1980 are extended into the time frame 1970 - 1980.

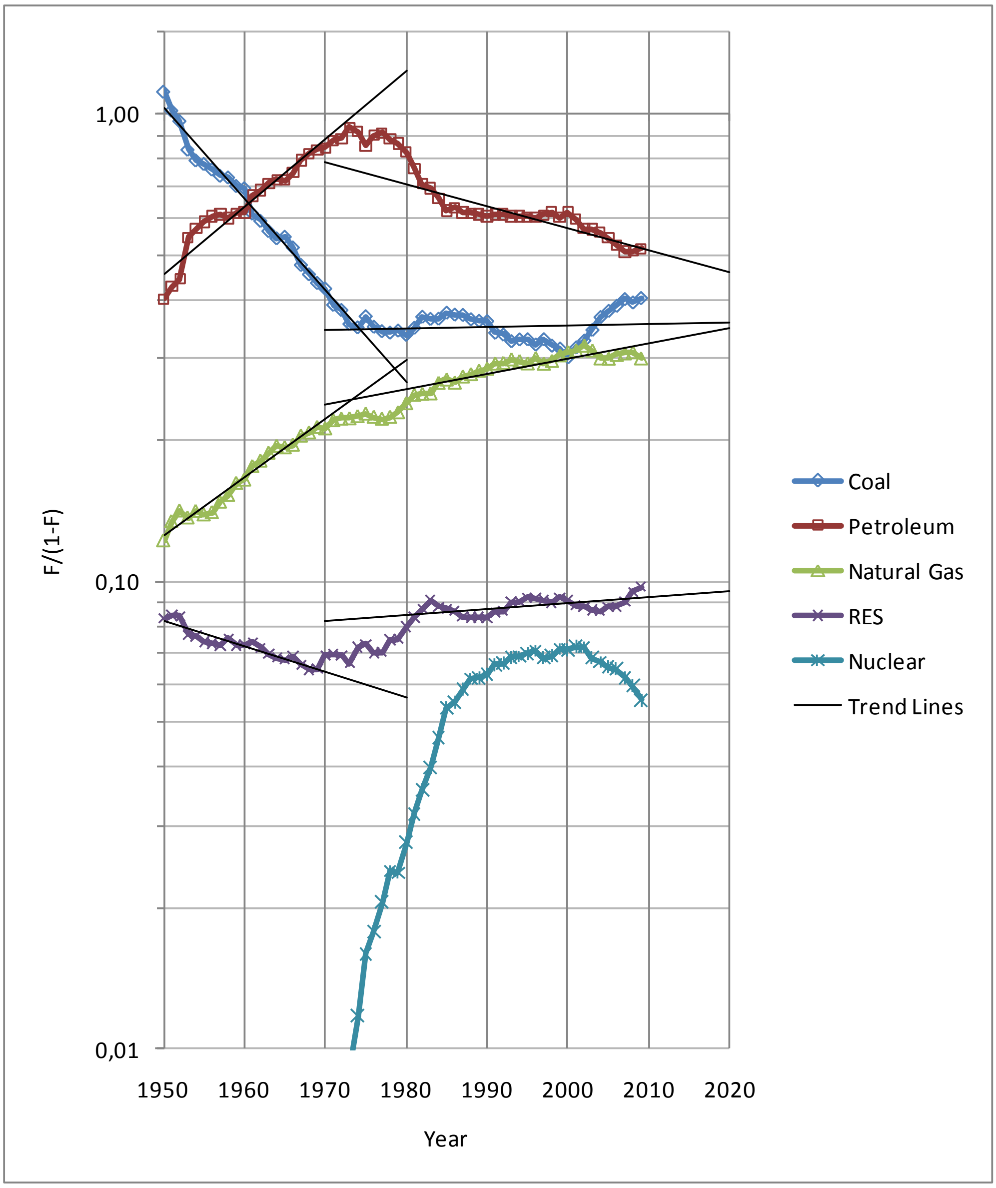


Figure 8: Primary energy substitution global 1950-2009

Data source 1950-1969: Coal, Petroleum, Natural Gas	Mitchell, B. R. (1993): *International historical statistics: Europe: 1750 - 1988,* 3rd ed., New York, N.Y, pp. 360–380. Mitchell, B. R. (1983): *The Americas and Australasia,* London, pp. 360–380. Mitchell, B. R. (1998): *International historical statistics: Africa, Asia & Oceania, 1750 - 1993,* 3rd ed., London, pp. 360–380, http://www.loc.gov/catdir/description/hol051/00552129.html
Data source 1950-1969: Hydro Power	Nakićenović, N. (12/1979): *Software Package for the Logistic Substitution Model,* Laxenburg, http://www.iiasa.ac.at/Publications/Documents/RR-79-012.pdf, February 2010.
Data source 1970-2007	U.S. Energy Information Administration : *Annual Energy Review 2009,*pp. Table 11.1, http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.
Data source 2008-2009	BP p.l.c. (2010): BP Statistical Review of World Energy June 2010, http://www.bp.com/statisticalreview, February 2011.

Table 1: Data sources for Figure 8

1950 – 1970

In 1950 coal was the most important energy source with the highest market share of roughly 50%. For the time period from 1950 to 1970, coal's market share is declining with an almost constant average change of approximately -11‰ per annum. As petroleum, which has the second highest market share of about 30%, continuously penetrated the market with an average increase of nearly 8‰ per annum in the years after 1950, it took over market leadership from coal in the early 1960s. Natural gas as energy source had a market share of about 10% in 1950 and was in the stage of expanding its importance for the energy market. The average increase in market share for natural gas was lower than that of petroleum in absolute terms but almost the same when considering the relative change. The calculation of the relative change is based on the actual market shares at the beginning of the decade. Petroleum and natural gas increased their fraction of the market in the 1950s by approximately one third of their market share of 1950. The increase in market share for petroleum and natural gas for the period from 1960 to 1970 was roughly one fifth of their share in 1960. So a reduction of their relative increase in matters of market share can be observed in the time from 1950 to 1970. For petroleum this was also true for the absolute increase in matters of market share. In contrast, coal's market share decreased in these two decades by more than 40%. This decline in market share did not mean decreasing production of coal in absolute terms. The total production of coal per year in terms of energy content was more than 80% higher in 1970 than in 1950. Similarly, the output of coal in weight units increased during these 20 years.

In this time period, nuclear energy did not play any role in the energy system, as the first nuclear power plants were finished in the second half of the 1950s. Parallel to the grid connection of the first nuclear power plants, the construction of more than 100 nuclear reactors started prior to 1970.[68]

Before 1970 only data for hydro power as electricity generating renewable energy source is available. Using just hydro power for this period is in fact a very good approximation, because other renewable sources contribute only a very small part. For example, hydro power accounts for about 90% of production from renewable sources in 1970. The absolute generation of hydro power increased during the 20 years after 1950. Nevertheless, a slight shrinkage of the market share of renewable energy sources, in particular hydro power, is observable. This development is more incisive in the 1950s with the loss of more than 10% of the market share related to the share at the beginning of the decade.

---

[68] International Atomic Energy Agency (2008): Nuclear Power Reactors in the World, Reference Data Series No. 2, p. 21, http://www-pub.iaea.org/MTCD/publications/PDF/RDS2-28_web.pdf

Similar to the previously discussed works on the primary energy market in section 2.3, the period before 1970 is characterized by relatively stable rates of change for the most important energy sources by that time, which are coal, petroleum and natural gas, in accordance with Figure 8.

1970 – 1980

The significantly rising oil price in 1973, also referred to as the first oil crisis, had immediate effects on the energy market. Two energy sources were highly affected. On the one hand, petroleum, as can be anticipated, and on the other hand coal changed their course rapidly. For petroleum the stage of growing market share on energy ended in the 1970s, as is shown in Figure 8Figure 8. On the contrary, the decline of coal's market share changed by 1973/74 into a more or less stable fraction of the market for coal in the next few years.

However, no immediate change in the course of the market share of natural gas is to be identified. When considering the average growth over the decade 1970 to 1980, a slowdown of the penetration is recognized. Natural gas extended its market share by approximately 10% in this decade in relation to its fraction in 1970, which is lower than in the previous decades.

With the grid connection of over 150 nuclear power reactors in the 1970s due to the massive construction work in the previous decade, the market share of nuclear energy increased significantly and exceeded the one percent mark rapidly.[69] An average increase of more than 2‰ per annum had led to a tenfold increase of nuclear energy's market share within this decade.

In absolute terms, the generation from renewable energy sources steadily increased from 1950 ongoing. Due to high growth rates of petroleum and natural gas the market share of renewable energy sources decreased in the two decades before 1970. With approximately the same absolute growth rate of production as before the market share of renewable energy sources increased in this decade by about 15% relative to 1970, mainly because of reduced growth of fossil fuels.

When considering the entire course of the market shares of the energy sources displayed in Figure 8, it seems that the 1970s caused variations in the energy system, but most sources returned to a more or less stable rate of change for the period after 1980, except for recent changes for coal's share and the saturation of nuclear energy. In the following, the evolution of each energy source is described in more detail for the time past 1980.

---

[69] International Atomic Energy Agency (2008): Nuclear Power Reactors in the World, Reference Data Series No. 2, p. 21, http://www-pub.iaea.org/MTCD/publications/PDF/RDS2-28_web.pdf

1980 – 2009

After some years with almost constant market share for petroleum in the later 1970s a second significant rise in oil prices in 1979/1980 seems to be the cause of a strong decline of oil's market share in the subsequent years. This rapid downturn stabilized in the mid 1980s. Nevertheless, an average decrease in market share of roughly -8‰ per annum is observed for petroleum for the decade from 1980 to 1990. Despite the high market share of petroleum in theses years the massive decline led to the loss of more than 15% of market share compared to 1980. The first half of this decade was also characterized by a decline of absolute values for petroleum. Such a decrease of absolute energy measures of an energy source over subsequent years had not happened before for any source. The drastic fall down of oil's fraction of the energy market faded to a period of about 15 years with almost constant share of petroleum until the beginning of the new century. Consequently, the market share of oil stayed relatively constant during the 1990s. Beginning in the year 2000 a second declining phase of petroleum's market share is shown in Figure 8. The major part of the market share lost by petroleum moved to coal. For this reason the next paragraph concentrates on the development of coal within the energy market during the past 30 years.

After coal's market share stopped declining in the 1970s and a subsequent phase of nearly constant share, a considerable increase in market share for the early years of the 1980s is visible in Figure 8. For the 1980s as a whole, this short growth phase followed by a time of merely small variations resulted in little average growth rate of about 1‰ for coal in this decade. The market share of coal decreased in the following decade to its absolute bottom value of slightly over 20% in the year 2000. The decreasing course of coal was more or less stable in the 1990s with an annual shrinkage rate of -3‰ in terms of market share. In the 21st century coal started anew a significant rise of its fraction of the energy market till 2009. On average, coal's market share increased by approximately 6‰ per annum within this decade. So, coal's gain by the year 2009 was roughly one fourth of its market share at the beginning of the century. For this reason, coal is the only energy source that significantly expanded its market share in the period 2000 to 2009, whereas this time frame was the first that indicates a decline in the market share of natural gas. This development is contrary to the trend at the end of 20th century when it seemed that natural gas will outperform coal in the next few years.

Corresponding with the considerable decrease of petroleum's market share in the 1980s, natural gas increased its fraction of the energy market similar to previous decades and raised its share by about 15% compared to 1980. For the following decades the growth of the market share of natural gas slowed down. In the 1990s the average growth rate of natural gas in terms of market share is about half of the previous decade's rate with slightly more than 1‰ per year. The growth of the market share of natural gas diminished in the 21st century. When considering the entire time period from 2000 to 2009, natural gas kept its market share almost constant.

Nuclear energy continued the steep increase in market share of the 1970s also in the following decade. With an average growth rate of slightly more than 3‰ per annum the use of nuclear energy indicated the highest rate of increase for the time frame from 1980 to 1990, which corresponds to more than doubling the market share in one decade. In the 1990s the market share growth of nuclear energy is flattening but also gaining an additional 10% of its 1990 fraction. When considering the decreasing market share of nuclear energy for the years after 2000, the slowdown of growth simultaneously marks the entry in the saturation phase. The decline of the market share of nuclear energy in the time frame from 2000 to 2009 is quite extensive, as this equates to the loss of approximately one fifth of the original market share at the beginning of the century. The year 1990 was the first year with fewer reactors in operation as in the preceding year, which coincides with the significant slowdown of the expansion of nuclear energy's market share in the 1990s in comparison to previous decades.

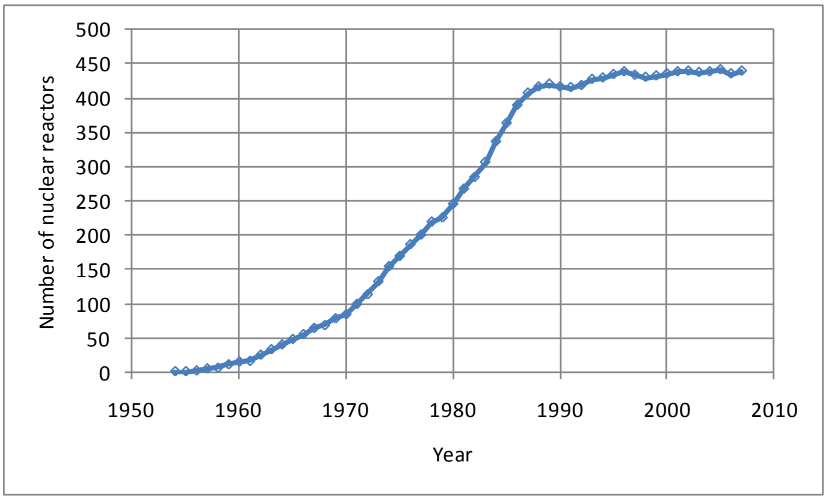


Figure 9: Number of nuclear reactors in operation worldwide 1950 -2007

Data source: International Atomic Energy Agency (2008): *Nuclear Power Reactors in the World,* Vienna, p. 21, http://www-pub.iaea.org/MTCD/publications/PDF/RDS2-28_web.pdf

For about 30 years the number of nuclear units in operation was growing exponentially. Therefore, the number of nuclear reactors in operation, shown in Figure 9, follows a logistic curve for the time of expansion. This is more distinctively visible in Figure 10. A linear regression trend line that clarifies the almost constant growth rate for the period from 1960 to 1990 is included in Figure 10. The Fisher-Pry transformed growth curve of operational nuclear reactors is illustrated in Figure 10 with F as a fraction of an assumed saturation level κ.

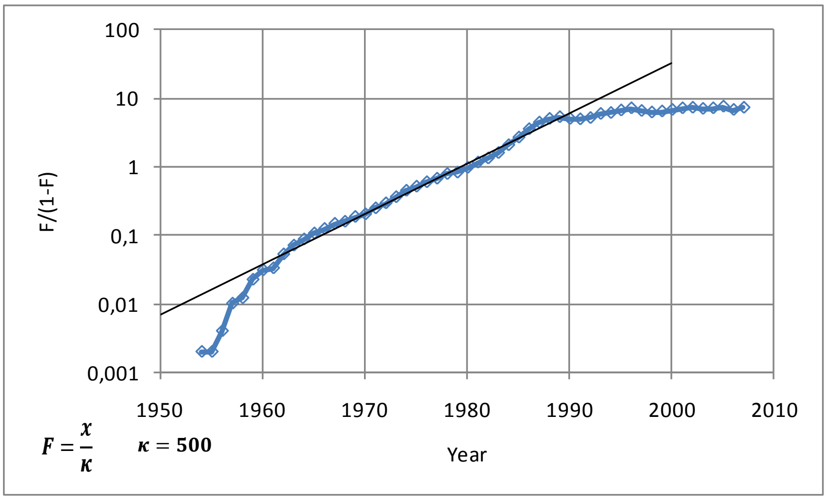


Figure 10: Number of operational nuclear reactors 1950 – 2007 plotting F/(1-F) with F as a fraction of an assumed saturation level κ.
Data source: International Atomic Energy Agency (2008): *Nuclear Power Reactors in the World,* Vienna, p. 21, http://www-pub.iaea.org/MTCD/publications/PDF/RDS2-28_web.pdf

In comparison to the remarkable increase of nuclear energy's fraction of the energy market, the growth of the market share of renewable energy sources is at a much lower level, as examined in the following paragraphs.

The trend of increasing market share for renewable energy sources starting in the 1970s continued for about half a decade. Together with small decreases of market share in the second half of the 1980s, renewable energy sources remained on the same level for this decade as a whole. In the 1990s renewable energy sources show a similar course with a small increase. It is remarkable that this small increase equals a raise of the market share of renewable energy sources by approximately 10% related to the level of 1990. Due to incomplete data for the year 2009, the amount of non-hydro electric renewable energies is estimated for this year based on the year 2008 with 7% annual growth in absolute production value, which equals the average growth rate since the year 2000. In contrary to the situation before 1970, non-hydro electric renewable energy sources cannot be neglected since they account for 20-30% of the production from renewable energy sources in the considered years of the 21th century. Additionally, this 7% growth rate is a rather pessimistic figure as the previous years possess higher increases. Under this assumption, the average annual growth rate for renewable energy sources increased slightly between 2000 and 2009.

Renewable energy sources increased their absolute values of production in the last 40 years such that an almost constant respectively slightly increased market share could be maintained. Moreover, the performance of renewable energy sources in terms of increase of market share until 2009 was definitely well beyond all other growth processes, observed within the considered period. A summary of the average change rate of the energy market shares for the different energy sources for the time under consideration is provided in Table 2.

Year	Coal	Petroleum	Natural Gas	RES	Nuclear
1950 - 1960	-12‰	9‰	3‰	-1‰	0‰
1960 - 1970	-11‰	8‰	3‰	-0‰	0‰
1970 - 1980	-5‰	-1‰	2‰	1‰	2‰
1980 - 1990	1‰	-8‰	3‰	0‰	3‰
1990 - 2000	-3‰	0‰	1‰	1‰	1‰
2000 - 2009	6‰	-5‰	-1‰	1‰	-2‰

Table 2: Average annual change of market share per decade on world level

Data source: See Table 1

The sum of the individual changes indicated in Table 2 need not equal zero due to independent rounding. For each decade the maximum increase in market share is highlighted in order to identify the energy source with the highest growth.

Interestingly the energy market shares behave in contrast to the general feeling that “the world is speeding up” and changes proceed faster. The energy system shows lower change rates since the 1970s. What can be observed is that changes happen more frequently, in particular for the most important energy sources oil and coal.

The average rate of change for the different energy sources for the time periods 1950 to 1970 and 1980 to 2009 that represent the slope of the trend lines in Figure 8 are listed in Table 3.

Year	Coal	Petroleum	Natural Gas	RES
1950 - 1970	-11‰	8‰	4‰	-1‰
1980 - 2009	0‰	-3‰	1‰	0‰

Table 3: Slope of the trend lines of Figure 8 as average annual change of market share

Data source: See Table 1

Nuclear energy is omitted in Table 3 because the time periods listed in this table do not represent meaningful time frames for nuclear energy.

The examination of the substitution processes in the energy market and the market shares on world level does not permit to conclusively link changes to single decisions because of the amount of simultaneous regional events. Therefore, this level of detail does not suffice to evaluate whether single decisions or events influence the course of the energy system or just optimize a predetermined course.

However, two events seem to be of such a world-wide impact that more than one energy source was considerably affected. In particular, these events are the two so-called oil crises with significant increases in prices for petroleum in the years 1973 and 1979/1980. As already anticipated with the term oil crisis, petroleum was abruptly affected by the increase of the petroleum prices. Secondly, the course of coal shows immediate effects for the time right after these events. Accordingly the two most important energy sources are affected. The changes of these two energy sources are almost completely reverse. So it seems that coal had absorbed the variations of oil's market share.

According to the rules of the original Primary Energy Substitution Model, described in section 2.2, oil was in its transition phase from growth to decline in this time anyway, since petroleum is the first non-declining energy source. Hence, it is difficult to determine whether petroleum's transition in the 1970s respectively 1980s was the next consequent change in the evolution of the energy system after the peak of coals market share in 1920s or this transition was solely caused by human decisions. Probably this question cannot be answered anyway because every changeover in systems, which are related to humans, is based on the concentration of similar individual choices of humans, regardless of logical or ideological motivated. When considering the transition from coal to oil as an example, V. Smil presumes that it were logical decisions of humans to prefer petroleum to coal, as already stated in section 2.3.[70] For this reason, it remains unsettled whether the events behind the oil crisis were just visible expressions of a consequent or in other words predetermined evolution of the energy system or the transition to a declining market share for petroleum in the 1970s was caused by these events.

The changes in the evolutionary pattern of coal in the 1970s must be examined under different preconditions. For coal's market share, the original Primary Energy Substitution Model definitely does not foresee an additional transition. Obviously, coals market share did not continue its previous course past the 1970s. Hence, the question arises if this change is a transition in the meaning of the model. Generally, the segment between growing and declining market share in the evolution of an energy source is declared as transition in the model. This is certainly not true for the coal's course in the considered time frame. If the

---

[70] Smil, V. (1998): Future of Oil: Trends and Surprises, in: OPEC Review, Vol. 22, Issue 4, pp. 253–276.

reversed process from declining to growing market share, which would in fact be a resurgence of coal, is defined as a transition in the meaning of the model, the question is whether the recent increase of coal in the 21st century is really durable or not.

Besides the two most important energy sources petroleum and coal, none of the analyzed energy sources shows such distinctive changes following the years of the oil crisis.

With a more detailed analysis on regional level in the following section, a deeper insight in relations among energy related events respectively decisions and changes in the evolutionary patterns in substitution processes for the energy market is gained.

3.2 Regional Analysis

Within this section the energy systems of three world regions that are major in relation to the world’s energy system are the matter of considerations. Unlike the global case for which the assumption of equal production and consumption seems to be valid, regional models need to consider exports and imports, which are becoming more important. Only on the global level, the assumption of equal production and consumption seem to be plausible because of relatively constant respectively slowly changing ratios between the average annual storage capacity and the production of the different energy sources. Moreover, for energy sources that are primarily related to electricity or surveyed based on electricity generation such as nuclear energy and renewable energy, storage capacity has not to be considered due to the fact that electric energy is not storable in mentionable amounts. This is the reason why energy production from renewable energy sources is considered to be entirely consumed in the year of production. Additionally, it is assumed that each region consumes its production from renewable energy sources. The reason behind this assumption is that none of the considered regions indicates such a high share of electricity generation from renewable energy sources so that it is forced to export this domestic energy production. At least for Europe and the USA this is a reasonable assumption. Since China is a net-exporter of electricity and had not imported significant amounts of coal, which is its primary fuel for electricity production, this assumption might not fully apply to the Chinese energy system, but is used for the sake of uniformity.

As already stated in the previous section 3.1, frequently more than one data source has to be employed in order to include a time period of more than 50 years. Not all employed time series contain all considered primary energy sources. Therefore, it is possible that the course of one single energy source does not have a continuation for certain time frames. To indicate artificial changes in the plot caused by this lack of data, the continuous line is then interrupted.

Nuclear energy is not included for the evaluation of domestic energy production data, because all of the analyzed regions import significant parts of the nuclear fuel. Consequently, the market share of domestic production of base material for nuclear fuel can be neglected.[71,72] For the examination of energy consumption, electricity generation from nuclear energy is considered.

3.2.1 Europe

This section presents the evolution of the European energy system from production and consumption perspective by use of the substitution model for the primary energy market in graphical form, as described in the previous sections. First some basic information on the European energy production and consumption is given and some key developments illustrated. For this analysis Europe refers to the countries of OECD Europe based on the OECD membership of 01.01.2010, which are Austria, Belgium, Czech Republic, Denmark, Finland, Former Czechoslovakia, France, Germany (East and West), Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

European domestic energy production

The European energy production was dominated by coal for a long time. Nevertheless, coal's market share decreased continuously through the years but with an almost constant share of about 20% of total energy production since 2000.

The share of petroleum production increased significantly in Europe in the 1970s due to the start of offshore production and peaked at the end of the 20th century. Production of natural gas in Europe increased significantly prior to the mid 1970s and slightly increased its market share in the period past the 1980s after a minor decrease of its fraction.

No noteworthy changes for the market share of renewable energy sources in production happened in the period from 1960 to 1990 since the changes leveled out for this time frame. The following decades show a considerable raise in market share for the production from renewable energy sources. Moreover, the growth rate of market share increased in the first decade of the 21st century compared to the previous decades, as shown in Figure 9.

It is remarkable that the change from declining to stable market share for coal matches chronologically with the peaking of oil's market share, which can be noticed for the global data of Figure 8 as well.

---

[71] World Nuclear Association (April 2011): World Uranium Mining, http://www.world-nuclear.org/info/inf23.html, 01.06.11.

[72] World Nuclear Association (April 2011): US Nuclear Fuel Cycle, http://www.world-nuclear.org/info/inf41_US_nuclear_fuel_cycle.html, 01.06.11.

On first sight, the evolution of market shares for the energy consumption market is different from the energy production market. This indicates the significance of international trade respectively imports for the European energy market.

Substitution processes in the European energy consumption

In the 1950s coal does not have that importance in the European energy consumption market as Figure 9 reveals for the production market. However, coal is still dominating until the mid 1960s for the European energy consumption and even longer for the primary energy production. Both figures show a declining fraction for coal in the energy market from the beginning of the analysis in the 1950s. Subsequently all statements within this section refer to the consumption market except noted otherwise.

Identical to the decline of coal's market share until the first half of the 1970s, petroleum extended its share in this time period. In the years around the first oil crisis of 1973 this pattern changed and converted into a stable fraction of the energy market for coal and a decrease for petroleum's market share.

After a few years of constant market share for petroleum in the late 1970s, a second significant decline of petroleum's share happened as a reaction to the second oil crisis in the years 1979/1980. This development finds its counterpart in an increasing market share for coal at the same time. The opposed development of petroleum and coal continues for the following years. After the mid 1980s petroleum fills an almost constant fraction of the energy market, whereas coal's market share declines notably. The evolution of the energy consumption market in Figure 10 highlights the impacts of the oil crisis, as described above.

Similar to the course of petroleum, the market share of natural gas raised remarkably from the 1950s to the mid 1970s. The break in the graph of the market share of natural gas in the mid 1970s contributed to the sudden change in the course of coal's market share at that time. This change of the growth rate of natural gas at a market share level of about 13% initiated a period of a relatively constant alteration for natural gas for the following years.

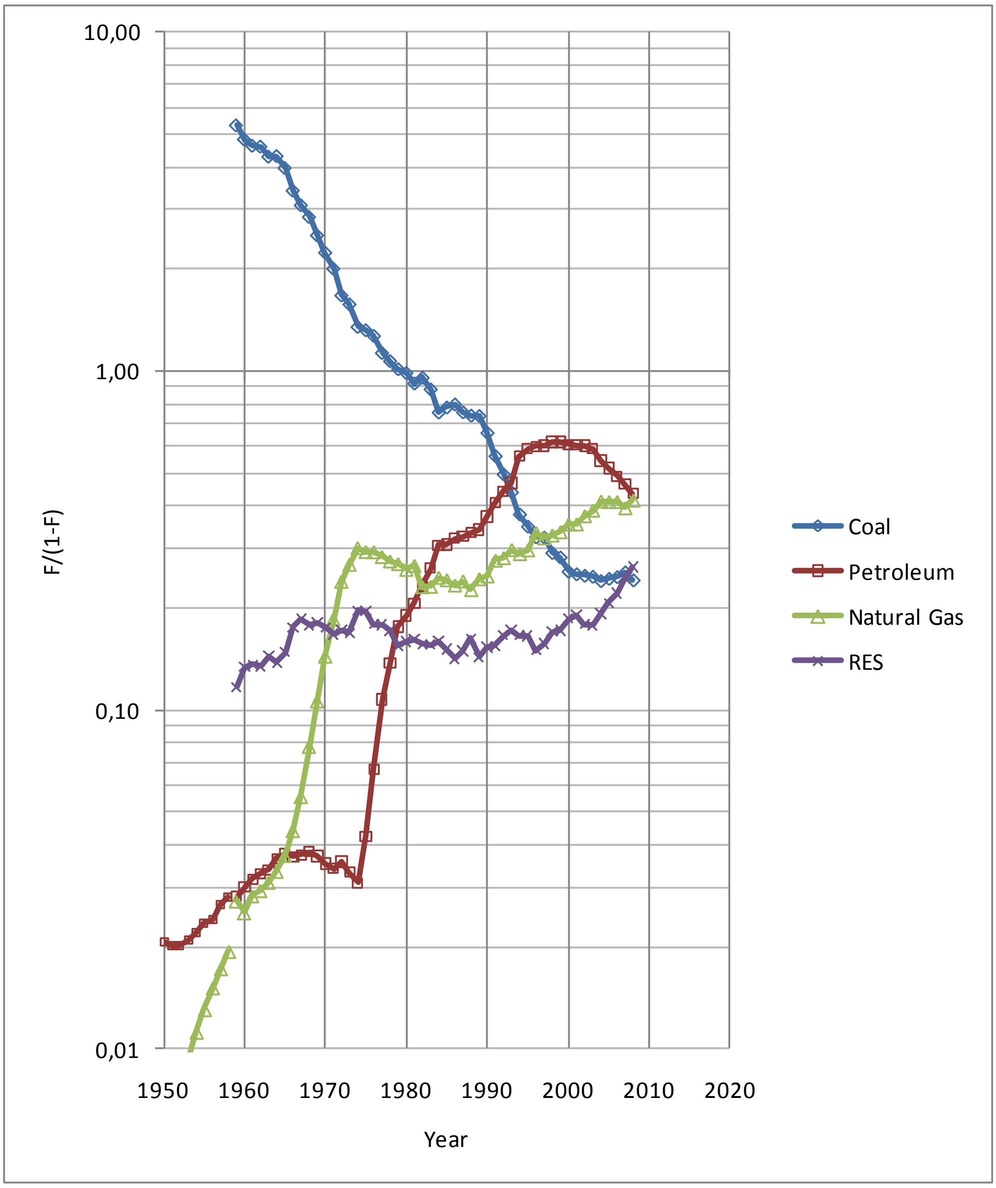


Figure 9: Domestic energy production and primary energy substitution OECD Europe 1950 - 2008

Data source 1950-1979:	Mitchell, B. R. (1993): *International historical statistics: Europe: 1750 - 1988,* 3rd ed., New York, N.Y, Mitchell, B. R. (1983): *The Americas and Australasia,* London, Mitchell, B. R. (1998): *International historical statistics: Africa, Asia & Oceania, 1750 - 1993,* 3rd ed., London, http://www.loc.gov/catdir/description/hol051/00552129.html
Data source 1980-2008	U.S. Energy Information Administration : International Energy Statistics, http://www.eia.gov/countries/data.cfm, 10.04.11.

Table 4: Data sources for Figure 9

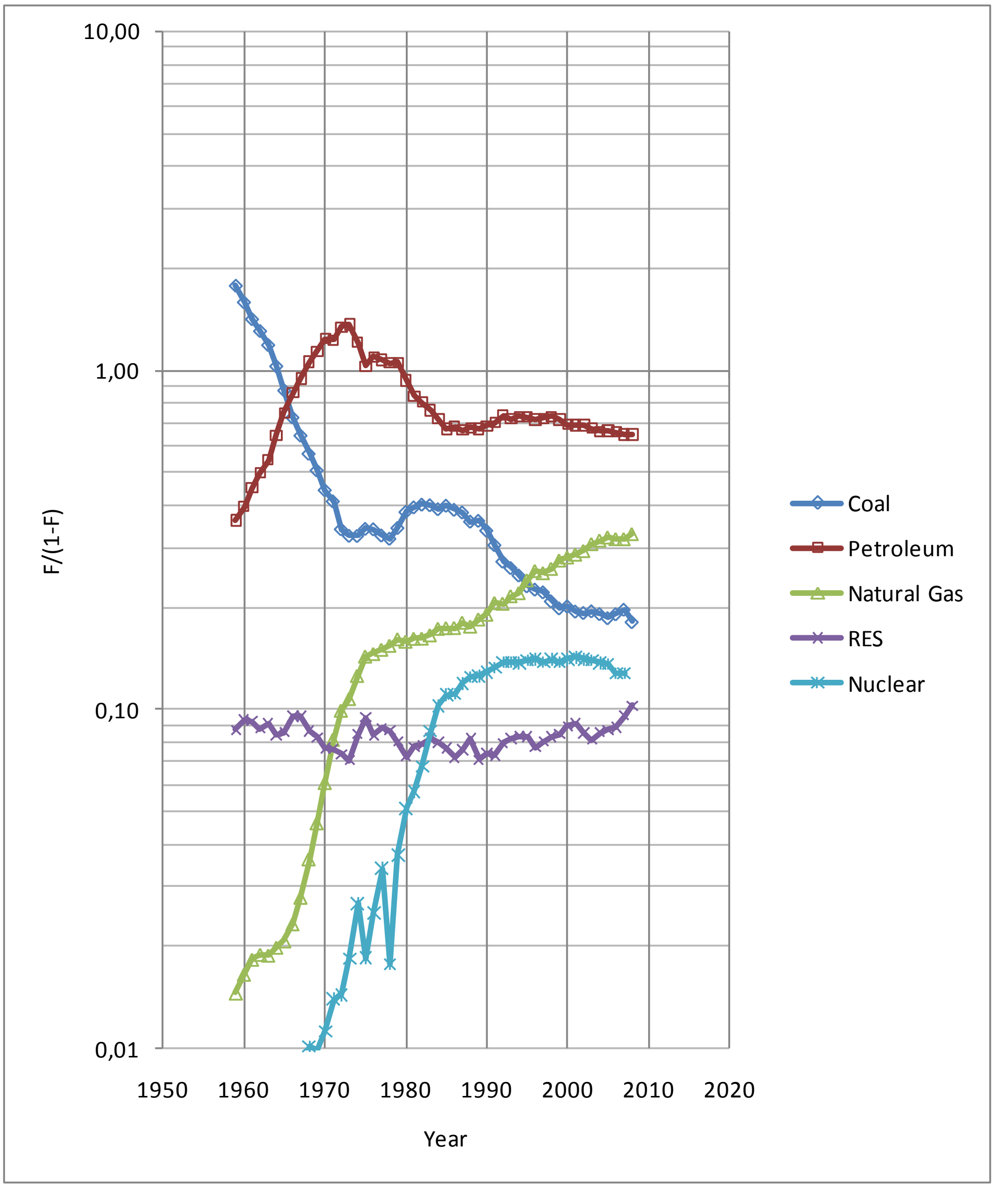


Figure 10: Energy consumption and primary energy substitution OECD Europe 1959-2008

Data source 1959-1973:	O.E.C.D. (1974): *Statistics on Energy 1959–1973,* Paris,
Data source 1974-1979	O.E.C.D. (1983): *Energy Statistics 1971-1981,* Paris,
Data source 1980-2008	U.S. Energy Information Administration : International Energy Statistics, http://www.eia.gov/countries/data.cfm, 10.04.11.

Table 5: Data sources for Figure 10

In the late 1960s nuclear power appears in the substitution model for primary energy consumption. The fraction of nuclear energy in the primary energy market raised considerable until the 1990s and reached its peak at 12%. The 1990s and the early years of the 21st century are characterized by an almost constant market share for nuclear energy. During the last years of the analysis the fraction of nuclear energy on the whole energy consumption has declined.

The share of renewable energy sources on the European energy consumption declined overall slightly from the 1950s to 1990 with highly dynamic changes. Since 1990 the fraction of renewable energy sources in the energy market increased in total with somewhat smaller variations in comparison to the previous period. The average increase of the market share of renewable energy sources per decade for the period from 1990 to 2009 is about 1%.

To summarize, the European energy market both for production and consumption significantly changed in the 1970s. A certain link between the changes of petroleum and coal seems to exist, whereas coal decreased in total and petroleum evolved to the most important energy source for the last decades. Natural gas increases its market share steadily and will obtain the highest fraction of European primary energy production soon in case of a stable further evolution. Nuclear energy reached a specific level of slightly over 10% market share and contributed this share almost constantly over the past 25 years. A similar constant market share can be identified for renewable energy sources for the last 60 years, but with an increasing share for the last decades.

In comparison to the evolution of the European energy system, the following section employs the US-American energy system.

3.2.2 USA

Similar to the analysis of the European energy system, this section describes the evolution of the US-American energy system from the production and consumption perspective in graphical form and highlights some key developments.

US domestic energy production

Contrary to Europe, the primary energy production of the USA did not have such a high proportion of coal in the 1950s. However, the fraction of petroleum and natural gas are higher. Similar to the European case is the decrease of coal’s market through the 1970s. For petroleum the production peak in terms of market share for the USA was far earlier than for Europe to be specific in the mid 1950s.

Natural gas experienced a remarkable gain of market share on the US-American primary energy production until the early 1970s, which is similar to the increase in the European energy system, but on a very different level since natural gas has the highest market share in the energy production market in the 1970s. The fraction of the energy market that renewable energy sources maintained decreased in the years from 1950 to 1970 as in the Europeans case.

The US-American petroleum production decreased in terms of market share in the primary energy sources market in a rather constant way throughout the time after the mid 1950s. In the early 1970s, natural gas gained its peak market share for the considered time period. After a phase of declining fraction of natural gas on the energy market in terms of production for about 15 years, its market share increased again but with a lower growth rate. Simultaneous with the market share peak of the natural gas production and its transition to a declining market share, the coal production stopped its declining course. Actually, the course of coal's market share reversed from declining to a sustainable increase, which lasts until the end of the considered time period. Since the mid 1980s, coal fills the largest fraction of the energy system with regard to production.

The evolution of the market share, of production from renewable energy sources in terms of electricity generation is characterized by an overall increase over the timer period from 1950 to 2009 but with wild oscillations in the annual production.

Substitution processes in the US energy consumption

From the consumption point of view the market share of petroleum shows an outstanding constancy. Apart from few ripples, petroleum has throughout the considered time frame the highest market share of all primary energy sources at a level of about 40%. By comparing Figure 10 with Figure 12, it seems that the oil crises of the 1970s had much weaker impacts on the course of the US-American petroleum consumption compared to the European, even though the evolution of the rate of petroleum imports to domestic production reveals an approximately ten year intermittence in its change pattern after the second oil crisis of 1979/1980.

The fraction of coal on the energy consumption in the USA decreased until the early 1970s when gas reached its peak and increased afterwards for more than a decade. The last quarter century coal's market share on the energy consumption was relatively constant at a level of about 20%. In contrast to the evolution of coal's market share natural gas increased its fraction on the primary energy market until the early 1970s and held a nearly constant market share at about the level of coal for the last quarter century after a period of declining market share in the 1970s and the 1980s.

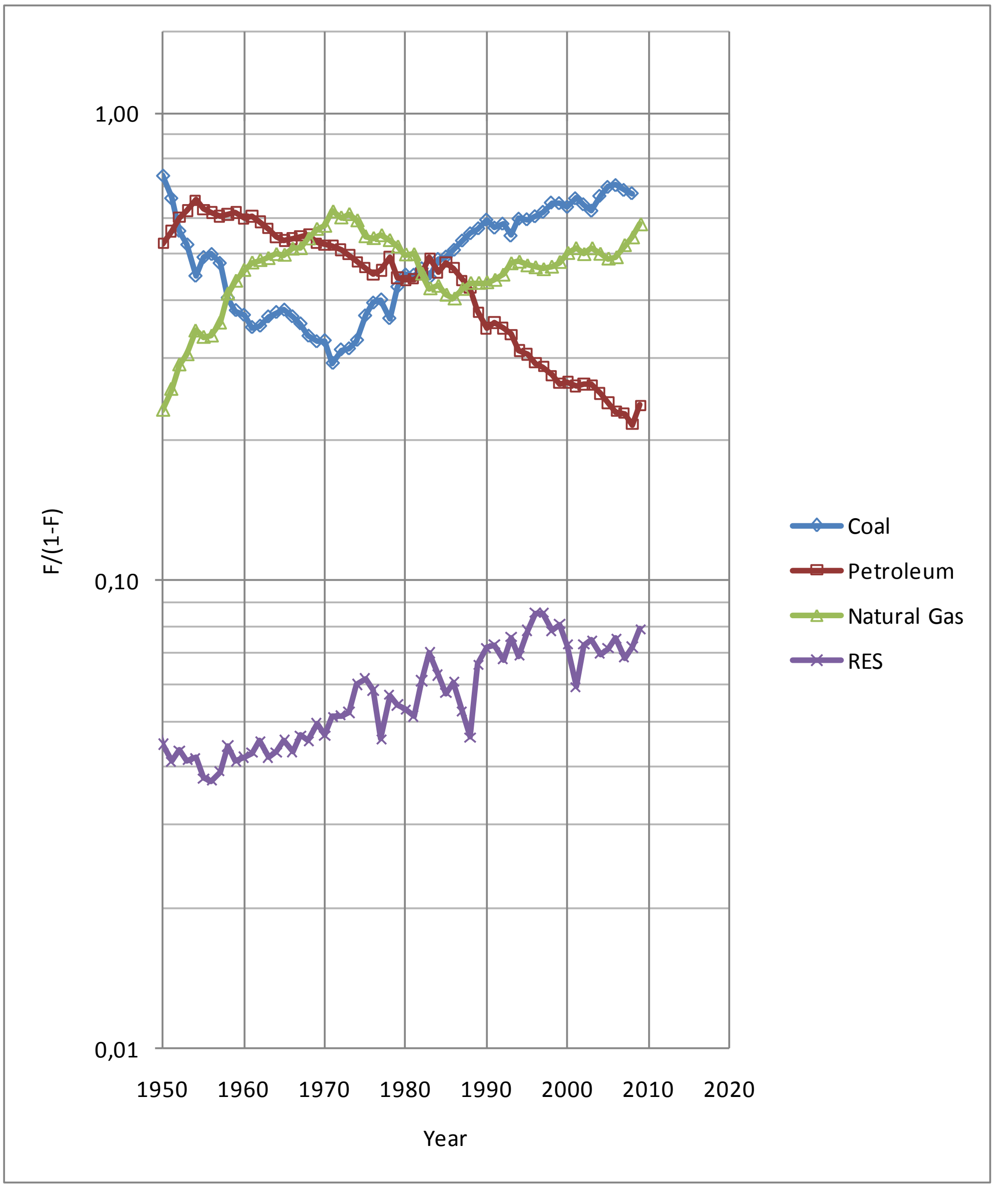


Figure 11: Domestic energy production and primary energy substitution USA 1950 - 2009

Data source: U.S. Energy Information Administration : *Annual Energy Review 2009,* http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.

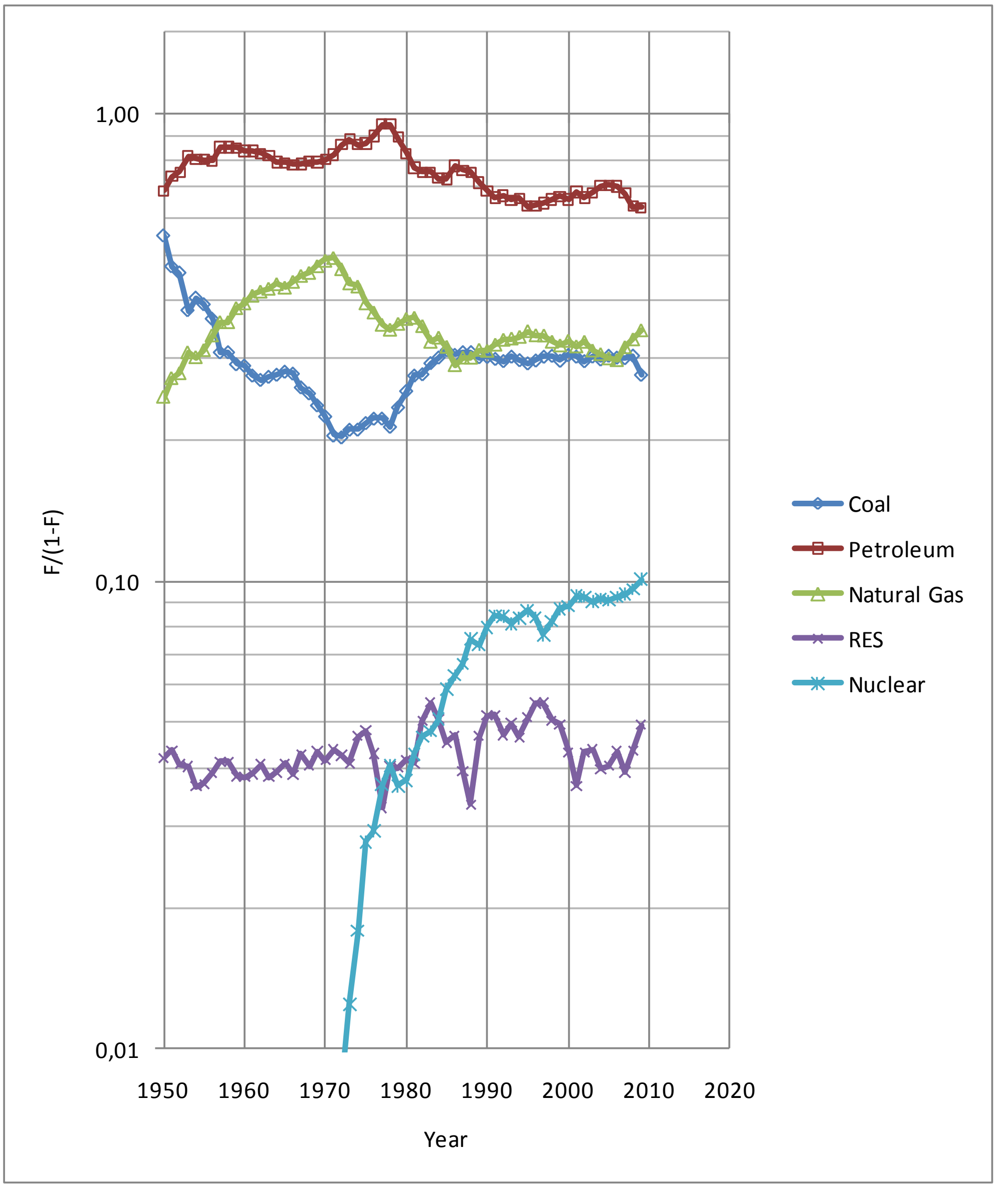


Figure 12: Energy consumption and primary energy substitution USA 1950 - 2009

Data source: U.S. Energy Information Administration : *Annual Energy Review 2009*, http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.

The evolution of nuclear energy in the USA is comparable to the European. After a significant rise of nuclear energy's market share in the 1970s and 1980s, the growth slowed down considerable and sustainable. For the last 20 years, the fraction of nuclear energy on the primary energy consumption slightly increased. Unlike the European development no decrease of nuclear energy's market share for the last considered decade is observable, but also no notable increase.

The course of the market share of consumed energy that is produced from renewable energy sources is very similar to the described pattern of production. One interesting difference is that the increasing fraction of renewable energy sources of the domestic energy production in the USA does not suffice to increase the market share on the consumption side, although no electricity is exported by the USA.

This situation suggests that the consumption of other energy sources increased more than their domestic production. Thus, the additional consumption is related to imports. The differences between the production and the consumption case in the paths for renewable energy sources suggest that an increasing share of the other energy sources is imported. If additionally the deviations of the course of the US-American natural gas production from the natural gas consumption and similar deviations for the path of coal, it seems that the high share of petroleum on the US-American energy consumption is possible due to imports. The fraction of petroleum imports on the US-American consumption rises since the mid 1950s.

The assumption that the oil crises did not have significant impacts on the course of the market share of petroleum seems to be valid for the energy system as a whole too since no really immediate variations in the system can be identified in connection with the two so called oil crises in the 1970s. The transition of the market share of natural gas from growth to decline in the early 1970s showed up before the actual oil crisis and was very likely the reaction on gas shortages and legal issues. In consequence of the gas curtailments of the early 1970s, the Powerplant and Industrial Fuel Use Act and the Natural Gas Policy Act, which regulated the natural gas market and limited the usage of oil and natural gas in power plants and other large boilers, were imposed by the US-government. The gas curtailments and these regulations seem to cause a shift in the energy system. This change was not as supposed in the original Primary Energy Substitution Model a shift of market share from natural gas to a new energy source, instead coal substituted natural gas, especially in electricity production. Hence, the Powerplant and Industrial Fuel Use Act of 1978 also regulated the use of petroleum as primary energy source for large boilers which most likely initiated the reduction of petroleum's market share after legal validity of the act. The changes in the natural gas demand and production in response to the legal actions and the repeal of the Powerplant and Industrial Fuel Use Act in 1987 led to a widely constant market share for natural gas respectively to a slight increase.[73]

The next section discusses the evolution of the energy system in one of the most emerging countries for the last decades, which is getting more and more important for the global energy system.

3.2.3 China

With its economic growth, China evolved also to a region of interest regarding energy issues, since energy is an important factor for the economic growth.

This section describes the evolution of the Chinese energy system. The development of the different primary energy sources is discussed and shown in graphical form in Figure 13 and Figure 14. The energy production and the energy consumption are considered separately in order to cover the supplies and sales market.

The early years of the analysis China’s energy system was more or less insular. The exploration of massive oil fields in combination with high oil prices and the demand for foreign currency as well as huge reserves of coal combined with sufficient production capacity led to more interconnections of the Chinese energy system in the 1970s. The increased involvement in international trade manifested mainly in exports. A considerable increase in demand for liquid fuels respectively petroleum, which was and is still mainly driven by the emerging demand for individual mobility, resulted in the need of oil imports since the mid 1990s.[74]

Due to the marginal external trade of China’s energy sector until the 1970s, the graphical models representing the energy system from the production side and from the consumption point of view are discussed together. The most important primary energy source for the Chinese energy system is coal for the entire time that is considered. Coal remarkably dominated the energy system in the 1950s. Along with the increasing market share of petroleum, the fraction of the energy market that is kept by coal decreased until the mid 1970s, when the petroleum’s market shared peaked. The fraction of natural gas on the Chinese energy system increased until 1980 but on a much lower level than in Europe and the US.

---

[73] U.S. Energy Information Administration : Major Legislative and Regulatory Actions (1935 - 2008), http://www.eia.gov/oil_gas/natural_gas/analysis_publications/ngmajorleg/ngmajorleg.html, 01.06.11.

[74] Locatelli, C. (1989): China's Energy Policy: Energy and Economic Development, in: Energy Studies Review, Vol. 1, Issue 2, pp. 144–158.

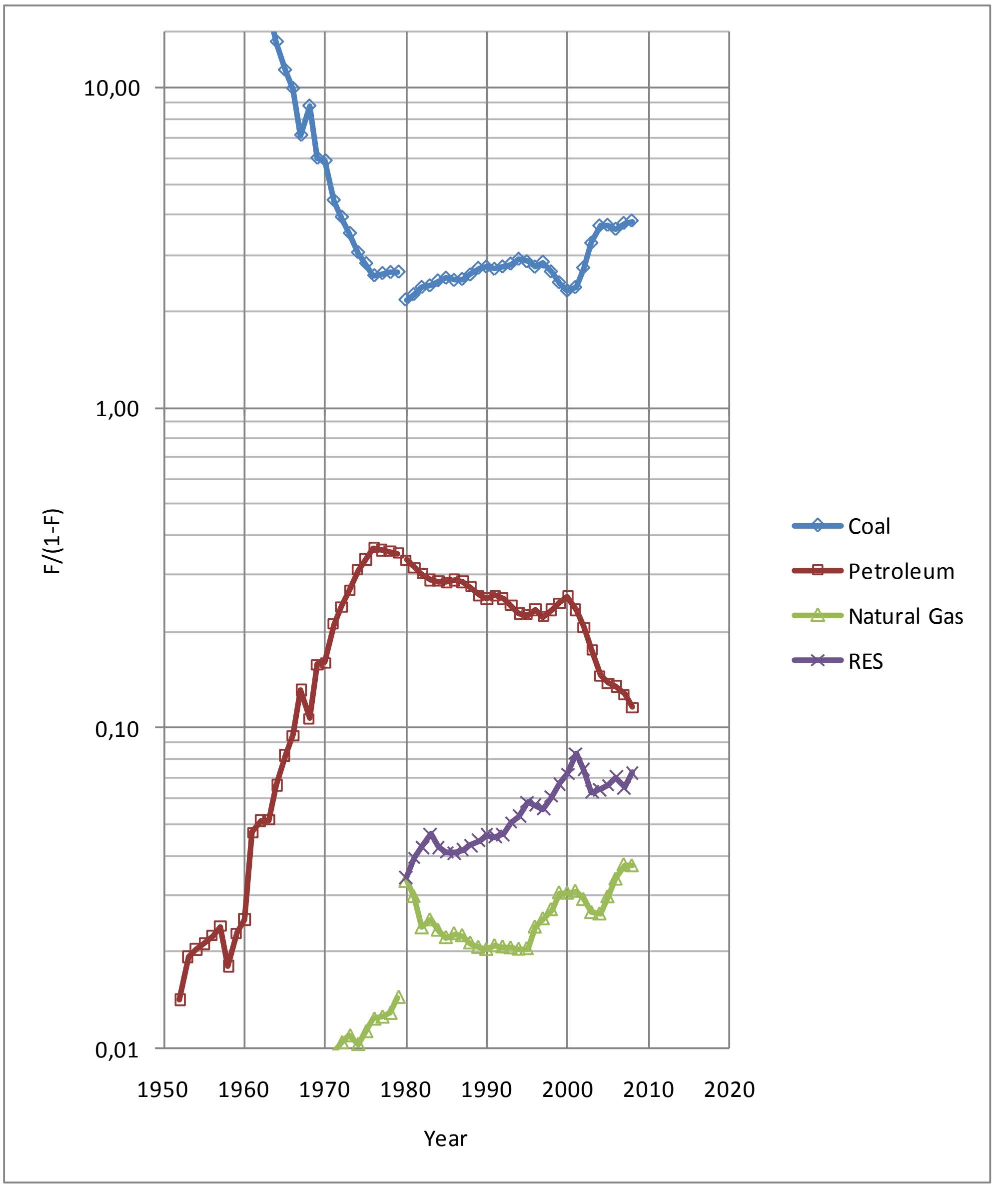


Figure 13: Domestic energy production and primary energy substitution China 1952-2008

Data source 1959-1979:	Mitchell, B. R. (1993): *International historical statistics: Europe: 1750 - 1988,* 3rd ed., New York, N.Y, Mitchell, B. R. (1983): *The Americas and Australasia,* London, Mitchell, B. R. (1998): *International historical statistics: Africa, Asia & Oceania, 1750 - 1993,* 3rd ed., London, http://www.loc.gov/catdir/description/hol051/00552129.html
Data source 1980-2008	U.S. Energy Information Administration : International Energy Statistics, http://www.eia.gov/countries/data.cfm, 10.04.11.

Table 6: Data sources for Figure 13

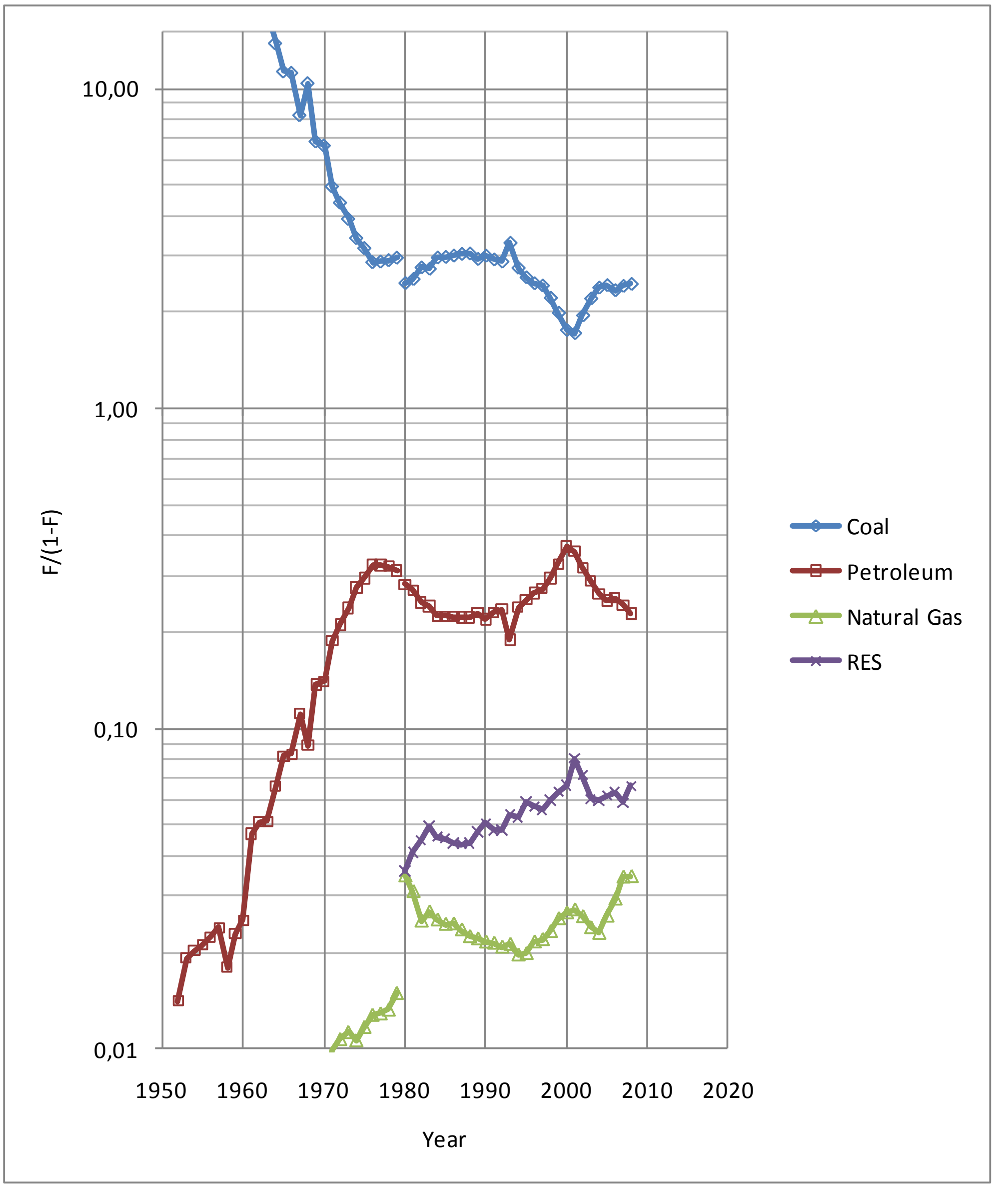


Figure 14: Energy consumption and primary energy substitution China 1952-2008

Data source 1952-1979:	Mitchell, B. R. (1993): *International historical statistics: Europe: 1750 - 1988,* 3rd ed., New York, N.Y, Mitchell, B. R. (1983): *The Americas and Australasia,* London, Mitchell, B. R. (1998): *International historical statistics: Africa, Asia & Oceania, 1750 - 1993,* 3rd ed., London, http://www.loc.gov/catdir/description/hol051/00552129.html
Data source 1952-1979	Exports estimated, based on Locatelli, C. (1989): China's Energy Policy: Energy and Economic Development, in: Energy Studies Review, Vol. 1, Issue 2, pp. 144–158.
Data source 1980-2008	U.S. Energy Information Administration : International Energy Statistics, http://www.eia.gov/countries/data.cfm, 10.04.11.

Table 7: Data sources for Figure 14

For the years prior to 1980, energy data for China is barely available. Therefore the path for the market share of renewable energy sources begins in 1980. For the same reason the energy consumption data for the time before 1980 is estimated based on the production data as indicated in Table 7. Accordingly, the shift in the development paths in 1980 is caused by dataset restrictions and does not indicate a real world change of the market shares. These shifts result from the integration of renewable energy source for the time after 1980.

China’s domestic energy production after 1970

As already seen in the European case, the petroleum production peak resulted in a transition of coal’s market share from declining to slightly increasing. Coal’s market share regarding production increased steadily after this transition aside from an interruption around the year 2000.

The fraction of petroleum on the Chinese primary energy production decreased after its peak in the end of the 1970s at a relatively constant rate until the decline accelerated in the 21st century after a short intermittence around the year 2000. The share of natural gas on the primary energy production of China slightly increased after 1980 when considering the entire following period at a quite low level of a few percent.

Renewable energy sources constantly increased their fraction on the primary energy production in China after 1980. In contrast to the European and US-American energy system, renewable energy sources contribute a bigger share to the energy supply than natural gas does. Nevertheless, the fraction of renewable energy sources on the entire primary energy production is lower than in Europe and the USA.

Substitution processes in the Chinese energy consumption

From the consumption point of view, the absolute peak of the market share of petroleum was not in the 1970s but around the millennium. Even so in the 1970s the course of petroleum’s market share changed from a significantly increasing path to a slightly decreasing one. Comparable to the production case discussed above, this transition in the course of petroleum’s market share matches temporarily with the change of coals course towards an almost constant share. Beginning in the early 1990s, petroleum’s market share increased until its peak around the year 2000. After this, the market share of petroleum decreased with a similar rate as it previously increased. Coal’s market share however decreased in the 1990s and returned to a more or less constant path after almost half a decade. Altogether the courses of coal and petroleum are generally inverted.

The market share of natural gas increased since the mid 1990s to a slightly higher level than un1980 after more than a decade of lower market share. However, natural gas merely contributes a few percent to the Chinese energy consumption.

Renewable energy sources constantly gained market share since 1980 in the Chinese energy system but account still for a rather low fraction of the energy market with clearly under ten percent.

Summarized, the evolution of the different energy sources in the Chinese energy system show a clear dominance of coal and a strong relation between the course of coal's market share and petroleum's share, are by far the two most important primary energy sources.

Based on this analysis of China's energy system, no explicit connection between the oil crisis and changes in the energy system can be identified. Although changes in the courses of coal's and petroleum's market share happen in the 1970s, it seems as they are not directly related to oil crisis because of low imports. Nevertheless, the oil crises might have affected the evolution of the energy system after 1980 especially in the following years.

The presented analysis of the European, US-American and Chinese energy system show three different energy markets and revealed differences in the temporal development of the primary energy sources among these regions.

Findings from the global and regional analyses on the energy system are discussed in the following section 3.3.

3.3 Energy Substitution Concluded

This section is intended to summarize the analyses on the energy systems and to derive conclusions from the findings. Similarities among the different levels of detail of the analysis of the energy system as well as links between the regional energy systems and the global energy market are discussed.

At first, a brief review of the situation on the examined primary energy markets and some basic facts are given. For about half a century, petroleum has been the most important primary energy source on the global level. This is also true for the regional energy systems of Europe and the USA in terms of consumption. Only for the Chinese primary energy consumption, petroleum does not deliver the highest share of the primary energy sources. In the Chinese energy system, coal has a special position and meets almost half of the primary energy demand. Globally, the second and third highest market shares are held by coal and natural gas. Around the year 2000, the market shares of natural gas and coal were almost equal, but the recent increase in coal’s market share made coal certainly to the primary energy source with the second highest fraction of the market. There is no common ranking of the market shares of coal and natural gas for the primary energy consumption in the different energy markets, since in the USA both have almost equal shares, in Europe the natural gas consumption exceeds that of coal, whereas in China a notably high market share for coal in combination with a very low share for natural gas is identified.

Clearly, fossil fuels dominate the primary energy market, as all three fossil primary energy sources are well above 20% market share and therewith more than the double of the shares of either renewable energy sources and nuclear energy. The data of the last decade show a slight increase for the market share of renewable energy sources and a decrease for the fraction of nuclear energy on the primary energy sources market.

One common characteristic in the dynamics of the analyzed energy systems is that in the 1970s, the previous trends for more than one primary energy source changed. According to the examinations of C. Marchetti based on Figure 5, this situation did not happen before at least not at this scale. Therefore, the assumption that the 1970s constitute a breakline for the evolution of the energy systems appears to be reasonable, since the evolutionary patterns of several energy sources changed in different regional energy systems concurrently in the same decade. Prior to 1970, trends in the development paths of the primary energy systems seem to be quite stable, as it was already stated by other authors based on former analyses, which are discussed in chapter 2. In general, the development paths in the analyzed energy systems are also relatively stable after the shift in the 1970s. Though, the assumption of long-time stability of change-processes that was ascribed to the energy system in previous works, which are quoted in chapter 2, is not supported by the actual developments after the 1970s.

Another common characteristic in the dynamics of the analyzed energy systems is that the course of coal’s market share always changes simultaneously to the peaking of another primary energy source. In the global case as well as for the European and the Chinese energy system, the evolutionary trend of the market share of coal changed at the same time as petroleum’s fraction of the primary energy market peaked and in the US-American case at the time when natural gas had its peak. According to these developments, the assumption that coal is used as a kind of “backup” energy source seems to be plausible, as coal takes over the market shares from energy sources after their peak.

Furthermore, this characteristic applies to the primary energy consumption as well as to the examination of the energy supply side. This special sensitivity of coal’s fraction of the primary energy market to the end of the growing phase of other energy sources is also revealed by the increase in global market share for coal after the year 2000, which occurs at the same time as the fraction of nuclear energy starts declining. Moreover, there are two rapid changes in the trend for the market share of coal in the US-American energy consumption, which both happen simultaneously to peaks in other energy sources. First the market share of natural gas peaked and coal's fraction of primary energy market in the USA stopped declining. Later, petroleum's fraction of the US-American primary energy market peaked and a phase of notable incline of coal's market share began. These changes in the trends of natural gas and coal are most likely caused by a modification of the legal conditions for energy usage in the USA, as already discussed in section 3.2.2. All these incidents seem to confirm the assumption that coal acts as a kind of “backup” energy source, which takes over the market shares that cannot be exploited by a peaking energy source anymore.

One possible explanation for this situation might be that no new respectively other energy source, which alternatively to coal could be expanded to compensate for the market shares that could not be attained by the peaking energy sources, was available. Due to the declining market share of coal at the time of the peaks, the absolute increase in coal extraction was not that high, so an expansion of the coal production capabilities was easier possible. Furthermore, the geological location of coal deposits makes it feasible for various world regions, including the analyzed regions Europe, USA and China, to extend the domestic coal production and therewith increase coal's market share without the need of imports. This is a particularly important issue since the major reserves of other fossil fuels are limited to few world regions and as a result of the oil price shocks in the 1970s the limitation of the dependence on these few supply regions plays a role in decisions concerning the energy system.

In contrast to the time when coal and wood dominated the market and consistently new energy sources like petroleum, natural gas and hydro power entered the market to substitute the old ones, no new source of primary energy achieved a significant market share for approximately 70 years until nuclear energy entered the energy market. This might be a reason why no other (new) energy source was available and also able to benefit from the growth possibilities due to the peak and subsequent decrease of a previously growing energy source, instead of coal. Thus, it seems as coal takes over the role of a new energy source and fills the lack of established but still emerging growth candidates in the energy market.

The recent increase of coal's market share in the world's energy system seems to be heavily driven by China. This is derived by comparing the recent developments at global level with the regional changes. The assumption that the recent global incline of the market share of coal originates basically from the Chinese energy consumption results from the fact that none of the other two examined regions features such a growth pattern. The recent growth in market share for coal at the global level is similar to coal's increase in the 1980s even if it is more distinctive. Still a tendency of saturation is already evident, as shown in Figure 8. For this reason, it seems possible that this recent resurgence of coal is just a temporary phenomenon, but it definitely affects more than one decade. Previously, no increase in market share of any primary energy source, which already had a phase of declining market share, occurred.

Additionally, the developments in the global energy system in terms of market share in the 21st century suggest that the estimation of C. Marchetti and N. Nakićenović on an unexpected pile out of nuclear energy by coal is at least partly legitimate, as the recent growth of coal's share occurs contemporaneously with the decrease of the fraction of nuclear energy in the primary energy market. Already in 1978 they considered a pile out of nuclear energy as an option, which might become reality 30 years later.[75] The fact that nuclear energy just supplies the niche of electrical energy in the entire primary energy market in combination with the enlarging portion of coal that goes into electricity production bolsters this assumption.

However the question arises how it is possible that coal, which is less convenient, more polluting and has a lower energy density, compared to other available energy sources, does not experience a decline in market share. In contrary, coal expands its share and remarkably outperforms other energy sources. A possible explanation might be that the primary energy sources are not consumed in its original form by the end user. This question is examined in the following.[76]

Energy Form of Final Consumption

In order to identify an explanation for the fact that coal is used intensely although it has certain drawbacks in comparison to other primary energy sources, the energy consumption is studied in more detail. In particular, an assessment of the energy form of the final consumption is performed. Since one disadvantage of coal is the inconvenient handling in the consumption process, one explanation for the ongoing strong position of coal might be that coal is not used as solid energy source for final consumption but converted to another form of energy as part of the resource allocation process from the end user's point of view. Therefore, it is examined to what extent the sources of primary energy are actually consumed in its original physical condition and if this parameter changes over time. A lot of renewable energy sources as well as nuclear energy are clearly not provided in its original

---

[75] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 25, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[76] Smil, V. (1998): Future of Oil: Trends and Surprises, in: OPEC Review, Vol. 22, Issue 4, pp. 253–276.

form of energy to the end user as they are typically employed for the generation of electricity. For fossil fuels, which are by now the most important primary energy sources, it is not that obvious.

If the energy form of final consumption differs from the original energy form, it is considered here as indirect use. For example, the quantity of natural gas that is used for the generation of electric power accounts for indirect use, but the quantity of natural gas that is employed as fuel for cars is considered as direct use of natural gas. So if the end user in the residential, commercial or industrial sector uses the primary energy source in its original physical form as solid, liquid or gaseous energy source, it is counted as direct use. Thus, the inputs for combined heat and power (CHP) plants as well as for pure electricity generation plants are assigned to the category indirect use.

The examination of changes in the energy form of the final consumption for the major primary energy sources is performed for the US-American energy market, since a complete and detailed data-set to conduct this analysis is available for the USA. For the other regions, considered in the previous analyses, the necessary data could not be obtained completely and for the entire region. Therefore, the US-American energy market is employed as an example and backed up with information from the European and the Chinese energy system.

The changes of the usage of the three major primary energy sources in the US-American energy system for the time period 1950 to 2009 are shown in Figure 15. Renewable energy sources and nuclear energy are not considered in Figure 15 as they are largely used to generate electricity. Figure 15 compares the direct use of petroleum, coal and natural gas with the total indirect use of these three primary energy sources, which is the sum of the individual components. Therefore, the total consumption of fossil fuels in the USA equals 100% for this analysis.

The underlying dataset for Figure 15 includes a modification in the compilation of the data for the years after 1988. Beginning in the year 1989, all fossil fuel use of combined heat and power plants is reported separately, which causes a shift in the curves of Figure 15. Therefore, the shift from 1988 to 1989 does not reflect an abrupt increase in the indirect use of primary energy sources.

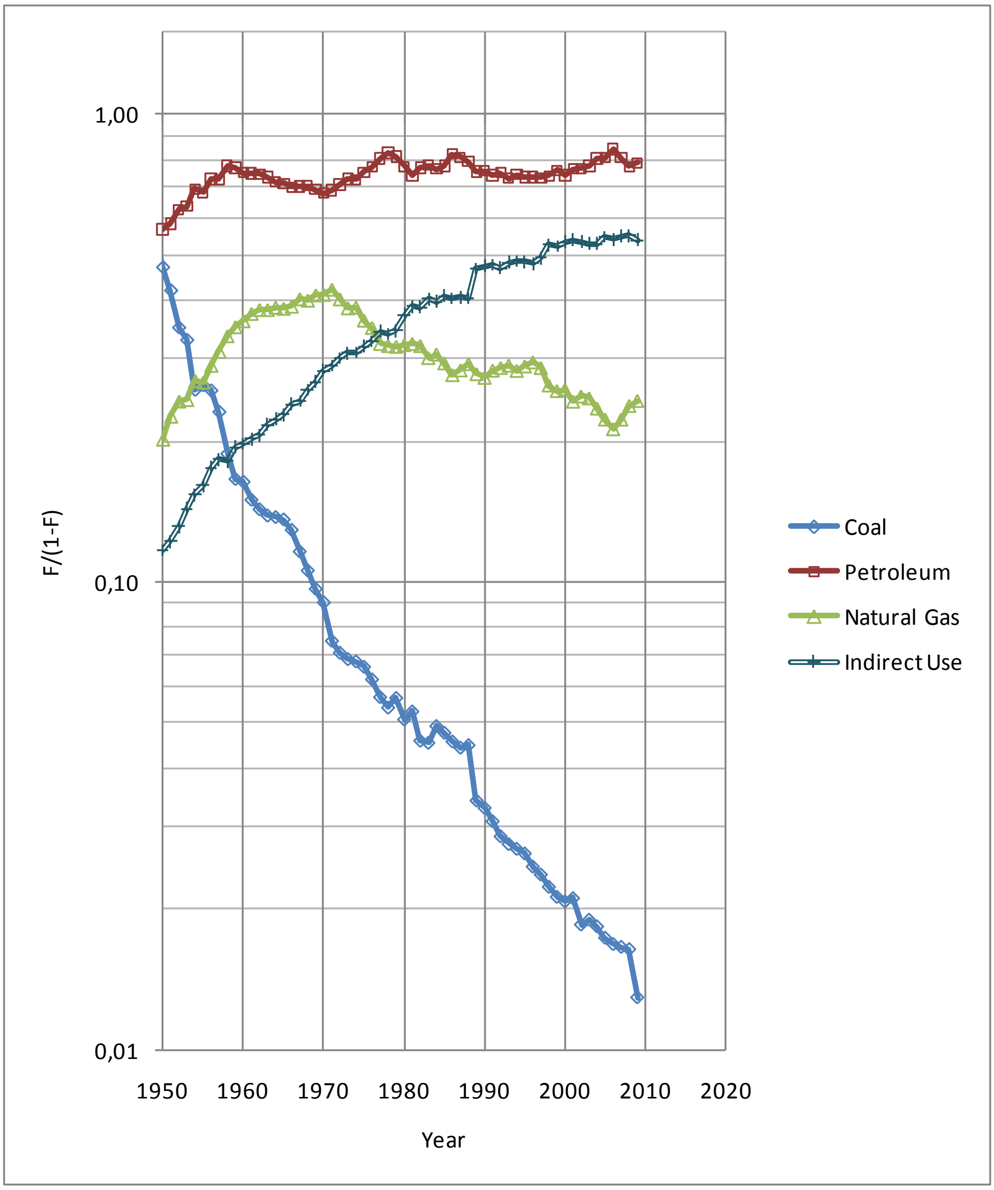


Figure 15: Indirect use of fossil fuels USA 1950-2009

Data source: U.S. Energy Information Administration : *Annual Energy Review 2009,* Table 5.13, Table 6.5; Table 7.03; Table 13.3, Table 13.4, Table 13.5, http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.

In Figure 15 the thin double line stands for the total indirect usage of fossil primary energy sources and the thick solid lines denote direct usage of fossil fuels.

The course of petroleum in Figure 15 is very similar to the already presented development of petroleum's share of the US-American primary energy consumption, which is shown in Figure 12. The peak of petroleum in the 1970s is not that conspicuous when considering direct usage only, since in this decade, the highest share of indirect petroleum use at a level of about 10% of the total petroleum use is observed in the USA. After the 1970s the indirect use of petroleum steadily diminishes and can be neglected for recent years. The reduction of the indirect use of petroleum resulted from the high petroleum prices in the 1970s and modifications in the legal system for US-American energy use. Thus, the development of the share of the directly used petroleum over the years is quite constant.[77]

The course of the direct use of natural gas is comparable to the development of the total share of natural gas consumption until the year 1987 when the Powerplant and Industrial Fuel Use Act, which limited the use of oil and natural gas usage in power plants and other large boilers, was repealed. Due to the rescission of the Powerplant and Industrial Fuel Use Act, the indirect use of natural gas was permitted, which had direct implications on the course of directly used natural gas, when comparing Figure 12 and Figure 15. Whereas the fraction of natural gas in total on the primary energy market remains almost constant over decades over two decades the share of directly used natural gas decreased furthermore mainly due to increased utilization for electric power generation. The portion of natural gas that is not used as gaseous energy source in final consumption increased to about a third of the total natural gas consumption for the last few years.

The most significant difference between the market share of an energy source on the primary energy consumption and its direct use share is observed for coal. The portion of coal that is used as solid energy source in final consumption increased continuously as shown in Figure 16. The change from direct coal usage to indirect use of coal follows approximately a logistic substitution process. The saturation tendency after the 1980s is probably a little stronger due to increased utilization of natural gas for electricity generation, as mentioned above. Only a relatively small amount of coal, slightly more than 5%, is used in its original physical condition in final consumption. Thus, coal is almost entirely converted to another form of energy in the process of allocation.

Since a diminishing portion of coal is provided in its original energy form to the consumers, the drawback of inconvenient handling of coal in the consumption process does not have significant consequences on the allocation of primary energy sources. Due to the conversion of coal into another form of energy, which is from the perspective of the end user a part of

---

[77] U.S. Energy Information Administration : PETROLEUM CHRONOLOGY OF EVENTS 1970 - 2000, http://www.eia.gov/pub/oil_gas/petroleum/analysis_publications/chronology/petroleumchronology2000.htm, 01.06.11.

the energy allocation process, coal's disadvantages do not affect the final consumption. So, one possible explanation why coal maintains a remarkable high markets share in the primary energy market could be identified.

Most likely a very similar result would be obtained for Europe, since more than two thirds of coal are used for electricity generation.[78] Moreover, the portion of natural gas that is converted as part of the allocation process to supply electricity and district heat to the end user increased considerably, which increases the percentage of indirect use. [79] Also in China the portion of coal that is used for the generation of electric power is high with about 50% of the total coal consumption.[80]

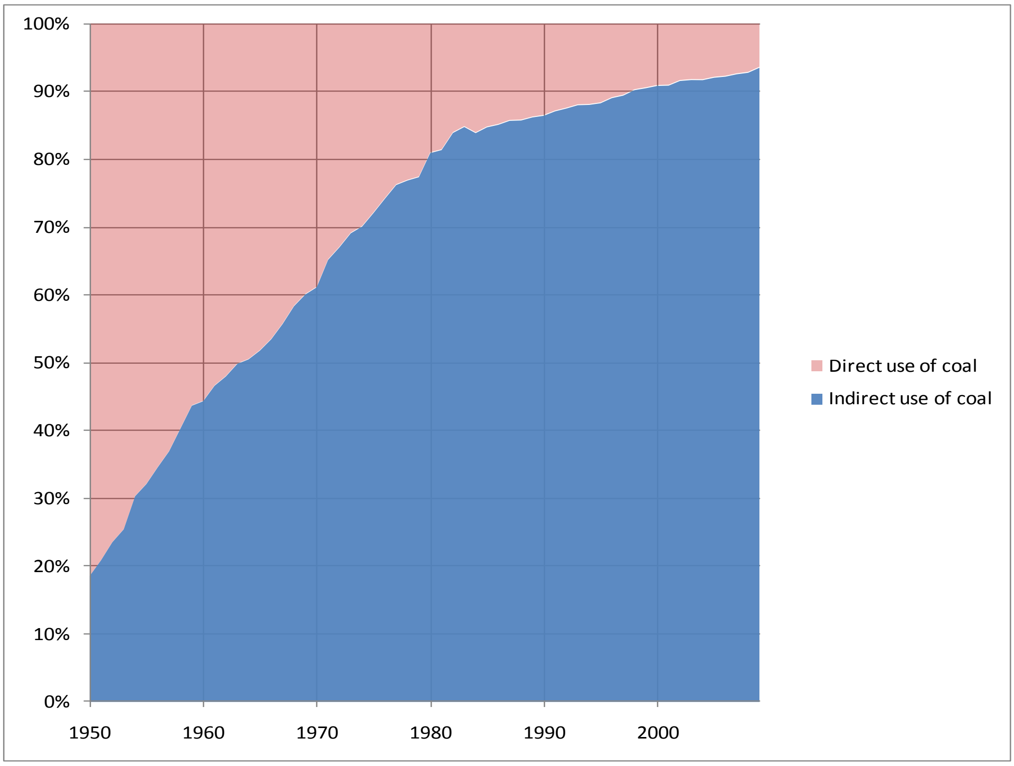


Figure 16: Direct vs. indirect use of coal USA 1950-2009

Data source: U.S. Energy Information Administration : *Annual Energy Review 2009,* Table 7.3, http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.

These results imply that there is another substitution going on in the energy system. It is not just a substitution of the different primary energy sources, the energy form that is delivered to the end users changes. For example in the 1950s, people used coal in their stoves for room

---

[78] U.S. Energy Information Administration (2010): International Energy Outlook 2010, p. 62, http://www.eia.gov/oiaf/ieo/pdf/0484(2010).pdf, 01.06.11.

[79] European Commission Eurostat (2009): Panorama of energy 2009 edition, http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-GH-09-001/EN/KS-GH-09-001-EN.PDF

[80] U.S. Energy Information Administration (2010): International Energy Outlook 2010, p. 63, http://www.eia.gov/oiaf/ieo/pdf/0484(2010).pdf, 01.06.11.

heating or even for cooking. Nowadays heat is delivered via district heating and electric energy is used for cooking. Maybe both, heat and electricity are still generated by coal but in a combined heat and power (CHP) plant and the end user does not obtain the original energy form. Similar changes also happen in the industrial sector as for instance electricity substitutes coal as energy source for the steel production.[81] So, the process of energy consumption is actually decoupled from the energy from of the primary energy source, as the exchange of the primary energy source for the CHP plant does not affect the consumption equipment. Accordingly, a substitution among the forms of energy of final consumption takes place besides the substitution of primary energy sources.

The remainder of this section, discusses more selected conclusions from the analyses on the energy system.

Due to the separate assessment of the regional primary energy production and the regional energy consumption, it is possible to obtain information about the international trade with primary energy sources. Differences among the paths of production and consumption of the energy sources for the different regions indicate international trade. The presented graphs provide in addition information about changes of net imports for the regions. Based on the graphical representations of the regional energy systems, it seems that the European and the US-American energy system are more interconnected with other regional energy markets than the Chinese energy system is, since there are larger differences between the production and the consumption paths than in China's case. As China's import of petroleum increases considerably, the interconnections of the Chinese energy system to other energy markets intensify as well.

On the basis of shown graphical representations of the different energy markets, common increasing trends for two energy sources for recent years can be observed. The fraction of natural gas and of renewable energy sources on the various energy markets increase. Overall, the market shares of petroleum tend to decrease in all regions and also on world level.

In any case, the evolution of the energy system cannot be considered as stable. With reference to the sustainable changes of the 1970s and the considerable variations in the years since then, the assumption that also the framework conditions for the energy system are not stable appears to be reasonable. This means in other words that the framework conditions are influenced externally. Further indications for this are the identified temporal links between major decisions and shifts in regional evolution patterns. Accordingly, C.

---

[81] Nakićenović, N. (1990): Dynamics of Change and Long Waves in: *Life cycles and long waves*, ed. T. Vasko, Berlin, pp. 131–133.

Marchetti's assumption that we are just optimizers and the system dynamics cannot be profoundly changed cannot be supported.[82]

The Primary Energy Substitution Model does not include the occurrence of discontinuities, as stable evolutions of the energy sources are assumed, which is represented by the opinion that perturbations are reabsorbed elastically.[83] Since the stability of the structure of the system is generally a precondition for the use of the Primary Energy Substitution Model for forecasting, predictions for the further development of the market shares in the energy system are not included in this work. A forecast based on an extrapolation of trend lines within the Primary Energy Substitution Model might be misleading, especially in the present situation since discontinuities are not integrated and many parts of the society currently anticipate or even promote changes in the energy system.

After the analysis of the energy market and technological growth processes in the previous sections the next chapter describes the economic forces that form the changes in the resource market. The discipline of resource economics deals with the market mechanisms that affect the substitution of energy resources. So, the following chapter provides economic theories that describe the background of the change processes, which are analyzed within this chapter. Since the energy system is characterized by very long-time process, the next chapter also discusses the influence of time. Especially the question how the energy resources should be used to permit long-time prosperity for our society is examined.

---

[82] Marchetti, C. (1979): Energy systems—The broader context, in: Technological Forecasting and Social Change, Vol. 14, Issue 3, pp. 191–203.

[83] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 25, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

4 Resource Economics and Intergenerational Issues

As the word composition “resource economics” already anticipates, there are two fields of interest within this subject. On the one hand this scientific discipline covers the topic of resources especially natural resources and on the other hand economic theories are considered. Resource economics attempt to bring these two elements together, as they are naturally and inevitably bound to each other, as human living and economic activity is not possible without the use of natural resources.[84]

Following to the profound treatise on resources and resource markets by the example of the energy system in the last chapter, this chapter addresses the economics of resources. The wording of the previous sentence already contains one important argument to back up the analysis of the energy system with the economic theory of resources. It is the fact that natural resources are in general traded on markets, which makes it necessary to deal with economic topics when studying the usage of natural resources. On the contrary, it is of particular interest to study natural resources in the framework of economic theory as they are inputs for almost all production processes. Besides the commonly recognized production factors labor and capital, natural resources are important inputs for every economy.[85] Certainly, natural resources are a kind of capital and therefore might be included in the production factor capital because of their similarity as both can be consumed or utilized in the production process and afterwards invested. Accordingly, natural resources are also referred to as natural capital. However, natural resources are somehow different since they are the base of all economic if not human activities as they generally materialized before the other economic commodities. A further difference between natural resources and the other production factors capital and labor is that natural resources usually have to be produced respectively extracted before they can be used in production.

---

[84] Endres, A. and Querner, I. (1993): *Die Ökonomie natürlicher Ressourcen: Eine Einführung,* Darmstadt, p. V.

[85] Ströbele, W. (1987): *Rohstoffökonomik: Theorie natürlicher Ressourcen mit Anwendungsbeispielen Öl, Kupfer, Uran und Fischerei,* München, p. 5.

Another special property of natural resources is their distinct temporal behavior. Based on the temporal consequences of the usage of natural resources, basically three classes are distinguished, which are explained in the following.[86]

- Resource type 1: Today's consumption of the resource has negative consequences on the usage of the resource for future generations. A lot of resources that are used today belong to this group, for example mineral resources or fossil fuels, which are quantitatively limited on earth, as well as regenerative resources like fishes and trees. For those resources, which are regenerative in general, overstraining of their natural regeneration function affects succeeding production, which is the reason for their assignment to this class of resources.
- Resource type 2: The current use of the resource does not affect the future utilization of this specific resource. Hence, the usage of the past is independent from the present and the future use of the resource and no intergenerational dependence is given for this type of resource. Examples for this kind of natural resource are not that obvious as for type one, nevertheless there are examples that are very important for mankind. For generally not storable flow resources the actual availability does not depend on past consumption. Solar energy does principally comply with this definition.[87]
  When considering resources that are in principle not consumable, land has also to be taken into account if thinking of land as a commodity that is still available after its usage. This might be true for the case when land is simply treated as a certain area on the surface of the earth. Increasing or decreasing is only an option if the extent of the sea changes. This definition does not include the natural properties and different functions of land, which would be a more realistic view.
- Resource type 3: The past consumption of a specific resource of this type accounts positively to the present availability of this resource. This is an absolute theoretical case, which is not further pursued.

As resource type 1 is subject to intergenerational issues and a very large part of presently used resources belong to this type, the following considerations concentrate on this kind of resource.

---

[86] Endres, A. and Querner, I. (1993): *Die Ökonomie natürlicher Ressourcen: Eine Einführung,* Darmstadt, p. 2.

[87] Ströbele, W. (1987): *Rohstoffökonomik: Theorie natürlicher Ressourcen mit Anwendungsbeispielen Öl, Kupfer, Uran und Fischerei,* München, pp. 1, 7, 13.

On the basis of the time scale of the relevant adjustment processes, a more precise description of the intergenerational effects of today's use on the future's consumption is possible.

- Non-renewable resources are characterized by adjustment speeds, which are so slow that the notion to be once and only once available by nature holds for the human time scale. Consequently, all generations together share one fixed stock. Coal, crude oil and mineral deposits are typical examples.[88]

  Within this class of resources two types need to be distinguished based on the consumption process. On the one hand these are resources that can be used several times and on the other hand resources that can be used only once.

  - Recyclable Resources: Mineral resources, which are not related to energy services, persist in a state that makes them available for subsequent use after they are transformed in a production or a consumption process. Through recycling these resources are made useable for the production process again and remain available in the system earth.
  - Exhaustible Resources: This group of non-renewable resources, which consists of energy resources in particular, differs in consideration of the following fact. Energy resources are converted from a state of high exergy to low temperature thermal energy with low exergy in the end. Heat exchange with the environment and finally radiation to space imply that it is no longer available for human use as it leaves the system earth.[89]

  However, the second law of thermodynamics has to be taken into account, when thinking of recycling. This second law of thermodynamics says that over time, differences in temperature, pressure, and chemical potential tend to equilibrate, which implies an increase in entropy. To reverse the raise in entropy, which results from manufacturing as well as from the consumption process of recyclable resources, energy has to be applied.

- Renewable resources adjust respectively renew themselves in time periods, which are relevant for human time scales and apply to economic decisions. More precise, they regenerate themselves without human interaction depending on their actual stock. Nevertheless, the usage in the past affects the present availability as a

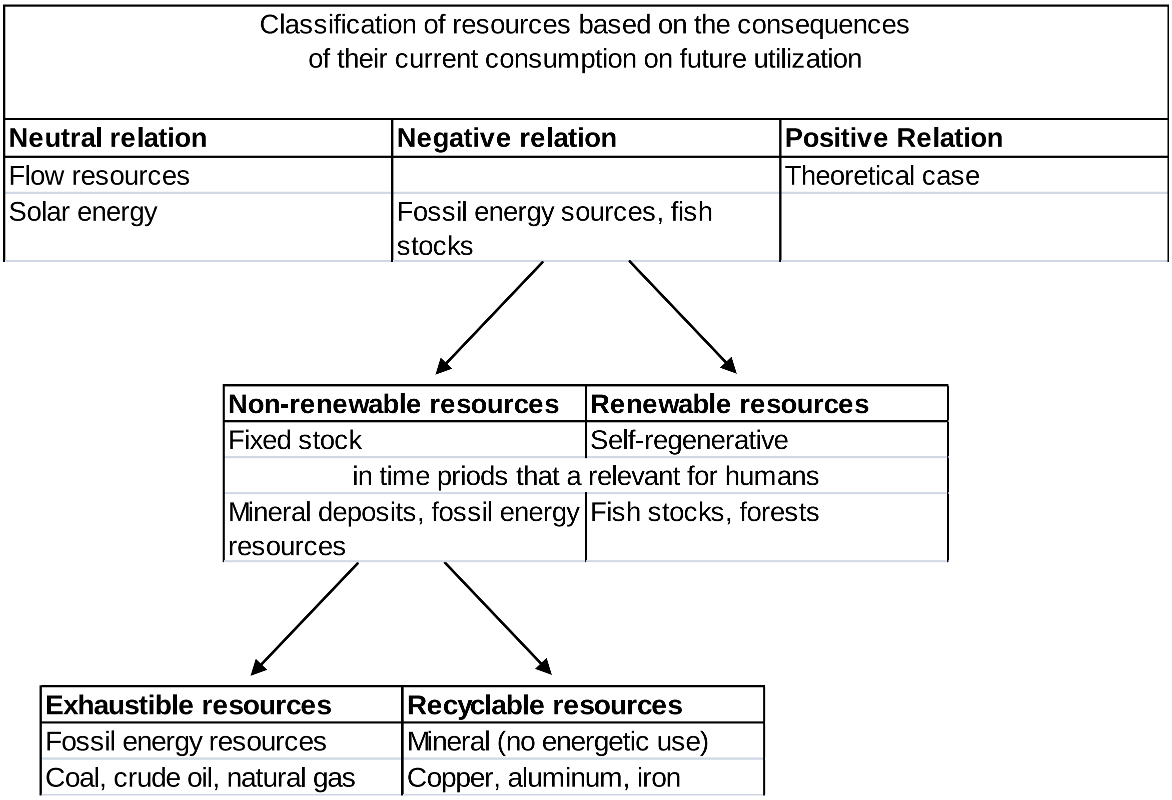
---

[88] Sweeney, J. L. (2006): Economic theory of depletable resources: An introduction in: *Handbook of natural resource and energy economics*, ed. Allen V. Kneese, Amsterdam, p. 764.

[89] Ströbele, W. (1987): *Rohstoffökonomik: Theorie natürlicher Ressourcen mit Anwendungsbeispielen Öl, Kupfer, Uran und Fischerei,* München, pp. 2,8.

consumed unit is no longer available but new units are added. This regeneration process is principally powered by an inexhaustible flow resource, in particular solar energy. The magnitude of present usage has implications on the future's availability, as consumption influences the natural regeneration function. In this context, overharvesting in one generation influences the natural regeneration function and reduces the possibilities for consumption for subsequent generations. For example, populations of fish or wild animals and forest products respectively timber belong to this resource type.

This classification gives an insight how important the factor time is for considerations about natural resources. A summary of the fundamentals of the described classification is given in Figure 17.



Classification of resources based on the consequences of their current consumption on future utilization

Neutral relation	**Negative relation**	**Positive Relation**
Flow resources		Theoretical case
Solar energy	Fossil energy sources, fish stocks	

Non-renewable resources	**Renewable resources**
Fixed stock	Self-regenerative
in time priods that a relevant for humans	
Mineral deposits, fossil energy resources	Fish stocks, forests

Exhaustible resources	**Recyclable resources**
Fossil energy resources	Mineral (no energetic use)
Coal, crude oil, natural gas	Copper, aluminum, iron

Figure 17: Classification of resources

By considering the described temporal dependence in the usage of most resources that are currently utilized, the importance of time for the allocation of natural resources becomes clear. Therefore, the allocation of natural resources and time are basically linked to each other. The allocation of capital is a very similar problem, which makes resource economics a specific subdomain of the theory of capital.[90]

The intertemporal dependency in the utilization of natural resources and the resulting long time frames that have to be considered for allocation decisions is the reason why the allocation of natural reasons is a central issue in intergenerational considerations.

The previous analysis of the energy system in chapter 3 confirms also the long time periods that need to be taken into account for resource related decisions. Long-time evolution processes are a particular characteristic of the energy system, as shown in the preceding chapter. The slow changes in the energy system are possibly related to the importance of energy supply for the economy. For this reason changes in the energy system affect a key element of the economy and changes as a kind of a social diffusion process happen slowly, especially for systems which affect so many individuals. Moreover, changes in the energy system involve major investments and are related to long-living assets, which both contribute to the long-term nature of energy system related decisions.

Exactly this characteristic of the energy system, the long life cycles, yields to intergenerational issues as today's decisions have effects on subsequent generations. Furthermore, the fact that the actual energy system is mainly based on fossil fuels raises intergenerational questions, as the intense utilization today affects the following generations. Since it is not known how many generations will follow, an immortal society and an indefinite number of generations are assumed. Prosperity of generations is related to consumption possibilities, which makes consumption to an indication of welfare and therefore to an important issue.

This chapter addresses some basic questions of resource economics in relation to intergenerational issues like the following.

- Is indefinitely ongoing consumption at all possible when considering the fact that society faces a finite stock of natural resources?
- What is the optimal allocation strategy for natural resources across all generations?
- Does a market economy allocate natural resources intergenerationally optimally?

These questions already indicate that intergenerational issues are somehow always related to ethics and a moral philosophy as it has to be clarified what is optimal and especially what is optimal in terms of allocation of natural resources.[91]

---

[90] Ströbele, W. (1987): *Rohstofföкonomik: Theorie natürlicher Ressourcen mit Anwendungsbeispielen Öl, Kupfer, Uran und Fischerei,* München, p. 14.

The attempt of this chapter is to provide an approach for answering the questions stated above. For this purpose, the theories and concepts of resource economics are introduced, which include also a brief discussion of the mentioned ethical issue. The structure of this chapter follows on the one hand the historical development and on the other hand the complexity of the concepts increases in the course of the discussion. Therefore, some basic economic theories are presented in the beginning in section 4.1. Section 4.2 then discusses the issue of intergenerational allocation of natural resources.

The following subsection is intended to provide an introduction in basic thoughts and concepts in the field of resource economics in order to gain insights for an application of these different notions on the issue of allocation of resources and in particular the allocation of energy resources. The structure of the subsection follows the historic development of the theories, which seems to be a reasonable approach as several ideas are built on the basis of previous conclusions.

4.1 Concepts in Resource Economics

The issue of intergenerational allocation of resource was originally not considered by the early economists but concerns about the finiteness of resources are recognized relatively early in the theory of economics. This should not be a surprise, as economic activities are all about dealing with scarce resources. Since natural resources ever played a major role in human activities, economic theory early includes natural resources.

The roots of resource economics can be found in the classical agriculture-oriented economic theory. Early the classical economist recognized the scarcity of resources as an important factor in economic decisions. The basics of the classical economic theories still play a significant role in considerations about natural resources and economy. This is the reason why the theories of the classical economics are introduced first.

4.1.1 Classical Economics

The first to define the market as the place where supply and demand meet and the price is the balancing commodity was Adam Smith (1723 - 1790). Competition is an important property of this market. Due to self-interested market participants under competition, supply and demand are balanced, like led by an “invisible hand”, as A. Smith termed it. Due to the system dynamics, market prices change and adjust supply and demand. The natural price is the state of balance where market prices tend to move under a competitive environment.

---

[91] Bengston, D. N. and Iverson, D. C. (2003): Reconstructing Conservation in an Age of Limits: An Ecological Economics Perspective in: *Reconstructing conservation: Finding common ground*, eds. Ben A. Minteer and Robert E. Manning, Washington, DC, pp. 223,226.

Consequently, the natural price represents steady effects and the market prices additionally include random events.[92]

In addition to that the market is also the physical place where goods are exchanged. The rate of exchange is defined according to the inputs of the three factors of production labor, capital and land. Smith introduced this three factor economy, which is found in several classical economic theories, that is represented by a production function as in equation (9).[93]

$$Y = F(L, K, R) \tag{9}$$

$Y \ldots$ *Net product*
$L \ldots$ *Labor input*
$K \ldots$ *Capital input*
$R \ldots$ *Land input*

Consequently, natural resources are already represented in A. Smith’s production function by the factor land. However, land has a special position in production when A. Smith states that the wages and profits are the cause of a high or low price of a commodity whereas the rent for the land is the result of the price. Besides, this specific indication for the provision for scarce resources no clear pattern is recognizable, when rent is also seen as one part of the price and as a result of the bounty of nature, which means that the rent is paid for the liberty of harvesting the fruits of this land and due to property rights on land. No indication about scarcity of a resource is found in these statements. It is assumed that natural resources provide unlimited possibilities for expansion.[94,95]

In general, A. Smith was aware of the influence of scarce resources but he did not include this notion in his theories. On the one hand he assigns the high price for Bordeaux wine to the high demand in combination with the limited high-quality land resource but on the other hand does not follow up with considerations regarding implications on rents or the market and opportunity costs are not considered.[96]

Still, the market is where resources are allocated, also including natural resources. A. Smith’s considerations are mainly directed to agricultural production but nevertheless also

---

[92] Sturn, R. (2008): Adam Smith in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 75.

[93] Sturn, R. (2008): Adam Smith in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, pp. 73–74.

[94] Sturn, R. (2008): Adam Smith in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 75.

[95] Kurz, H. D. and Salvadori, N. (2009): Ricardo on Exhaustible Resources, and the Hotelling Rule in: *The History of Economic Theory: Festschrift in Honour of Takashi Negishi*, eds. A. Ikeo and Heinz Dieter Kurz, London, p. 73.

[96] Sturn, R. (2008): Adam Smith in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 75.

mines are part of his thoughts. The price of the commodities acts as decentralized sign for adjustments in the market for individual market actors led by self-interest and expresses the system dynamics whereas the price is not linked to availability or scarcity of resources by A. Smith.

Based on and in some points opposing to A. Smith's statements David Ricardo (1772 -1823) builds various economic theories, including the theory of land rent, which incorporates the idea of scarce natural resources.

D. Ricardo specifies the concept of the average rate of profit of an economy as follows. On a free competitive market, which is for him without barriers to entry or exit the market, capital and labor force will seek for the economic sector with the highest profit respectively the highest wages if free movements between different economic sectors are assumed. For this reason, differing rates of profit in different economic sectors are adjusted and a common rate of profit established. Capital owner enforce this trend by primarily providing financial capabilities for the most profitable economic sector preferentially. Accordingly, a positive deviation of the market price from the natural price in one economic sector causes higher relative profits. This attracts self-interested market participants to move in this economic sector. Accordingly, the production in this sector increases relative to the demand, which results in decreasing market prices. Furthermore, this lowers the profits in this sector and induces a trend of convergence towards the natural price, which covers all production costs for labor, capital and natural resources.[97]

D. Ricardo defines the rent as the return on the land based on the "indestructible powers of the soil" and opposes A. Smith's opinion that the rent is paid for the liberty of harvesting the fruits of the land.[98]

The scarcity of natural resources is reflected in the theory of rent established by D. Ricardo. The considered scarce natural resource is mainly land as factor of production. The theory of rent deals with the price of the natural resource, the rent of land, and defines the principles of diminishing returns at the extensive and the intensive margin. Whereas extensive means applying the same input to different types of land and intensive stands for using more inputs on the same land. This is described more precisely in the following, since this is one of the first and in any a case an important concept in the field of resource-economics.

---

[97] Kurz, H. D. (2008): David Ricardo in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 125.

[98] Kurz, H. D. and Salvadori, N. (2009): Ricardo on Exhaustible Resources, and the Hotelling Rule in: *The History of Economic Theory: Festschrift in Honour of Takashi Negishi*, eds. A. Ikeo and Heinz Dieter Kurz, London, pp. 70, 73.

In order to discuss D. Ricardo's theory of land rent, a certain finite amount of land, which is available on an island, in a country or on world as a whole, is considered. For the reason of further simplification, it is assumed that the land is used to produce only one single commodity.

Land rent at the extensive margin

At the extensive margin, more and more land is used in order to meet increasing demand. First the most fertile part of the available land is employed. Consequently, the available land is ordered according to its fertility, which is measured based on a predefined technical knowledge. This ranking coincides with the costs of production for one unit output. The most fertile ground complies with the lowest unit costs and therefore the least fertile land to the highest costs per unit output. As long as it is sufficient to utilize the most fertile land to meet the demand, cost-minimizing producers won't use land with lower fertility, as the unit costs would be higher. Under this assumption this most fertile land is not scarce and hence not the entire high quality land has to be utilized. Additionally, competition among the land owners for tenants results in rents for the land that converge to zero.

In case the most fertile land does not suffice to produce enough output to meet the demand this high-quality land is scarce and the land that is ranked as second fertile ground has to be utilized at least partly. For the reason of higher unit costs on the second most fertile land, the price of one unit of output has to be increased. Since there is only one single price for one unit of output, the lower unit costs on the most fertile land yield to a difference between the production costs on this land and price. Due to this fact the land owners of the most fertile land obtain a rent for their property, which is as high as the difference in costs between the most fertile and the second fertile land so that both production costs converge to the same value. This is once again caused by self-interested behavior of market participants as cost minimizing producers would always offer higher rents until the difference in production costs between the two different qualities of land diminishes. The second most fertile land does not earn any rent under these circumstances as this kind of land resource is not scarce. This procedure goes on as more output is demanded until all land is utilized.[99]

According to this theory, the return on the land is the differential rent, which originates from the usage of land with different fertilities and is determined through the different production costs on these different kinds of land. The least fertile land, which is utilized, is also denoted as marginal land.

---

[99] Kurz, H. D. (2008): David Ricardo in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, pp. 128–129.

It is assumed that corn is produced on the entire land. Therefore, the inputs to the production process are seeds and labor. When assuming that the wages for the workers are paid in units of the output, the production costs can be measured by the input factor capital, which includes seeds and wages and is measured in units of output. In case of a given wage rate, for instance derived from the subsistence level for workers, the rate of profit on the utilized capital decreases as the land rent increases. The output as a function of the input production factor capital, which accounts for labor and inputted capital (seeds), with different fertile land resources is shown in Figure 18.

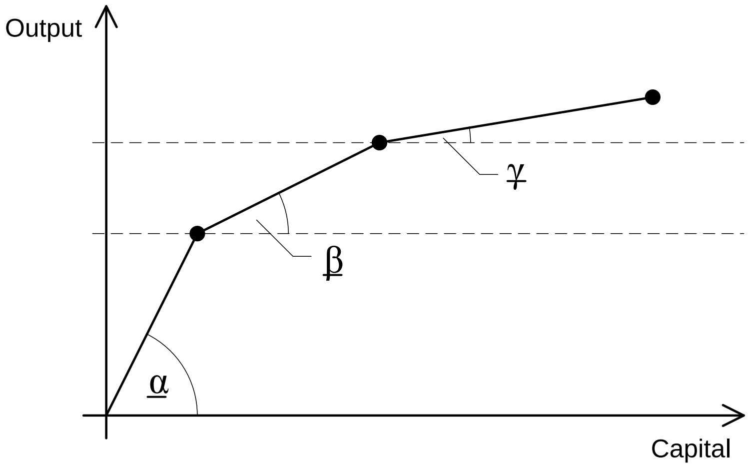


Figure 18: Diminishing returns at the extensive margin

$\underline{\alpha}$, $\underline{\beta}$, $\underline{\gamma}$ ... Marginal product of capital

The differences in fertility are indicated by the decreasing marginal products of the production factor capital (labor + seeds), denoted as $\underline{\alpha}$, $\underline{\beta}$ and $\underline{\gamma}$. Since at the extensive margin the same amount of labor respectively capital is applied to all kinds of land per unit of land, the marginal product of capital identifies the fertility of the land.

The distributed of the price between the production factors is shown in Figure 19, whereat labor and capital is covered in one combined factor. The production costs on the marginal land define the per unit price of the output. Labor and capital input on each kind of land account for the production costs. The difference between price and production costs belongs to the land owner as rent. Hence the most fertile land with fertility $\underline{\alpha}$ earns the most rent per unit of land.

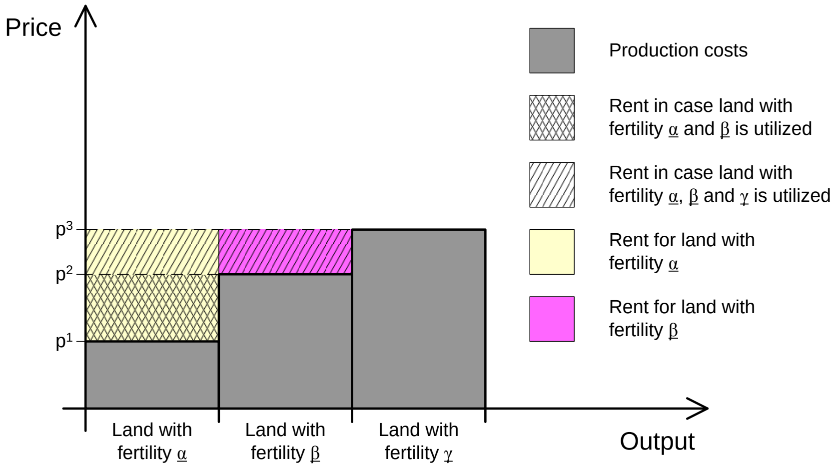


Figure 19: Production costs and land rent at the extensive margin

p^x … Price x

Land rent at the intensive margin

In the case of diminishing returns at the intensive margin, the entire available land is assumed to be equally fertile. Once the entire available land is used, an increasing production is only possible by a more intensive utilization of the given resource. In this context intensive is conceived in terms of a more costly or cost-intensive method. Consequently, there is a ranking order of the methods of production, beginning with the method of least costs in terms of labor and capital and the highest demand of land per unit of output. The method that is ranked second utilizes more labor and capital but less land per unit of output.

Similar to the case at the extensive margin, no rent is paid when the demand is met by using the method with the lowest costs and it is sufficient to use only parts of the available land. Once again this results from the fact that the land is not scarce. If the demand exceeds the production capabilities on the given land by the use of method with the lowest costs, the secondly ranked method is used for parts of the land and land becomes a scarce resource. As a consequence of the higher per unit costs of the secondly ranked method, the price for one unit of output increases, as previously discussed. Due to the competition of producers, the difference in production costs between the two different methods of production diminishes as the rents increase. Rent is paid for the parts of the land that use the production method with the highest land requirements. For this reason, equal production costs including rents for the production of one unit of output are the result. With increasing demand more and more the secondly ranked method is substituting the least land-efficient method. To meet an even higher demand, a more cost-intensive method has to be utilized and the method that requires more labor and capital but less land in comparison to another is also the one that earns less rent.[100]

Other authors transferred this notion later from land to other production factors like labor and capital and applied it to other economic sectors.[101] D. Ricardo himself extended this concept from land use to mines, in particular coal mines and stone quarries. In this context, he speaks about different “fertile” mines, which means getting one unit of output from one mine is associated with higher production costs than from another. Because of limited output capacity of one mine, he assumes that several mines have to be operated simultaneously. According to his theory of land rent, there is no need to pay a rent for a mine if the production of equally “fertile” mines is sufficient to meet the demand. In case that mines with different requirements of labor and capital for the extraction of one unit of output have to be operated at the same time, rents for the most “fertile” mines, identical to the land rent at the extensive margin, need to be paid. For the case of coal mines, he indicates that progress in the mining process could lead to a higher amount of extracted material per time period, which causes a lower price and leads to the situation that the operation of some mines is not necessary in order to meet the demand. Consequently this supersedes the mines with the highest extraction respectively production costs.[102] As D. Ricardo fundamentally supports Say’s law, which says that every aggregate supply creates an equal aggregate demand, he might argue that the higher production would find its demand anyway.[103]

Rent on mines

Exhaustibility of resources is included in the considerations of A. Smith and D. Ricardo in terms of exhaustion of single deposits. Even so, the exhaustibility of a resource as a whole was not taken into account to be an option, as by this time there were seemingly unlimited resources. In this manner they think that after exhaustion of one mine another deposit is discovered. A. Smith besides considers the option that more “fertile” mines are discovered

---

[100] Kurz, H. D. (2008): David Ricardo in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 129.

[101] Kurz, H. D. (2008): David Ricardo in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 129.

[102] Kurz, H. D. and Salvadori, N. (2009): Ricardo on Exhaustible Resources, and the Hotelling Rule in: *The History of Economic Theory: Festschrift in Honour of Takashi Negishi*, eds. A. Ikeo and Heinz Dieter Kurz, London, pp. 72–73.

[103] Kalmbach, P. (2008): Thomas Robert Malthus in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 101.

later on.[104] Taking D. Ricardo's notion of capacity constraints for single mines and the need to usually employ several mines at the same time into account, the possibility of a continuous use of the resource is generally assumed.[105]

But D. Ricardo did not emphasize scarcity as an issue for human development. Thomas Robert. Malthus' concerns are directed to the provision of food for the human population. He states that the population development has the tendency to exceed food production continuously. The question how an ever growing population is compatible with limited food production capabilities, is central to his work. As already noted section 2.1, T. R. Malthus assumed population growth to follow a geometrical series. Since he considers that food production increases linearly as an arithmetical series, a scarcity of food is inevitable. [106] Also by taking D. Ricardo's theory of diminishing returns into account for the expansion of food production is no solution. In case of increasing labor and capital input for food production the marginal product of the sum of these production factors decreases. Therefore, the output per unit of labor respectively per worker would decrease. In case of extending the land resource for food production, the most fertile lands would be used first and the marginal product of land decreases for all consecutive land resources utilized. For this reason, R. T. Malthus supposed that food production won't suffice for the exponential population growth and would be the limiting factor. Technological progress is not considered to be a reasonable option, which might result from the fact that technological advancements occurred very seldom up to this time. The technological progress and increased productivity were no big issues, neither for R. T. Malthus nor for other classical economists, but should become more important, as the actual development has shown.[107] However, D. Ricardo analyzed technological progress by means of a more land-efficient production method as a factor, which causes higher profits and lowers rents.[108]

R T. Malthus questioned the issue of scarcity and growth as one of the first economist and already very early in history of economic theory. His considerations influenced the

---

[104] Kurz, H. D. and Salvadori, N. (2009): Ricardo on Exhaustible Resources, and the Hotelling Rule in: *The History of Economic Theory: Festschrift in Honour of Takashi Negishi*, eds. A. Ikeo and Heinz Dieter Kurz, London, p. 74.

[105] Kurz, H. D. and Salvadori, N. (2009): Ricardo on Exhaustible Resources, and the Hotelling Rule in: *The History of Economic Theory: Festschrift in Honour of Takashi Negishi*, eds. A. Ikeo and Heinz Dieter Kurz, London, p. 70.

[106] Kalmbach, P. (2008): Thomas Robert Malthus in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, pp. 93–95.

[107] Krautkraemer, J. A. (2005): Economics of Scaricity: The State of the Debate in: *Scarcity and growth revisited: Natural resources and the environment in the new millennium*, eds. Ralph David Simpson, Michael A. Toman and Robert U. Ayres, Washington, DC, pp. 2–4.

[108] Kurz, H. D. (2008): David Ricardo in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 134.

development of economic theory with respect to the integration of population growth, in the main as an endogenous variable.

Primarily the classical economists concentrate on agriculture as productive process, which results from the fact that during this time agriculture was the most important economic activity. From this perspective, the classical economists provide important notions concerning scarce respectively limited resources and present first but nevertheless significant theories how scarcity affects economic processes.

The period of neoclassical economists more or less follows the time of the classic economic theory. Many neoclassical concepts are based on the classical economic models but are generally not related to agriculture, which is a result of the industrialization and a change of the importance of the economic sector agriculture.

4.1.2 Neoclassical Economics

Neoclassical economics cover a range of economic theories in the time period from the mid 19th century to the 1930s, which supersede the classical economic mindset and are followed by the economic concepts that go back to John M. Keynes. Probably, the most important notion introduced by neoclassical thinkers is the use of the marginal concept. This neoclassical approach has already been included in the previous discussion by example of the marginal product of production factors. The concept of marginalism refers to specific changes in the use of quantities as determinants of economic decisions.[109]

The period of neoclassical economics does not particularly address natural resources in their considerations. Since some notions are still important for later discussions the following paragraphs are intended to provide some basic thoughts.[110]

Utilitarism

One important idea primarily expressed by Jeremy Bentham (1748 - 1842) and later refined by one of his students John Stuart Mill (1806 - 1873) is the allocation of utilities for specific actions. The utility of any action defines its moral worth. This school of thought is based on the hedonic idea that the only good is pleasure, which defines the value of every object and action.[111] Therewith, utility is the core indicator for moral quality of an action, which is for example the consumption of a commodity. The general goal is to obtain the “greatest happiness for the greatest number”, which means that an action’s value is high if the

---

[109] Felderer, B./Homburg, S. (2005): Makroökonomik und neue Makroökonomik, http://dx.doi.org/10.1007/b137628,

[110] Farmer, K./Bednar-Friedl, B. (2010): Intertemporal Resource Economics: An Introduction to the Overlapping Generations Approach, http://dx.doi.org/10.1007/978-3-642-13229-2, January 2011.

[111] Citatition to be added

happiness of as many people as possible increases. This approach is known as utilitarianism.[112]

Accordingly, it is not the physical consumption of a quantity that is subject to maximization, it is the utility gained from consumption that is significant. The maximization is subject to the aggregate utility which is gained from the consumption of different goods or over a certain time. If considering the society as a whole, the social welfare is the aggregation of individual utilities. A further discussion on this conception is found in section 4.2.1

Diminishing marginal utility

Herman Heinrich Gossen (1810 - 1858) refined the utilitarian approach and defined the law of diminishing marginal utility, which means that the amount of one specific pleasure decreases with every additional unit enjoyed if this specific pleasure is consumed continuously.[113]

Since every utility gained accounts for the total utility, the last consumed unit of every pleasure has to have the same marginal utility. According to this assumption, the consumption of different pleasures respectively goods is naturally adjusted due to desire to maximize one's utility.[114]

The price theory of the classical economists assumes that natural prices are basically determined by the amount of labor that is needed in the production process. The natural prices as a steady state of the market are therefore determinants of the market balance. Based on this assumption, the result of the market balancing process derives in general from the supply side with respect to the production price in units of labor. Besides this classical approach, the neoclassical view considers the demand side as the second parameter for the setting of prices.

Considering diminishing marginal utilities trade is one way how to achieve the state of balanced utilities between different goods in order to maximize the total utility. Consequently, an individual will exchange a commodity with a lower marginal utility for another commodity that has a higher subjective marginal utility. As the utility loss due to the commodity that is given away is smaller than the utility gained by the commodity that is obtained, the exchange of the commodities makes the trader better off. In a money based economy, the price is a measure for the exchange rate of goods. For this reason, a certain commodity is subject to

---

[112] Aßländer, M. S. and Nutzinger, H. G. (2008): John Stuart Mill in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 183.

[113] Kurz, H. D. (2008): Hermann Heinrich Gossen in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 206.

[114] Kurz, H. D. (2008): Hermann Heinrich Gossen in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 208.

an exchange if the marginal utility of this commodity is higher than the price respectively the marginal utility of other commodities. In other words, the marginal utility of money is determined by the subjective best product that can be purchased under the consideration of the budget constraint.

The marginal utility is representative for the demand side in the adjustment process on the market under a competitive environment. As a consequence, the marginal utility underlies the demand price function, which defines the demanded quantity as a function of the price in a modeling of the market. The demand price function represents the prices that buyers are willing to pay for a certain amount of a commodity. Therefore, it is of denoted as maximum willingness to pay. This is an extension to the classical view on the demand, which says that the amount of a commodity that is demanded decreases when the price increases and vice versa.

One of the most well known neoclassical economists William Stanley Jevons (1835 -1882) addressed the subject of natural resources besides the typical neoclassical topics. His publication “The Coal Question” is one of the earliest works in the field of resource economics. Contrary to the classical view of the general inexhaustibility of a resource, he considers the depletion of coal at least on the British island. As a conslusion, he supposes that the increasing price of coal leads to substitution of coal. [115]

Furthermore he recognizes the paradox that higher efficiency in the use of an energy sources leads to an increasing demand for this specific source. He derives this notion from the drop in costs as a result of the higher efficiency, which causes the implementation of more applications of this technology and involves higher consumption of the energy source.[116]

Due to the ongoing industrialization and the increasing utilization of the steam engine, which was in the main powered by coal, the coal consumption increased significantly and became an important factor in production. The importance of coal was recognized and encouraged the assessment of energy sources as factors for economic growth. However, it soon became clear that a possible insular depletion of coal does not prevent its economy from growing.[117]

Additionally, Willian S. Jevons raises the question of a connection of depletion of exhaustible natural resources and intergenerational obligations. In particular, he thinks that due to the

---

[115] Santum, U. von (2008): Willian Stanley Jevons in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 276.

[116] Santum, U. von (2008): Willian Stanley Jevons in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, pp. 276–277.

[117] Santum, U. von (2008): Willian Stanley Jevons in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, p. 277.

fact that a reduced stock of natural resources is passed to the next generation at least a balanced national budget should be left for the successors.

Other famous neoclassical economists Léon Walras (1834 - 1910) and Carl Menger (1840 - 1921) do not explicitly refer to natural resources in their considerations. In neoclassical concepts a new market participant, the entrepreneur, is introduced besides the classical ones worker, capitalist, and land owner. In addition, it is assumed that not just goods are traded on markets but also other production factors, such as labor. Consequently, wages above the subsistence level are considered.

Alfred Marshall (1842 - 1922) introduces the concept of marginalism in the representation of the supply side and a differentiation in the temporal market properties, which is described in the following. Basically, he interprets the price, as a measure of the worth of a commodity, as determined through both sides (demand and supply) of the market and as a result of the conjunction of utility and "real" costs, defined as "labor and waiting". [118]

Marginal costs

A. Marshall distinguishes between the market period, the short period and the long period, which all differ in the capabilities of producers to adjust the output. The fish market is used as an example for the market period. The amount of fish that can be sold is determined by the previously captured amount of fish. So the quantity of supply is fixed, if storage is not considered for the market period. Due to the fixed quantity he assumes that the price is adjusted in order to sell the entire supply.

In contrast to the market period he assumes that the quantities are variable in short period due to storage capacities. Nevertheless the production capacity is constant in the short period, which implies the production costs to be determined by fixed and variable costs.

Differently to the short period, the production capacity is adjustable in the long period and no fix costs are present because the costs vary with the produced quantity. Based on these considerations, he describes the supply price function, which defines the quantity supplied as a function of the price, as determined by the costs in the short period and the marginal costs in the long period.[119]

In his economic analysis, A. Marshall referred to a partial analysis of one single market with limited interdependences among different markets. At the market equilibrium, the price that the consumers are willing to pay (demand side) and of the supply price match, which

---

[118] Caspari, V. (2008): Alfred Marshall in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, pp. 333–336.

[119] Caspari, V. (2008): Alfred Marshall in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, pp. 333–336.

corresponds to the intersection of demand price function and supply price function. In the short period, the return on the capital that is utilized might be higher or lower as in the long period equilibrium since the production capacity might be too high or low in comparison to the traded quantity. The long period is very important for him as he assumes "free competition" for the long period with minor market entry and exit barriers and therefore optimal production adjustments. He also considers increasing returns to scale, which implies that the supply price function need not to be monotonically increasing in the long period as many previous concepts assume. Accordingly, the marginal costs and therewith the supply price function decreases partially if increasing returns to scale are present in the considered economic sector. Moreover, he introduces the notion of the price elasticity of demand, which describes the change in the demand for a certain good if the price of this specific commodity changes.[120,121]

Besides the already mentioned and probably most famous neoclassical economists also important concepts for the field of resource economics are introduced, which are described in the following.

A systematic economic approach for considerations about exhaustible resources was introduced by Lewis C. Gray (1881 - 1952). He studied how to deal with exhaustible resources in a theoretical economic framework. His concerns were about the conservation of natural wealth and he was also aware of the ethical issues linked to the use of exhaustible resources in terms of intergenerational equity. As the allocation of exhaustible resources is inevitable bound to temporal concerns, he considers the discount rate, which is the common way to compare economic effects of events that happen at different points in time, to be related to the extraction of resources.[122]

Opportunity costs of the extraction of exhaustible resources

Based on the following considerations, L. Gray supposed that the extraction of resources has to be treated differently than the production of goods and the classical theory of land rent is also not appropriate. The price of a unit of an extracted, non-renewable resource is not solely determined by the marginal costs of extraction. The unit price has to include a kind of rent as representation of the opportunity costs, which results from the fact that the extraction and sale of one unit adds utility for the owner of the mine in the present but excludes the

---

[120] Caspari, V. (2008): Alfred Marshall in: *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall*, ed. Heinz Dieter Kurz, München, pp. 332–336.

[121] Kurz, H. D. (2009): Pierro Sraffa in: *Klassiker des ökonomischen Denkens 2: Von Vilfredo Pareto bis Amartya Sen*, ed. Heinz Dieter Kurz, München, p. 211.

[122] Gorostiza, J. L. R. (2002): Ethics and economics: Lewis Gray and the conservation question, Documentos de trabajo de la Facultad de Ciencias Económicas y Empresariales, http://eprints.ucm.es/6768/1/0206.pdf

possibility of a further unit of utility in the future as one extracted unit is not available for extraction in the future. Based on this notion, he describes a model for the optimization of the extraction path of a limited stock of a resource. The extraction path describes the quantities that are extracted from the deposit as a function of time.[123]

The model described by L. Gray is based on the following constraints. The price of the resource per unit is constant and determined exogenously and the entire resource is assumed to homogenous. Moreover, the entire amount of the resource that is available is a priori known. He assumes the extraction costs to depend on the quantity that is extracted and to increase by raising the extraction quantity. Additionally, the discount rate is a constant, exogenous determined variable. The resource is extracted until its depletion at the end of the extraction period.[124]

As a consequence of the a priori known size of the considered deposit and the non-renewability of the resource, the available stock decreases with every unit extracted. The purpose of the optimization is to maximize the present value of the returns on the extraction and sale of the resource over the entire extraction period, which is described in equation (10). The owner of the mine is indifferent between extracting respectively selling one unit of the resource from the limited deposit now and selling this unit in the next period if the return on the sale of one unit of the exhaustible resource in the next period is equal to case of extracting this unit now and assessing the profit on the sale on the capital market. Therefore, the returns on the sale of the exhaustible resource need to increase in accordance with the rate of interest in order to avoid arbitrage. If the return on the sale of the exhaustible resource in the next period exceeds the sum of the return of instantaneous extraction and sale plus the one period interest earnings on the return, the operator of the mine will leave the resource in situ because of the economic advantage of the later extraction. Consequenly, the exhaustible natural resource has similar properties than capital.[125]

---

[123] Wacker, H. and Blank, J. E. (1999): *Ressourcenökonomik: Einführung in die Theorie erschöpfbarer natürlicher Ressourcen,* München, Wien, pp. 10–11.

[124] Wacker, H. and Blank, J. E. (1999): *Ressourcenökonomik: Einführung in die Theorie erschöpfbarer natürlicher Ressourcen,* München, Wien, p. 11.

[125] Wacker, H. and Blank, J. E. (1999): *Ressourcenökonomik: Einführung in die Theorie erschöpfbarer natürlicher Ressourcen,* München, Wien, pp. 12–14.

(10)
$$\max_{R_t,T} \pi = \bar{\bar{p}}\, R_0 - C(R_0) + [\bar{\bar{p}}\, R_1 - C(R_1)]\left(\frac{1}{1+r}\right) + \cdots + [\bar{\bar{p}}\, R_T - C(R_T)]\left(\frac{1}{1+r}\right)^T \qquad \sum_{t=0}^{T} R_t \leq S_0 \quad R_t \geq 0 \quad t = 0 \ldots T$$

π...	*Profit*
R ...	*Quantity of the resource that is extracted*
$C\,(R_t)$...	*Extraction costs at time t*
T ...	*Time of depletion of the resource*
$\bar{\bar{p}}$ ...	*Constant price*
r ...	*Rate of discount / interest rate*

As a result of the first order maximization conditions for the resource quantities that are extracted each period, the present value of the return on the sale of the extracted resource of every period needs to be equal, according to equation (11).

(11)
$$[\bar{\bar{p}} - c(R_t)] = \left(\frac{1}{1+r}\right)[\bar{\bar{p}} - c(R_{t+1})]$$

(12)
$$r = \frac{[\bar{\bar{p}} - c(R_{t+1})] - [\bar{\bar{p}} - c(R_t)]}{[\bar{\bar{p}} - c(R_t)]}$$

$c(R_t) = \frac{dC\,(R_t)}{d R_t}$... *Marginal costs of extraction at time t*

As shown in equation (12), the difference between the marginal revenue on the sale of the exhaustible resource and the marginal costs of extraction, which is termed as economic rent, increases temporally in accordance with the interest rate. The opportunity costs of the extraction of one unit of the exhaustible resource in the present are the marginal extraction costs plus the costs of the reduced extraction possibilities in the future. The economic rent is a sign for the scarcity of the exhaustible resource.

L. Gray assumes that in the last period, only an infinitesimal small quantity of the resource is extracted and thus the economic rent is maximal and is in fact equal to the price as the extraction costs are infinitesimal small. Based on the last period, the extraction quantity of the previous period is calculated according to equation (11). In this way all previous extraction quantities and extraction costs are determined until the entire resource stock is extracted. Therewith the extraction quantity and extraction costs of the first period are also determined. The growth in the economic rent, as the difference between the constant price and the extraction costs over time is consequently explained by tracing the extraction cost curve back down period by period. [126]

The same result as L. Gray's increasing economic rent on the extraction of non-renewable resources was obtained later using another modeling framework, which allows a variable resource price. This model with changing resource prices is presented subsequently. Due to the property of a constant resource price sometimes the approach of L. Gray is assumed to represent the short run, since prices are generally supposed to be fixed for the short period.

Hotelling price path of exhaustible resources

A similar approach with different framework conditions is proposed by Harold Hotelling (1895 - 1973). In contrast to L. Gray's constraint of a constant price, H. Hotelling supposes perfect competition among suppliers, so no one is able to change the price by setting its supply quantity. Furthermore, every supplier is aware of the entire resource stock of all suppliers. For all resource deposits, constant and equal extraction costs are assumed. The price at every point in time, present and future, is known to all suppliers. This is equal to the assumption of perfect forward markets, which allows market participants to close contracts for all goods for the present and future dates. The contracts are based on equilibrium prices that are achieved through an auctioneer that calls for prices for various dates until the equilibrium prices are attained. No goods are exchange until the auction is finished. This kind of price setting process goes back to L. Walras. Through this approach, the price path that yields to a balance among supply and demand over time is determined. Thus, the main differences between the approach of H. Hotelling and L. Gray are the constraints regarding the price and the extraction costs.[127]

Each resource supplier has to determine his optimal extraction path. The suppliers are faced with similar questions as discussed before in the model of L. Gray. As one unit that is extracted and sold now, which results in a return in the present, is not available for sale in the future the returns in the future are lowered. It is possible for the resource supplier to assess the current returns on the sale of the extracted resource at the capital market's interest rate, which is incorporated by discounting the future returns on the sale of the extracted resource at the market's interest rate. Accordingly, future returns are weighted less than current ones, which favors higher extraction quantities now. In contrast to the model of L. Gray, price adjustments are permitted in the framework of H. Hotelling. Correspondingly, it has to be considered that the price of the resource might increase over time as a consequence of

---

[126] Wacker, H. and Blank, J. E. (1999): *Ressourcenökonomik: Einführung in die Theorie erschöpfbarer natürlicher Ressourcen,* München, Wien, pp. 13–14.

[127] Wacker, H. and Blank, J. E. (1999): *Ressourcenökonomik: Einführung in die Theorie erschöpfbarer natürlicher Ressourcen,* München, Wien, pp. 15–16.

scarcity, which leads to a lower extraction rate. If the unit price of the exhaustible resource increases and the corresponding present value of the returns in the future exceeds the return that can be utilized in the present, the effect of the price increase is stronger than the effect of discounting and suppliers would shift extraction from the present period to the next. In this case, the supply of resources for the current period decreases, which results in higher prices and higher returns in this period. An equilibrium is achieved when the present value of the returns for all periods is equal. Then the resource price increases in accordance with the rate of interest on the capital market, which establishes a balance between an investment on the capital market and the stock investment in the resource market, as represented in equations (13) and (14). Therefore the resource supplier's aim is to maximize the sum of their discounted returns on the sale of the extracted resource, which implies the determination of the optimal extraction path.

(13) $$(p_t - MEC)(1+r)^{-t} = const. \qquad t \geq 0$$

(14) $$p_t = MEC + (p_0 - MEC)(1+r)^{-t}$$

p_0… Price at time $t=0$
MEC … Marginal extraction costs

A formal derivation of equation (14) can be found in [Wacker, Blank (1999) pp. 16-20]. The price p_0 at time $t=0$ as well as the maximum price p_M, which is the price where no additional unit is demanded at higher prices, are determined by the demand function. Correspondingly, p_M is the price at which nobody is willing to buy the resource any more. For Figure 20 a linear demand function is taken as basis, which is discussed in more detail in section 4.2.2.

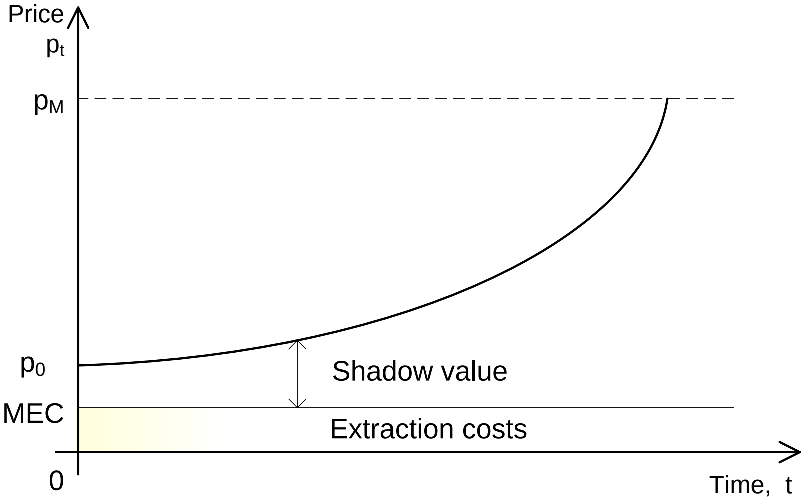


Figure 20: Hotelling price path

p_M … Maximum price

The development of the price of a non-renewable resource also known as Hotelling price path is shown in Figure 20. The shadow value is the difference between the price and the marginal extraction costs and increases according to the discount rate. The shadow value represents the costs of the reduced extraction possibilities in the future, which are equal to the costs of leaving the resource in situ and surrender the interest on the sales returns, as the Hotelling price path is an equilibrium price path.

H. Hotelling examines the development of the resource price in the form of a partial market analyzes. Thus, one single resource sector is evaluated. This includes the assumption that each single firm behaves identical to the entire industry. For this reason, a perfect competitive market and the homogeneity of the resource deposits are assumed. [128]

Due to the limitation to one single market in a partial analyzes, certain arguments like the substitution of the resources and the resulting changes in demand are not included in this model. To study the effects of factor substitution in the production process and the implications on the use of resources, a common economic model, which incorporates the process of production of an economy, is introduced in the following. Thereafter, in section 4.2.2 the situation of different resource deposits and the utilization of natural resources for production is discussed.

---

[128] Wacker, H. and Blank, J. E. (1999): *Ressourcenökonomik: Einführung in die Theorie erschöpfbarer natürlicher Ressourcen,* München, Wien, pp. 15–16.

Neoclassical economic model

In order to provide basic information for distinct analysis approaches in modern resource economics, an often used neoclassical economic model is introduced in the following. At first the presented basic model does not refer explicitly to natural resources but is extended for the analysis in the next section.

The basic cause of all considerations of resource economics is the utilization of natural resources in the economic process as factor for production or for direct consumption. As natural resources are often not suitable for direct consumption and have to be extracted before consumption, natural resources are generally inputs to the economic process of production. This specific matter has not been considered yet. A basic feature of the neoclassical economic model is the production process, which enables examinations on the role of natural resources for the production process and the economy.

Consumption as another aspect of the economy is also included in the neoclassical economic model. As the consumption of goods principally increases the personal and public utility, it is often related to the individual and social welfare. Correspondingly, the aim of increasing welfare is linked to the possibility of consumption. According to the neoclassical model, consumption on its part is related to economic growth, Based on this interrelations economic growth and the consequential increase in consumption account for the general aim of maximizing welfare and are subject to considerations within the neoclassical economic model, as described in the following.

In order to discuss economic growth the framework of the neoclassical economic model is used to obtain a complexity level that is manageable for considerations and discussions. The model supports the understanding of basic factors of economic growth and how they are interrelated. The neoclassical economic model is often called Solow-Growth-Model and is described in the following as basis for the subsequent discussion whether ongoing economic growth and associated prosperity is compatible with limited natural resources.

The main parts of the neoclassical growth model, which are pioneered by the works of Robert M. Solow and Trevor W. Swan, are the production function, which describes how the output is generated, and a relationship for the change of the capital stock, which generally explains the distribution of the output.[129] The production process of the modeled economy utilizes two inputs, labor and capital, to produce output. Capital is commonly seen as the physical capital stock, which includes buildings, machines, computers, etc. and labor input represents manhours or number of workers. Besides the inputs, the production process is

---

[129] Solow, R. M. (1956): A Contribution to the Theory of Growth, in: The Quarterly Journal of Economics, Vol. 70, Issue 1, pp. 65–94.

described by the technology, which stands for the combined processing of the inputs to create output. The main purpose of the model is to explain changes in the physical capital stock. Thereto, the model is based on some simplifying assumptions. In the model some aspects, such as short-run fluctuations in employment and savings rates are neglected in order to create a model to describe the long-run changes of an economy.

Production function

The production function is a relationship that describes how labor and capital are transformed by technology into output. This production function is described by equation (15).

(15)

$$Y_t = F(K_t, A_t\ L_t) \qquad K_t > 0,\quad A_t > 0,\quad L_t > 0$$

Y_t ... Output at time t
K_t ... Capital at time t
A_t ... Technology at time t
L_t ... Labor at time t

Technological progress means that an increase in A_t implies higher output without the need to raise inputs. In this model technological progress is solely labor augmenting, as indicated in equation (15), which means that technological progress reduces the amount of labor needed for a unit of output. Sometimes technological progress is applied to all production factors, which is eventually the same as the presented set-up. In this case A_t is usually referred as total factor productivity (TFP).

The production function is characterized by the absolute necessity of the two production factors labor and capital, which means that the output is zero in the absence of either one of the production factors. Furthermore, the marginal productivity of the capital is assumed to be positive for all $K \geq 0$, which means that an increase in capital also yields to a raise of output.

The production function is assumed to have constant returns to scale for the input factors, which means a doubling in the production factors labor or capital results in a doubling of the output. Furthermore, the production function is characterized by diminishing returns to labor and capital separately. Consequently, further increases of one input factor yields to fewer and fewer additional units of output, when holding the other constant at the same time.

As the output is described by these three factors, growth in output, which is commonly understood as economic growth, is associated with growth in capital, labor or technological progress. Accordingly, higher output in an economy can be achieved by more workers, more machines, or better knowledge how to put capital and labor together.

In many cases, a production function of the Cobb-Douglas form, as shown in equation (16), is used in the neoclassical growth model.

(16)
$$Y = K^{\alpha}(AL)^{1-\alpha} \qquad 0 < \alpha < 1$$

The growth of the input factor labor, which is for simplicity reasons often equalized with population growth and concurrently assumed that the entire population contributes to the labor force, is given exogenously by a constant rate λ, as specified by equation (17). The assumption to count the entire population as labor force is no limitation of generality because taking the working part of the population as labor force would just introduce an additional multiplicative factor.

(17)
$$\Delta L = \lambda L_t \qquad \lambda > 0$$

λ *... Rate of population growth*
$\Delta L = L_{t+1} - L_t$

Similarly to the population growth, the technological progress is also given exogenously by a constant rate g, as indicated in equation (18).

(18)
$$\Delta A = gA_t \qquad g > 0$$

g *... Rate of technological progress*
$\Delta A = A_{t+1} - A_t$

For easier mathematical handling, the production function is often expressed per effective labor, which is permitted due to the property of constant returns to scale for the input factors. This is shown in equation (19).

(19)
$$y = \frac{Y}{AL} = F\left(\frac{K}{(AL)}, 1\right) = f(k)$$

$y = \frac{Y}{AL}$ *... Output per unit of effective labor*
$k = \frac{K}{AL}$ *... Capital per unit of effective labor*
AL *...* *Effective labor*

In mathematical terms the function *f(k)* is assumed to be increasing, concave, and twice continuously differentiable. In the next step the model is extended by specifications for the production factor capital, which also describes in some way how the output is used in the economy.

Capital accumulation

One of the basic ideas of the model is that the society saves a constant fraction of its income. The income of the society as a whole is the output of the economy. The members of the society have to decide how to use their income either for saving or for consumption. The assumption of a constant savings rate is equivalent to consuming a certain constant proportion of the income. In the model, the savings rate s is given exogenously. It is assumed that the saved capital does not just lie idle but is available for another use than consumption. The approach of the model is that the entire saved capital is used for investment in the capital stock of the economy and enhancing the production possibilities of the economy. The mathematical representations of these relationships are given in equation (20) and (21).

(20)
$$Y_t = I_t + Co_t$$

(21)
$$I_t = sY_t$$

I_t … *Investment at time t*
Co_t … *Consumption at time t*
s … *Saving rate*

Investment in the capital stock means that the saved amount of the output is added to the production factor capital, as seen in equation (22). This implies that in the next period, a larger amount of the input factor capital is available for production, which enables a higher production output.

(22)
$$K_{t+1} = K_t + I_t - \delta K_t$$

K_{t+1} … *Capital at time t+1 (in the next period)*
δ … *Depreciation factor*

In addition to the characteristic of capital accumulation the model includes also depreciation of the actual capital stock, as indicated in equation (22). Practically, capital needs to be replaced due to wear and tear as for example machinery needs servicing to preserve the originally condition. If the total savings respectively the investment exceeds the replacement investment caused by the depreciation, the capital stocks increases.

The question that is analyzed in the Solow-Growth-Model framework is how to maximize the consumption per capita, which is used as a measure for welfare. As the consumption is proportional to the output, an increase in output per capita implies also higher consumption per person. Consequently, a maximization of the output per worker, which is related to economic growth, equals the original maximization problem. The central quantity of the Solow-Growth Model is the capital stock. For this reason the development of the capital stock under the influence of the exogenous given quantities, labor and technological progress, is analyzed.

As the output is a function of the capital, according to equation (19), the development of the capital stock per unit of effective labor is examined with respect to the consumption. The relationship between the rate of change of the capital stock per effective unit of effective labor and the other quantities of the model is derived according to equation (23) and shown in equation (24).

(23) $$\frac{\Delta k}{k}=\frac{\Delta K}{K}-\frac{\Delta L}{L}-\frac{\Delta A}{A}=\frac{\Delta K}{K}-\lambda-g$$ with $\Delta K = K_{t+1}-K_t$

(24) $$\frac{\Delta k}{k}=s\frac{y}{k}-(\delta+\lambda+g)$$ and $\Delta K = sY-\delta K$

According to equation (24), the relationships among the growth rate of capital per effective unit of labor k and the savings rate s, the depreciation rate δ, the population growth rate λ, the rate of technological progress g and the ratio of output y to capital k is as follows.

- Growth in capital stock is positively related to the saving rate s, which means that a higher rate of savings yields to higher growth rate of capital.
- The capital growth rate depends positively on the ratio of output to capital $\frac{Y}{K}$. Consequently, the higher the capital productivity the higher is the rate of capital accumulation.
- The depreciation rate δ is negatively related to the growth of capital, which corresponds to a lower rate of growth in capital if a higher percentage of the capital depreciates.
- The faster the population grows, the lower is the rate of growth of the capital stock per unit of effective labor.
- Technological progress is negatively related to the growth of capital, which means that a higher rate of technological progress lowers the rate of growth of capital per unit of effective labor.

In order to derive further properties, the model is simplified for the next step by neglecting technological progress. In the absence of technological progress, Tjalling C. Koopmans says that there exists a golden rule for capital accumulation. By golden rule he means a capital stock per capita that maximizes the consumption per capita. This specific capital stock represents a steady state for the growth model, as a further growth as well as a reduction in the capital stock per capita result in a reduction of the consumption, as shown in Figure 21.[130]

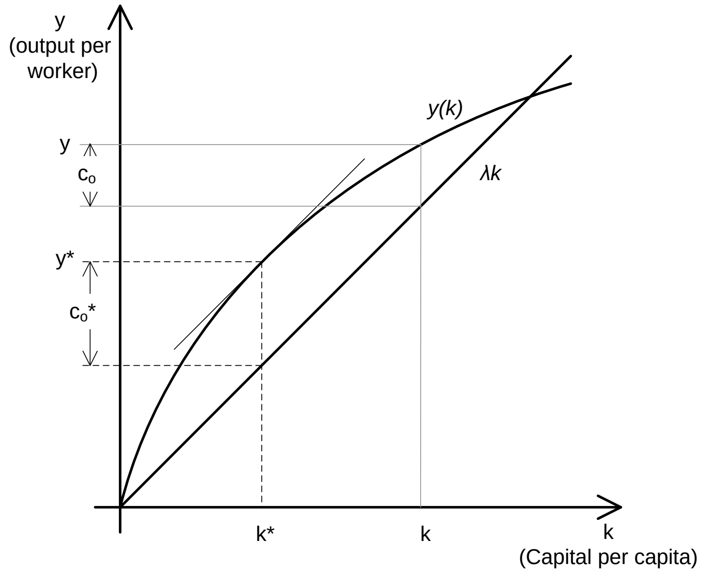


Figure 21: Golden rule of capital accumulation

k ... Golden rule capital stock per unit of effective labor*
y ... Golden rule output per unit of effective labor*
co ... Consumption per unit of effective labor
co ... Golden rule consumption per unit of effective labor*

In the case considered by T. Koopmans with no technological progress, the maximum consumption per capita that can be achieved and maintained is attained when the marginal productivity of capital $\frac{\Delta Y}{\Delta K}$ is equal to the sum of population growth λ and depreciation rate δ. This situation is shown in Figure 21 at the capital stock k^*, where the tangent to $y(k)$ is identical to $(\lambda+\delta)k$, which is the investment that is needed to keep the per capita capital stock constant.[131]

---

[130] Koopmans, T. C. (1967): Intertemporal Distribution and 'Optimal' Aggregate Economic Growth in: *Economic Studies in the Tradition of Irving Fisher,* pp. 99–100.

[131] Koopmans, T. C. (1967): Intertemporal Distribution and 'Optimal' Aggregate Economic Growth in: *Economic Studies in the Tradition of Irving Fisher,* pp. 99–100.

The steady state is desirable because a capital stock per unit of labor (=worker) above and beneath this state results in a lower consumption level per worker (=capita). In the steady state without technological progress, the capital stock per worker is constant, which means that the capital stock increases at a rate of λ. The assumed diminishing returns to the production factors have to be kept in mind. By adding capital to the existing capital stock each year, the capital intensity, which reflects the capital per unit of labor, will increase in general. Due to diminishing returns to the production factors, the additional capital injections cause ever smaller contributions to the production. Accordingly, the economy approaches a state of nearly identical growth rates for capital, labor and total production in the long run if no technological progress is present. By taking technological progress into account the improvements in the production technology can offset the diminishing returns to capital.

In addition, diminishing returns mean that the higher the factor inputs to the production are the lower is the respective factor productivity. But high factor inputs also imply a high level of output, as output increases by a raise in factor inputs. Correspondingly, a low productivity of capital with respect to output implies a high level of output. For this reason a low steady state ratio of output per capita to capital per capita is desirable to achieve a high steady state level of output per capita respectively consumption per capita. Consequently, a high steady state output, capital stock and therewith consumption level is attained by a low depreciation rate, a low population growth or a high savings rate.

When considering additionally technological progress, a steady state is obtained by meeting the condition shown in equation (25).

$$\frac{y^*}{k^*} = \frac{\delta + \lambda + g}{s} \tag{25}$$

The steady state condition of equation (25) is derived from the first order maximization condition for k, which means setting equation (24) equal to zero. In the steady state the capital per unit of effective labor as well as the output per unit of effective labor stays constant, whereas the capital per unit of labor (=worker) and the output per worker (=capita) grow at a rate of g. Hence, the capital per worker k and the output per worker y grow in the steady state and the equilibrium (steady state) rate of growth of output per capita is determined by the technological progress g. Since the output per worker grows by a rate of g, the output itself grows at a rate $(n+g)$ in the steady state. Therefore this growth rate $(n+g)$ is quite often termed as “natural” growth rate.

This model is often used to discuss intergenerational issues. The topic of the following section is modern resource economics, which deals with intergenerational issues and employs the Solow-Growth-Model for the discussion of implications of exhaustible resources on economic growth.

4.2 Modern Resource Economics

The term modern resource economics is used here for the theories and notions in the field of resource economics past 1970. The time after H. Hotelling's work on exhaustible resources, the topics of resource economics were more or less neglected. By the 1970s, indications for an end of the period of high growth after World War II and negative impacts of the industrial production on the environment became visible.[132] An expression of this development was the publication of "The Limits to growth"[133] by D.H. Meadows et al. in a report to the Club of Rome. In the report, the ideas of R. T. Malthus concerning population growth and limited availability of resources were taken and were examined in the "World Model" as the authors called their framework for analyses. The report questions how exponential growth of population can be compatible with food production on a limited world and how ongoing economic growth is possible with exhaustible resources. The report shows projections of the evolution of different systems such as population, food production and exhaustible natural resource and emphasizes on the linkage between economy and the environment. The report even specified static ranges for various resources, which shocked a lot of people. Possibly the most prominent message of the report is that continuous economic growth reaches the limits of environmental compatibility, which results most probably in the collapse of the persisting economic system.[134] With this proposition, "The Limits to Growth" was very influential and triggered a lot of subsequent works in the field of resource economics.

Due to the oil price shock of 1973, the subject of resource economics advanced to a political topic and also general public became aware of the finiteness of natural resources. As a result of the increased popularity, the scientific community addressed this topic and several works on resource economics were published in the following years.

Considerations on resources inevitable lead to the question of the allocation of the resources over time. Due to the finiteness of a lot of natural resources and the fact that one unit used today is not available for tomorrow's usage the issue of resource allocation is naturally bound to the factor time. Accordingly, the subject of resource economics is linked to the intergenerational issues.

---

[132] Farmer, K./Bednar-Friedl, B. (2010): Intertemporal Resource Economics: An Introduction to the Overlapping Generations Approach, http://dx.doi.org/10.1007/978-3-642-13229-2, January 2011.

[133] Meadows, D. et al. (1972): *The limits to growth: A report for the Club of Rome's project on the predicament of Mankind,* New York,

[134] Turner, G. M. (2008): A Comparison of the Limits to Growth with Thirty Years of Reality, Socio-Economics and the Environment in Discussion (SEED) Working Paper Series 2008-09, p. 1.

The matter of temporal allocation of finite resources is often denoted as Cake-Eating-Problem, which describes the fact that only a given finite deposit, one cake, is available and any consumption reduces the stock. Nevertheless, the cake is delicious and the consumption of a piece of the pie increases the personal utility. Nevertheless, the question what is a smart and fair way of consumption persists. The next subsection provides some insights for answering this question.

Thus, the fundamental question of resource economics is to find the best consumption path for the limited natural resources for sequent human generations, which is also termed as the intergenerational allocation problem. [135]

4.2.1 Intergenerational Efficiency and Intergenerational Equity

This section is intended to provide some basic scientific concepts in order to find an answer for the question what is smart and fair related to the consumption of limited resources. In this context also difference between the terms intergenerational efficiency and intergenerational equity is clarified. First the concept of economic efficiency is introduced and the meaning of intergenerational efficiency derived. Secondly, the term intergenerational equity, which is more an ethical question, is discussed.

The etymological view on terms usually provides a suitable introduction into new subjects. Therefore a short etymological description of the term “efficiency” is given. The term “efficiency” is based on the Latin words efficientia / efficere / facere which stand for to accomplish or to do / make. The meaning of the term efficiency developed from identifying power to accomplish something to the ratio of useful work performed to the total energy expended in technical terms.[136,137] Expressed in more economic terms, this would mean that efficiency stands for the ratio of the output of a process or an action to the inputs. The output of an action is interpreted as the state after the action is accomplished. In order that the state after an action is more efficient than the state before the action is accomplished, certain criteria have to be fulfilled. Two of various available criteria are inspected in more detail in the following.

Probably the most popular criterion for economic efficiency goes back to Vilfredo Pareto (1848 - 1923). The criterion of Pareto efficiency states that a certain state is Pareto efficient if

---

[135] Farmer, K./Bednar-Friedl, B. (2010): Intertemporal Resource Economics: An Introduction to the Overlapping Generations Approach, http://dx.doi.org/10.1007/978-3-642-13229-2, January 2011.

[136] Oxford University Press. : Oxford Dictionaries, http://oxforddictionaries.com, 30.05.11.

[137] Douglas Harper : Online Etymology Dictionary, http://www.etymonline.com, 30.05.11.

there are no possibilities to improve the situation without changing the situation for the worse for at least one individual.[138]

In terms of intergenerational allocation the criterion of Pareto efficiency could be formulated as follows. A resource harvesting path or consumption path is intergenerational efficient in if no other path can be found that permits a higher utility for one generation without imposing a utility loss to other generations.

The Kaldor-Hicks criterion can be seen as an extension of the Pareto's notion. According to this criterion a state B is more efficient than another state A if based on state A at least one individual can be made better off and no other individual suffers an impairment of its situation under the consideration of compensation transfers from those that experience improvements to those that are made worse off. Due to the compensation transfers all involved are made better off or at least equal to state A in state B.[139]

The issue of intergenerational allocation involves a further constraint when considering compensation transfers for achieving efficiency because only unidirectional transfers are possible. Intergenerational transfers are inevitably directed towards future generations, as future generations cannot invest anything today to improve the situation of the present generation since they do not exist in the presence.

Exactly this situation also inhibits the determination of an optimal path based on negotiations, as no member of future generations, who could express the needs and desires of the future generation, is available today. As a consequence, it is solely the present generation that makes the decisions about the resource use paths. Due to the temporal dependency of the future's use of non-renewable resources from the current usage decisions, present decisions have impacts on the consumption possibilities of future generations.

It is efficient to use the entire stock of the resource over the whole time horizon, if the resource can be used productively. Leaving only one unit of the resource behind would be wastefully because this unit could generate an additional utility for at least one generation.[140]

When considering that the market allocation on a perfect market is Pareto efficient, the already discussed question how scarce resources are allocated on the market arises.[141] Accordingly, the Hotelling rule for the determination of resource prices over time, which is described in section 4.1.2, has to be taken into account. Consequently, the Hotelling rule is

---

[138] Wagener, H.-J. (2009): Vilfredo Pareto in: *Klassiker des ökonomischen Denkens 2: Von Vilfredo Pareto bis Amartya Sen*, ed. Heinz Dieter Kurz, München, p. 40.

[139] Feess, E. (2004): *Mikroökonomie: Eine spieltheoretisch- und anwendungsorientierte Einführung,* 3rd ed., Marburg, p. 59.

[140] Ströbele, W. (1987): *Rohstoffökonomik: Theorie natürlicher Ressourcen mit Anwendungsbeispielen Öl, Kupfer, Uran und Fischerei,* München, p. 25.

[141] Hanusch, H./ Kuhn, T./Cantner, U. (2002): *Volkswirtschaftslehre,* 6th ed., Berlin, p. 225.

the principle of dynamic efficiency, which completes the previous criteria for static efficiency.[142]

After examining the concept of economic efficiency regarding of intergenerational allocation of resources, in the following the issue of intergenerational equity is discussed. In contrast to economic efficiency, which addresses the question what is the best way to utilize a given stock of a resource, the issue of equity deals with the question how the utility respectively wealth, which can be gained from the usage of the resource, has to be distributed. Therefore, equity is linked to moral judgments and is a more a matter of ethics. [143]

On the basis of intergenerational efficiency multiple resource allocation paths can be determined. The problem is that these intergenerationally efficient paths may differ significantly in the distribution of utilities across generations. Hence, the condition of intergenerational efficiency does not inhibit unequal distribution across subsequent generations. However, many economists assume that intergenerational efficiency is a necessary condition for intergenerational equity.[144]

To determine which of the intergenerationally efficient paths to choose, criteria for intergenerational equity are needed. Due to the temporal component of the decision on the optimal resource allocation path, these criteria involve a weighting of the utilities of different generations. In the following, two well-known approaches are described.

Rawls' Maximin criterion

This concept of equity is introduced by the philosopher John Bordley Rawls (1921 – 2002) and emphasizes in particular on the least-well off. The basic idea is that the situation of the poorest is the determinant for social welfare. Consequently, the social welfare can only be increased if the situation of the least well is improved. If welfare is expressed in terms of utilities, Rawls' Maximin Criterion can be written as shown in equation (26).

---

[142] Ströbele, W. (1987): *Rohstoffökonomik: Theorie natürlicher Ressourcen mit Anwendungsbeispielen Öl, Kupfer, Uran und Fischerei,* München, pp. 25–26.

[143] Tsur, Y. and Dinar, A. (1995): Efficiency and Equity Considerations in Pricing and Allocating Irrigation Water, p. 1, http://go.worldbank.org/JLE7Q9NR90, 30.05.11.

[144] Farmer, K./Bednar-Friedl, B. (2010): Intertemporal Resource Economics: An Introduction to the Overlapping Generations Approach, http://dx.doi.org/10.1007/978-3-642-13229-2, January 2011.

(26) $$W = \min(U_1, \ldots, U_n)$$

$W \ldots$ Social welfare function
$U_1 \ldots U_n \ldots$ Individual utilities or utilities of generation 1 … n

According to equation (26), the maximization of the social welfare is only achieved by a increasing the minimal occurring utility. The social welfare is thus only sensitive to changes in the utility of the least well off.

With respect to the intergenerational allocation problem the Maximin criterion proposes that the path which maximizes the utility of the poorest generation is favorable. Unlike to the utilitarian criterion, which is described hereafter, Rawls' equity criterion does not permit any marginal utility loss for one generation, not even if all subsequent generations would gain increased utility from that. Accordingly, the Maximin criterion claims for an allocation path with a constant non-zero consumption per head for any generation over time. Hence, the question on the optimal capital accumulation and optimal resource use arises, which is further discussed in section 4.2.2.[145]

Utilitarian criterion

Following the introduction into the utilitarian approach in section 4.1.2, social states are defined as a function of utilities of individuals. It matters how the individual utilities are aggregated. Supposing that individuals are identical, which includes that they have equal preferences and therefore the all members of a group (e.g. society) prefer option A to B, then the group's utility function is a weighted sum of the individual utility functions. This implies that losses for one individual can be offset by increases in the utilities of other members of the group. Hence, sacrifices of an individual are accepted which could also apply to the poorest member of the group. Nevertheless, the approach of summation of utilities is widely accepted in utilitarianism and usually considered as given.[146] [147]

In the context of economics and intergenerational allocation, the utilitarian notion was established by Frank Plumpton Ramsey (1903 - 1930). He considers the individual lifetime wellbeing as the flow of utilities one enjoys and the intergenerational wellbeing as the

---

[145] Solow, R. M. (1974): Intergenerational Equity and Exhaustible Resources, in: The Review of Economic Studies, Vol. 41, pp. 29–45.

[146] Solow, R. M. (1974): Intergenerational Equity and Exhaustible Resources, in: The Review of Economic Studies, Vol. 41, pp. 29–45.

[147] Risse, M. (2002): Harsanyi's 'Utilitarian Theorem' and Utilitarianism, in: Nous, Vol. 36, Issue 4, pp. 550–577.

aggregate of the individual lifetime wellbeings. As suitable method for the aggregation, he considers summation, according to equation (27).[148]

(27)
$$W_t = \sum_{\tau=t}^{\infty} U_\tau \, (1+z)^{-(\tau-t)}$$

W_t … *Aggregate social welfare at time t*
U_τ … *Utilities of generation* τ
z … *Social rate of discount*

F. P. Ramsey does not consider any weighting factor for the utilities of different generations ($z=0$) because he thinks that weighting the utility of one generation other than another one is ethically indefensible. [149] The weighting factor $(1+z)$ in equation (27) accounts for the discount factor as the weighting of points in time is commonly known as discounting. The influence of discounting is discussed after some basic thoughts about the utilitarian criterion for the intergenerational resource allocation.

Due to the way of aggregating the individual utilities (summation), the primary concern and therefore the maximization criterion is in general the size of the entire welfare pie. The distribution among the concerned individuals is not the most important matter. Considering a production economy as described by the Solow-model and the fact that only transfers towards the future are possible, any saving, which is tantamount to surrender consumption, enables higher consumption for the subsequent generations. Accordingly, sacrifices of the earlier generations, maybe even unaccountable sacrifices, might be demanded for the advantage of the future generation and the maximization of the total pie.[150]

Before discussing the influence of the discount rate, a third criterion for intergenerational equity is discussed. This approach, which was introduced by Graciela Chichilnisky, can be summarized as no dictatorship, neither by the present nor by the future, which is attained by presetting upper as well as lower bounds for the utility function.[151]

The utilitarian criterion is the far most often used approach to rate intergenerational equity. For this reason, the utilitarian approach is used in subsequent considerations unless specified otherwise.

---

[148] Dasgupta, P. (2005): Three Conceptions of Intergenerational Justice in: *Ramsey's legacy*, eds. H. Lillehammer and D. H. Mellor, Oxford, pp. 1–3.

[149] Dasgupta, P. (2005): Three Conceptions of Intergenerational Justice in: *Ramsey's legacy*, eds. H. Lillehammer and D. H. Mellor, Oxford, p. 6.

[150] Gosseries, A. (2008): Theories of intergenerational justice: a synopsis, in: Surveys and Perspectives Integrating Environment and Society, Vol. 1, Issue 1, pp. 39–49.

[151] Chichilnisky, G. (1997): What Is Sustainable Development?, in: Land Economics, Vol. 73, Issue 4, pp. 467–491.

Since discounting is an issue of not too less significance for evaluating intergenerational allocation paths, in the following elementary thoughts concerning discounting are discussed.

Discounting as an approach to account for the factor time

Discounting is the most common way how to consider the factor time as a parameter for future effects. The approach of discounting is a formal principle of how to determine the current value of a quantity at a certain point in the future, which is given in equation (28).

(28)
$$X_t = X_\tau (1+d)^{-(\tau - t)} \qquad t \geq \tau$$

X_t ... Quantity X at time t
X_τ ... Quantity X at time τ
d... Discount rate

There are several motivations and interpretations for discounting. Three argumentation approaches are discussed in the following.

One motivation for discounting is the assumption that humans have a time preference and naturally favor present consumption over future consumption. As reasons for this characteristic the human impatience or a finite and unknown life expectancy are designated. Impatience in terms of not wanting to postpone the enjoyment leads to a biased valuation of future utilities. The resulting depreciation of future utilities is one of the reasons for discounting future quantities. The unknown life expectancy reflects another reason for discounting, which is the concern of considering the uncertainty of future effects.[152]

Due to uncertainty, the secure consumption now is higher rated than the same consumption in the future because one cannot be sure if she or he is able to consume in the future or if the future's consumption generates an equally high utility as the present consumption. Based on this notion discounting can be an approach to account for uncertainty and the resulting lower value of vague future utilities.[153]

Discounting can also be used to rate alternatives at different points in time based on the opportunity costs. Opportunity costs describe the costs of the usage of a resource for a certain utility generating action that arise from the fact that the same resource cannot be used for another action. This is a way to compare the different usages of the resource in order to determine which action generates the highest utility. For example if anyone offers an apple or a peach to you for free under the constraint that you will get just one of these

---

[152] Geyler, S. (2008): *Ökonomisch-ökologische Bewertung von regionalen Trinkwasserschutzoptionen,* 1st ed., Frankfurt am Main, Leipzig, pp. 69–71.

[153] Geyler, S. (2008): *Ökonomisch-ökologische Bewertung von regionalen Trinkwasserschutzoptionen,* 1st ed., Frankfurt am Main, Leipzig, pp. 69,73.

alternatives, the opportunity costs of choosing an apple are that you cannot eat the peach. If your individual utility of eating an apple is higher than your individual utility of eating a peach, the opportunity costs of eating the apple, which are due to not having the peach, are lower than the utility gained from eating the apple. Therefore, the decision is beneficial. Accordingly, a decision for one alternative is reasonable if the opportunity costs of not deciding for any other alternative are lower than the advantage gained from the chosen alternative. If the possible alternatives are available at different points in time, one has to consider the opportunity costs, which originate from the parameter time. This situation is also discussed in section 4.1.2 as part of the derivation of the Hottelling rule. The two alternatives selling one unit of a resource today or selling this unit in one year from now are considered. The sale of one unit of the resource yields sales revenues, which can be invested in different markets. For simplicity we consider an investment in the capital market. The investment of the sales revenue earns interest for one year. Consequently, the opportunity costs of the sale of one unit of the resource one year later are the not received sales revenue of the previous year plus the earnings on interest. For this reason, any future sale has to earn the same revenue as the comparable sale now plus the interest yield need to be equal to the sale in the present. In order to compare the future’s sales revenue with the present one, the revenue in the future is discounted using the interest rate of the alternative investment as discount factor.[154]

Discounting allows for the provision of the factor time in decision situations but also involves uncertainties about the discounting itself. Doubts about the height of the discount rate are a major issue. One manifestation of this uncertainty is discussed subsequently.[155]

Private vs. social rate of discount

If one wants to achieve a socially optimal outcome and includes discounting in the considerations, the question whether rates of discount are equal for the private individuals and for the society as a whole. Differences may originate from the different motivations for discounting. For example, assuming a constant rate of time preference does not comply with reality and the actual behavior of individuals. Seemingly, the time preference depends on the time span between the decision and the actual event.[156] Furthermore, the time preferences may differ between the individual and the society. A kind of free-ride problem plays a certain role in the determination of the time preference. Saving and the resulting renunciation of

---

[154] Geyler, S. (2008): *Ökonomisch-ökologische Bewertung von regionalen Trinkwasserschutzoptionen,* 1st ed., Frankfurt am Main, Leipzig, pp. 67–68.

[155] Geyler, S. (2008): *Ökonomisch-ökologische Bewertung von regionalen Trinkwasserschutzoptionen,* 1st ed., Frankfurt am Main, Leipzig, pp. 72–73.

[156] Geraats, P. M. (2006): Intertemporal Substitution and Hyperbolic Discounting, pp. 2–3, www.econ.cam.ac.uk/faculty/geraats/cons_hyperb.pdf, 30.05.11.

consumption is a private concern of the individual but the advantage due to enhanced production respectively consumption possibilities as a result of the capital investments that are enabled through the savings serve the whole society. Thus, the private tendency to save is lower compared to the public and therefore the private rate of time preference is higher than the social. Associated with this is that the society perceives a certain duty to care for future generations.

As previously discussed, the rate of discount might also include a component that represents the risk about future events. Most likely this risk component differs between one single private person and the society as a whole, which results on the diversification of risk among the members of the society, Moreover, the uncertainty about life expectancy is in general not present for the immortal society as whole.[157]

For these reasons, a private discount rate is likely to be higher than the social discount rate. Accordingly, applying the private rate of discount does not lead to social optimal outcome. In the case of intergenerational allocation, a higher discount rate results in a privilege for the present and a too fast extraction of exhaustible resources. To distinguish between the social and private rate of discount in this work, the social discount rate is denoted as z and the private discount rate as r.

In the next section the applications of the concepts of intergenerational efficiency and intergenerational equity in resource economics are discussed and the question whether these concepts are compatible with finite natural resources is analyzed.

4.2.2 Intergenerational Utilization of Nonrenewable Resources

In direct succession to the discussion on the social rate of discount the concept of the socially optimal rate of resource extraction is described. Thereafter, finite resources are introduced in the previously explained Solow-Growth-Model and implications of this extension on temporal consumption paths respectively economic growth are analyzed.

Socially optimal rate of extraction

The concept or the socially optimal rate of resource extraction assumes that a society has a certain finite and a priori known stock of a homogeneous, non-renewable natural resource that is essential for consumption. Furthermore, the society is faced with constant marginal costs for the extraction of the resource. This model is used to determine a socially optimal temporal path of resource extraction, which means to maximize the social welfare

---

[157] Tietenberg, T. H. (2006): *Environmental and natural resource economics,* 7th ed., Boston, Mass, pp. 79–80.

respectively utility of the society for a certain planning horizon. In general the planning horizon should be indefinite when considering an immortal society. For the sake of simplicity a finite planning period is employed and the results generalized.[158]

The model additionally assumes the utility to be a function of the consumption and being positively related to the consumption of the resource but with diminishing marginal utilities. Furthermore, the utilitarian criterion is used to determine the social welfare. As weighting factor in the utilitarian sum of utilities, according to equation (19) the social rate of discount is employed. Correspondingly, the optimization of the total social welfare is equal to the maximization of the sum of the discounted values (present values) of the utilities of all periods (generations). The optimization problem can be viewed from the perspective of an social planner.[159]

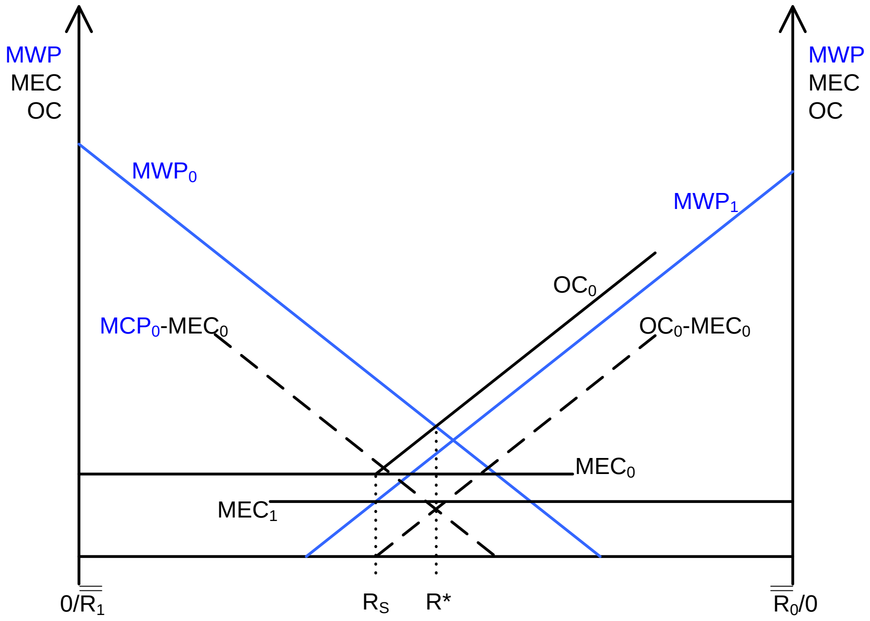


Figure 22: Socially optimal rate of extraction

MWP_x ... Marginal willingness to pay in period x

MEC ... Marginal extraction costs in period x

OC_x ... Opportunity costs of the extraction in period x

$\bar{\bar{R}}$ ... Total stock of the resource

---

[158] Endres, A. and Querner, I. (1993): *Die Ökonomie natürlicher Ressourcen: Eine Einführung,* Darmstadt, p. 25.

[159] Endres, A. and Querner, I. (1993): *Die Ökonomie natürlicher Ressourcen: Eine Einführung,* Darmstadt, pp. 25–26.

The maximization implies that the marginal utility of the usage of the resource in one period is greater than the opportunity costs of the usage. The opportunity costs of the usage consist of the extraction costs and the present value of the future's reduction in utility. The marginal utility is here indicated by marginal willingness to pay. Consequently, it is reasonable to consume one unit of the resource in the present period if the marginal willingness to pay exceeds the opportunity costs. Otherwise the total social welfare is increased if this unit is saved for future generations. This situation is illustrated in Figure 22 for a two period optimization.[160]

In Figure 22, the x-axis is counted positively from the left to right for period 0 and negatively for period 1. This means that the utilized quantity of the resource in period 0 increases from the left to the right and at the same time decreases for period 1 as both periods share the same resource stock. Furthermore, to compare the two periods, all quantities need to be based on the same point in time. Hence, the illustrated quantities of period 1 are discounted values.

For the derivation of the optimal distribution of the resource between the two periods first it has to be considered that an efficient utilization of the resource is only possible if the marginal willingness to pay exceeds the extraction costs. Otherwise the resource is not worth being extracted. Therefore, there is no competition for the resource until R_S units of the resource are extracted in period 0. So, it is sufficient to consider only the extraction costs for the assessment of the reasonability of the extraction. Hence, the extraction is advantageous because the marginal willingness to pay is higher than the extraction costs in period 0. At the point at which the resource stock is depleted to $\bar{\bar{R}} - R_S$, a competitive situation for the resource arises because $\bar{\bar{R}} - R_S$ units of the resource can be extracted in period 1 beneficially, which means that the marginal willingness to pay of period 1 exceeds the extraction costs of period 1. From this point on, competition for the resource between period 0 and period 1 has to be considered. For this reason, the opportunity costs of the usage of the resource in period 0 have to include the present value of the reduced utility in period 1 as a result of the lower consumption possibilities for period 1 due to the decreased resource stock. The consumption of the resource in period 0 is beneficial until R^* units of the resource are extracted and as long as the marginal willingness to pay for the resource of period 0 exceeds the opportunity costs. This is indicated by the interception of the MWP_0 and OC_0 in Figure 22. For every further unit that is extracted, the opportunity costs are higher than the

---

[160] Endres, A. and Querner, I. (1993): *Die Ökonomie natürlicher Ressourcen: Eine Einführung,* Darmstadt, pp. 31–32.

marginal willingness to pay in period 0, so it is advantageous to save this unit for usage in period 1 in order to maximize the total social welfare.[161]

The point where the marginal willingness to pay of period 0 is equal to the opportunity costs of the usage of the resource in period 0 marks the point of optimal distribution of the resource between period 0 and period 1. In the optimum, the “net marginal utility” of extraction in period 0, which corresponds to the marginal willingness to pay minus the extraction costs (MWP_0-MEC_0), equals the present value of the reduction in utility of period 1 due to the reduced stock of the resource and consumption possibilities (OC_0-MEC_0). The result that the discounted net marginal utilities have to be equivalent for all periods is also true for the case of optimization of multiple periods and is identical to the findings of L. Gray and H. Hotelling discussed in section 4.1.2.[162]

Thus the problem of finding the socially optimal rate of resource extraction is very similar to the task behind the Hotelling rule, which represents the solution for the resource allocation problem on a perfectly competitive market. The two solutions are identical if the following properties hold.[163]

- The resource price equals the marginal utility of the resource in the equilibrium state.
- The extraction costs of the supplier are the same as the social opportunity costs of the extraction (external effects).
- The private rate of discount is identical to the social discount rate.

Therefore, the resource allocation on a perfectly competitive market can be socially optimal under certain constraints. In the following, some considerations about possible temporal extraction paths of resources based on the Hotelling rule are discussed. As before, constant marginal extraction costs are assumed unless otherwise specified and also the constraints of the Hotelling model, defined in section 4.1.2, apply for the following analyses.

In case of a linear demand function, which is shown in the upper left quadrant of Figure 23, the resource price is bounded above by the maximum price p_M as already discussed in section 4.1.2. The determination of the initial price p_0 using the demand function is also illustrated in Figure 23. From the initial extraction quantity ΔR_0, which is determined from the efficiency constraint that the entire resource has to be used until time T, follows a certain initial demand, which is determining the initial price p_0. The course of the price of the

---

[161] Endres, A. and Querner, I. (1993): *Die Ökonomie natürlicher Ressourcen: Eine Einführung,* Darmstadt, pp. 32–34.

[162] Endres, A. and Querner, I. (1993): *Die Ökonomie natürlicher Ressourcen: Eine Einführung,* Darmstadt, pp. 34–35.

[163] Endres, A. and Querner, I. (1993): *Die Ökonomie natürlicher Ressourcen: Eine Einführung,* Darmstadt, p. 40.

resource based on the Hotelling rule is shown in the upper right quadrant of Figure 23. The lower right quadrant illustrates the extraction path for the resource. To be efficient, the extraction path has to ensure that the whole stock of the resource $\bar{\bar{R}}$ is extracted at time T. Therefore the total area under the extraction path, which represents the sum of the periodical extracted quantities, equals the total resource stock $\bar{\bar{R}}$ since the entire resource is used. For the sake of completeness it is mentioned that the lower left quadrant is just used to transform the extraction path on the demand function.

Additionally, the effect of different rates of discount is illustrated in Figure 23, whereat discount rate r^a is lower than discount rate r^b $(r^a < r^b)$ and all other parameters stay equal (ceteris paribus). As already mentioned in the previous section, a higher rate of discount results in a faster extraction and consequently in an earlier depletion of the resource, which is also shown by the extraction paths in the Figure 23. Due to the higher discount rate r^b, the according price path is characterized by a faster increase. In order to achieve an efficient extraction path, the resource needs to be fully extracted at time T^b, because there is no additional demand after this point in time. Since T^b is earlier than T^a, the time to depletion is shorter for the higher discount rate. Thus, the initial rate of extraction needs to be higher to deplete the resource in a shorter time period. Based on the higher rate of extraction, a lower initial price p_0^b is determined using the demand. It has to be considered that this analysis of the effects of a higher discount rate is a partial analysis and other effects are possible in a general equilibrium examination.[164]

---

[164] Wacker, H. and Blank, J. E. (1999): *Ressourcenökonomik: Einführung in die Theorie erschöpfbarer natürlicher Ressourcen,* München, Wien, pp. 39–40.

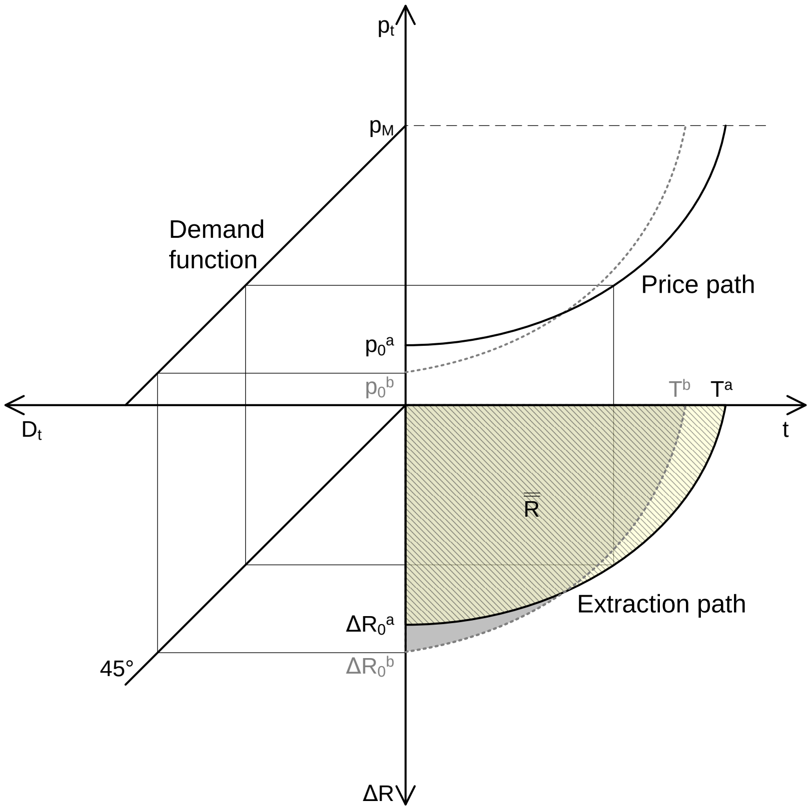


Figure 23: Hotelling price and extraction path for a linear demand function

D_t ... *Demand function*
ΔR_t ... *Extraction quantity at time t*
ΔR_0^x ... *Extraction quantity at time t=0 and discount rate x*
p_0^x ... *Price at time t=0 at discount rate x*
T_x ... *Time of resource depletion at discount rate x*

In addition to the examination using a linear demand function, Figure 24 shows the Hotelling price and extraction path for an isoelastic demand function. In contrast to the linear demand function, the isoelastic demand is characterized by an ongoing lowering of the demand for arbitrary high prices. Thus, no upper bound for the price is given. Due to the ongoing demand at high prices, the resource is not fully extracted in finite time, since the rising prices always enable higher returns on sale per unit to comply with the Hotelling rule and to establish a constant present value of the returns on sale. The initial price of the resource is determined as described previously, based on the initial extraction quantity and by the use of the demand function, which is shown in Figure 24. In order to fulfill the efficiency constraint of not leaving any resource unused, the indefinite sum of all extracted quantities has to equal the total stock of the resource $\bar{\bar{R}}$.[165]

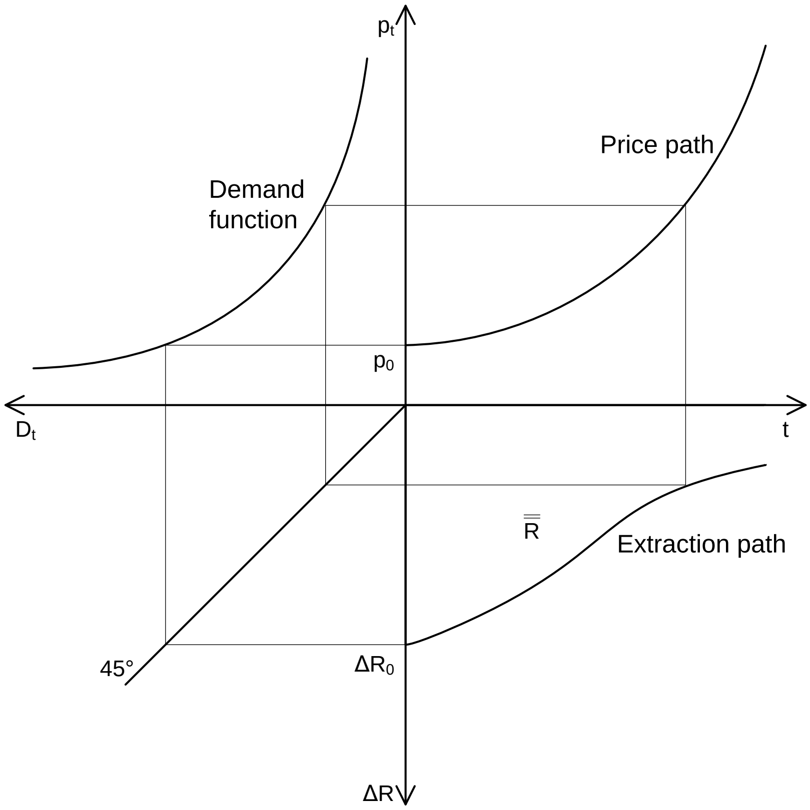


Figure 24: Hotelling price and extraction path for an isoelastic demand function

The illustrated resource extraction paths of Figure 23 and Figure 24 are based on the assumption of a homogenous and a priori known stock of resource. The same situation but with the resource stock distributed in two deposits with different marginal extraction costs is illustrated in Figure 25. This reminds on the situation discussed by Ricardo in the theory of rents on mines in section 4.1.2, but Ricardo's considerations are extended by the exhaustion of the resource, which is claimed due to the efficiency constraint. The marginal costs of extraction are assumed to be different between the resource deposits but constant. In this case it has to be kept in mind that the extraction of a unit of the resource is only reasonable if the unit price at least covers the marginal extraction costs. Assume that the resource deposit A has lower marginal extraction costs than the resource deposit B. Thus, the owner of resource deposit A extracts the resource, if his marginal extraction costs are covered by the price. The initial price p_0^A is determined by the initial extraction quantity and the demand function, as discussed above. However, it is assumed that the price p_0^A is lower than the

---

[165] Wacker, H. and Blank, J. E. (1999): *Ressourcenökonomik: Einführung in die Theorie erschöpfbarer natürlicher Ressourcen,* München, Wien, pp. 26–27.

marginal extraction costs of deposit B. So the resource extraction from deposit B is not cost-effective and no resource is extracted from deposit B. If the resource price equals the marginal extraction costs MEC^B of deposit B, it would be cost-effective to extract resources from the deposit, but resource extraction from deposit B does not start until the resource deposit A is depleted. This is because it is beneficial for the owner of deposit B to leave the resource in situ as long as the price rises according to the price path of the resource in deposit A. This is because the price path of the resource in deposit A is steeper than the actual price path of the resource of deposit B is. Hence, leaving one unit of the resource in situ and extracting this unit later at an increased price is better for the owner of deposit B than extracting one unit and obtaining interest for the sales revenue. Therefore, the owner of the deposit B starts extracting at the time when his opportunity costs, which are the marginal extraction costs MEC^B of deposit B plus the costs of leaving the resource in situ, in other words surrender the returns on interest, are equal to the resource price. Hence, deposit A has to be depleted before the resource in deposit B is extracted. This is illustrated by the intersection of the price paths of the two deposits in Figure 25. After the depletion of deposit A, the price is determined based on the opportunity costs of resource deposit B.[166,167]

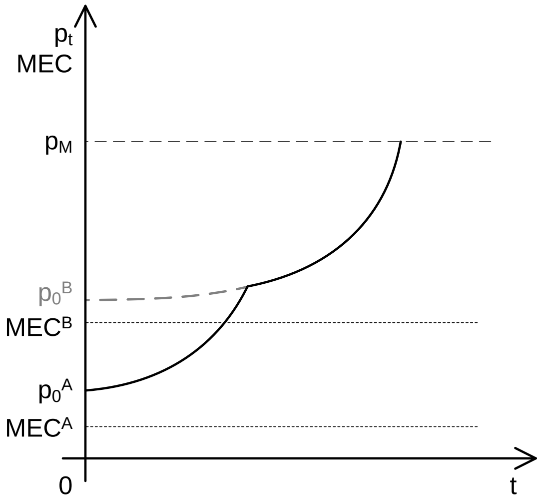


Figure 25: Hotelling price path and different extraction costs

p_0^X … Price at time t=0 for deposit X
MEC^X… Marginal extraction costs for deposit X

---

[166] Endres, A. and Querner, I. (1993): *Die Ökonomie natürlicher Ressourcen: Eine Einführung,* Darmstadt, pp. 48–52.

[167] Wacker, H. and Blank, J. E. (1999): *Ressourcenökonomik: Einführung in die Theorie erschöpfbarer natürlicher Ressourcen,* München, Wien, pp. 29–33.

When considering equal but decreasing marginal extraction costs for all deposits, the price path tendency of the two components of the opportunity costs interfere with each other in the determination of the price path.

Continuously decreasing marginal costs of extraction may be possible due to technological progress that lowers the costs for the extraction of the resource. For the sake of simplicity a constant rate of reduction of extraction costs over time is considered in the following. The sum of the descending marginal extraction costs and the increasing costs of leaving the resource in situ form an U-shaped price path, as shown in for Figure 27.

In the earlier part of the U-shaped price path, the technological progress and the resulting reduction in extraction costs exceed the effect of the increasing shadow value of the resource extraction. This shows that technological progress might lead to decreasing resource prices although the shadow price of the resource steadily inclines.[168]

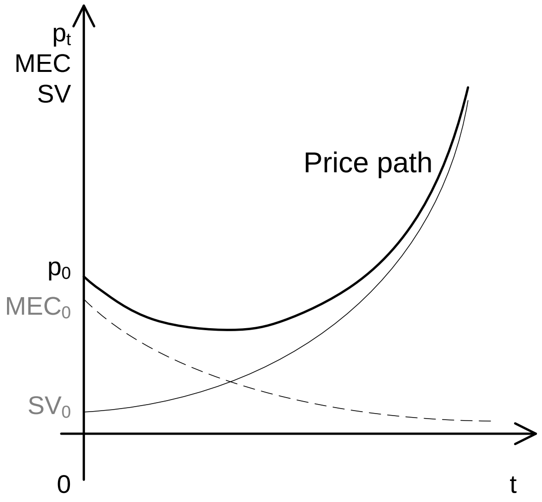


Figure 26: Hotelling price path disclosure of new reserves

SV_0 ... Shadow value at time t=0

As last exemplary case of a price path based on the Hotelling rule the situation of discoveries of new resource deposits over time is examined. For this reason, the constraint of knowing the full size of the stock a priori is relaxed. Moreover, it is more realistic to assume discoveries of new resource deposits. Success in exploration activities is also influenced by technological progress as more advanced equipment may reveal so far undetected resource deposits. The effects of the discovery of new reserves on the Hotelling price path are shown in Figure 27.

---

[168] Wacker, H. and Blank, J. E. (1999): *Ressourcenökonomik: Einführung in die Theorie erschöpfbarer natürlicher Ressourcen,* München, Wien, pp. 40–41.

The initial development of the resource price follows a standard Hotelling path until the first discovery at time t_a. As a consequence of the increased reserves due to the discovery, the initial determination of the extraction quantity and the resulting price path become invalid, because the underlying resource stock increased. Including the new knowledge about the extent of the resource stock, a new price and extraction path is determined. The resulting new initial price p_0^{ta} needs to be lower than the original initial price p_0, as a higher resource stock is linked to a higher initial extraction quantity, which causes a lower initial price if applied to the same demand function. In the case of a linear demand function, the raised resource stock also affects the point of depletion, which is postponed. Every new discovery changes the previous price path in the described way, as illustrated in Figure 27.[169]

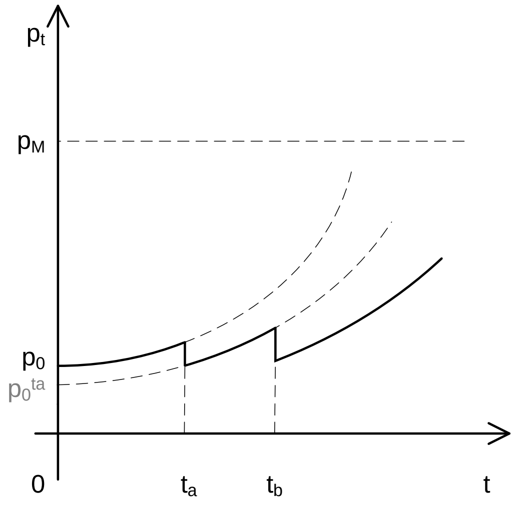


Figure 27: Hotelling price path and the discovery of new reserves

The previous analysis show how non-renewable resources are represented on the market through the price of the resource. The next step is to analyze whether ongoing prosperity is even possible if a finite resource is used in the economy. This issue is discussed in the framework of the previously presented neoclassical economic model.

The Solow-Growth-Model and finite resources

The preceding analyzes based on the Hotelling rule represent a partial analysis of one particular market of a single non-renewable resource. This kind of analyzes does not account for interdependencies of different markets. For example substitution processes, as intensively discussed in chapter 2 and 3, are not included. To broaden the view, another modeling framework is employed. In the following, the Solow-Growth-Model, which is

---

[169] Endres, A. and Querner, I. (1993): *Die Ökonomie natürlicher Ressourcen: Eine Einführung,* Darmstadt, pp. 57–58.

introduced in section 4.1.2, is extended in order to analyze implications of the special features of a finite, non-renewable resource. The substitution among production factors, which is one of the key elements of this neoclassical economic model and the considerations on the efficient extraction of non-renewable resources can be combined to gain deeper insights in the economics of resources.

Furthermore, the Solow-Growth-Model with a finite non-renewable resource is employed to study whether the finiteness of natural resources is compatible with the need of indefinite consumption for an immortal society.

Before introducing a finite resource to the Solow-Growth-Model, it is analyzed how the proposed golden rule capital to maintain the highest sustainable consumption per capita could or should be attained from an initial configuration that differs from the steady state under consideration of intergenerational equity and efficiency matters. This question is of special interest concerning intergenerational equity because the buildup of the golden rule capital stock involves greater savings of all generations before the actual golden rule capital stock is achieved. Therefore, the buildup of capital stock implies sacrifices to all generations before the steady state capital stock is reached. By applying the Rawl’s Maximin criterion, the steady state is only reached when the initial capital meets the golden rule condition, because only a path of constant consumption per capita is rated as desirable. For the utilitarian case, which allows for different consumptions per head in order to obtain the maximum social welfare, the way of approaching the golden rule capital stock is crucial.

Starting from the capital dynamics equation (24) and inserting the steady state output to capital ratio yields an expression for the relative rate of capital growth. In equation (29) the steady state output to capital ratio depends on the difference between the actual ratio of output to capital and the golden rule ratio.

(29)
$$\frac{\Delta k}{k} = s\left(\frac{y}{k} - \frac{y^*}{k^*}\right)$$

The higher the rate of capital growth, the larger is the difference between the actual ratio of output to capital and the golden rule ratio. This can be interpreted as follows. The further away the economy is from the steady state, the higher is the capital growth rate. Furthermore, the capital growth rate is positively related to the savings rate and higher relative savings result in a higher rate of capital growth.

However, this does not mean anything about how much each generation should save respectively what sacrifices are demanded when the savings rate is exogenously given. Based on the utilitarian logic and F. Ramsey’s theory of optimum saving T. Koopmans formulated an approach for a path of optimal saving (=investment) as follows. The optimal investment path is characterized the maximal sustainable utility level, which is derived from the golden rule consumption, the utility of the present consumption and the marginal utility of the current consumption, as described in equation (30).[170]

(30) $$\Delta k = \frac{u(co^*) - u(co)}{u'(co)}$$

$u(co^*)$ … *Utility of the golden rule consumption*
$u(co)$ … *Utility of the actual consumption*
$u'(co)$ … *Marginal utility of the actual consumption*

According to equation (30), the larger the difference between the utility of the actual consumption and the utility of the golden rule consumption co^*, the higher is the net investment Δk. This is similar to the previous statement and says that the further away the actual consumption is from the steady state golden rule consumption the higher is the saving (=investment). Due to the fact that the marginal utility is diminishing, it acts as a counterforce, which lowers the saving if an additional unit of consumption generates a big increase in utility. According to the diminishing marginal utility high marginal utilities concur to low consumption. If a standard utility function for the society is assumed T. Koopmans notes that a low "curvature" of the utility function favors the posterity.[171]

So, it has to be examined if ongoing consumption is at possible when finite natural resources are necessary for production. For this purpose the Solow-Growth-Model is extended by an additional parameter R that represents a finite non-renewable natural resource that is essential for the production process. Thus, the production function is extended as shown in equation (31). Furthermore, it needs to be considered that each extraction decreases the resource stock, which is available in the next period respectively for the use by the subsequent generations. This is represented by the resource dynamics equation (32).

---

[170] Koopmans, T. C. (1967): Intertemporal Distribution and 'Optimal' Aggregate Economic Growth in: *Economic Studies in the Tradition of Irving Fisher,* pp. 114–116.

[171] Koopmans, T. C. (1967): Intertemporal Distribution and 'Optimal' Aggregate Economic Growth in: *Economic Studies in the Tradition of Irving Fisher,* pp. 114–116.

(31) $$Y_t = F(K_t, L_t, R_t, A_t)$$

(32) $$R_{t+1} = R_t - \Delta R_t$$

$R_t \ldots \text{Resource input at time } t$

The first question is whether an indefinite stream of consumption for a generally immortal society is at all feasible with a necessary, finite production factor R. The constraint of essentiality of the natural resource to the production of output means that if the natural resource input is zero, there is also no output. Therefore, it becomes clear that the output per unit of the resource R, which is the productivity of the natural resource, needs to approach infinity to maintain a nonzero output even if the resource input vanishes. This implies that the marginal product of the natural resource is unbound.[172,173]

However, there two forces, in particular capital accumulation and technological change that counteract a decline of output due to decreasing resource inputs, which is inevitable with a finite natural resource and indefinite time.[174] Considering that the capital accumulation is an option to counterfeit decreasing output respectively consumption due to declining resource inputs in the production process, it has to be possible to substitute the production factor resource for another production input, which is capital in the considered case.

To examine the effects of capital accumulation at first no technological change is considered. Additionally, no population growth is assumed for now. Under these assumptions, capital accumulation can offset the decreasing resource inputs if the elasticity of output with respect to capital is higher than the elasticity of output with respect to the natural resource. This means that capital is more productive than the natural resource respectively capital is a "more important" production factor than the resource. Therefore, the declining resource inputs can be compensated by capital accumulation, which implies a declining stock of the natural resource and an increase in the capital stock over time. Hence, it is possible to achieve at least a constant consumption stream with a necessary, finite resource and a constant savings rate.[175,176]

---

[172] Solow, R. M. (1974): Intergenerational Equity and Exhaustible Resources, in: The Review of Economic Studies, Vol. 41, pp. 29–45.

[173] Dasgupta, P./Heal, G. (1974): The Optimal Depletion of Exhaustible Resources, in: The Review of Economic Studies, Vol. 41, pp. 3–28.

[174] Stiglitz, J. (1974): Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths, in: The Review of Economic Studies, Vol. 41, pp. 123–137.

[175] Solow, R. M. (1974): Intergenerational Equity and Exhaustible Resources, in: The Review of Economic Studies, Vol. 41, pp. 29–45.

[176] Stiglitz, J. (1974): Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths, in: The Review of Economic Studies, Vol. 41, pp. 123–137.

Taking population growth into account complicates the situation as the output needs to rise to achieve a constant per capita consumption. The analyzed situation without a finite natural resource showed that there exists a maximum maintainable consumption stream under the assumption of a constant population growth, even with no technological progress. To attain a constant per capita consumption in an economy with an essential, finite resource and with a exponentially growing population, technological progress is needed. Moreover, the technological progress has to be resource augmenting, which means that the resource input is reduced for one unit of output and all other input factors remain constant. This is different to the previously assumed labor augmenting technological progress in section 4.1.2. A positive rate of population growth requires that the resource augmenting technological change needs to be at least equal to the rate of population growth. Thus, technological progress with respect to the natural resource is necessary to offset a growing population in order to maintain a constant per capita consumption.[177]

Hartwick rule

Following the afore mentioned assumptions, John M. Hartwick developed a more concrete suggestion for the substitution among the production factors capital and natural resource. Based on a model without technological progress and population growth, he specified a criterion for maintaining a constant consumption in the presence of an essential but finite non-renewable natural resource. A constant consumption is possible if the economic rents on the extraction of the non-renewable natural resource R, which do comply to the intergenerational efficiency constraints, are invested entirely in the capital stock K, which is assumed not to depreciate. Therefore, if the resource prices change efficiently according to the Hotelling rule, the society may consume the remainder of the output and the consumption will just stay constant. So, the capital accumulation due to the investment of the economic rent on the extraction of the non-renewable resource offsets the decrease in the input of exactly this resource to the production. This investment rule, also known as Hartwick rule, means that the total capital stock remains constant as the non-renewable capital stock is transformed into a reproducible capital stock, for instance machines, buildings, etc.. In this sense, the productive capital stock as the sum of the initial stock of the non-renewable resource plus the initial capital stock does not deplete. Here, the stock of the non-renewable resource is seen as compatible to capital, as already indicated by the Hotelling rule since the

---

[177] Stiglitz, J. (1974): Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths, in: The Review of Economic Studies, Vol. 41, pp. 123–137.

capital increase on the resource deposit equals the rate of return on the capital market respectively the interest rate.[178,179]

If depreciation of the capital stock is assumed, the investment that compensates the depreciation has to be considered separately as the Hartwick rule of investment does not include any savings for depreciation. Thus, the net investment, which is the excess of the entire investment over the capital deprecation, has to equal the economic resource rentals. All these notions do not include technological progress and population growth. However, the Hartwick rule does not change anything on the above stated condition that technological progress is needed to offset exponential population growth and also to overcome capital depreciation. In comparison to the model without a non-renewable resource, technological change was not required for achieving a constant per capita consumption. Technological progress is less effective if an essential non-renewable resource is used in production.[180]

Population growth is sometimes excluded from the analysis simply because of the surface area restriction of the earth, which does not allow exponential population growth over indefinite time. Considering that the time for resource extraction process is large enough, the assumption of exponential population growth is discarded.[181] Another approach to relax the implications of population growth is to change the assumption on the characteristics of population increase from a geometrical to a quasi-arithmetic growth, according to equation (33).

$$L_t = L_0(1 + \Gamma t)^{\xi} \tag{33}$$

L_t ... *Population at time t*
L_0 ... *Initial Population*
Γ, ξ ... *Positive constants*

When considering population growth, it has to be determined how much is needed to save in excess to the requirements of the Hartwick rule to achieve constant per capita consumption. The additional savings need to be again a certain constant fraction of the output, whereat this

---

[178] Hartwick, J. (1977): Intergenerational Equity and the Investing of Rents from Exhaustible Resources, in: The American Economic Review, Vol. 67, Issue 5, pp. .

[179] Solow, R. M. (1986): On the Intergenerational Allocation of Natural Resources, in: The Scandinavian Journal of Economics, Vol. 88, Issue 1, pp. 141–149.

[180] Solow, R. M. (1986): On the Intergenerational Allocation of Natural Resources, in: The Scandinavian Journal of Economics, Vol. 88, Issue 1, pp. 141–149.

[181] Solow, R. M. (1974): Intergenerational Equity and Exhaustible Resources, in: The Review of Economic Studies, Vol. 41, pp. 29–45.

constant savings rate is dependent on the quasi-arithmetic population growth. The additional savings might also be used to achieve output and consumption growth.[182]

All the presented notions and constraints for an at least non-declining consumption stream if an essential non-renewable natural resource is considered rely on the assumption that sufficient substitutability among production inputs exist. The topic of substitutability of natural resources is often discussed under the term of sustainability. A review among different approaches of substitutability of natural capital is given in the following section.

4.2.3 Sustainability and Capital Stock

Since the term sustainability is widely used in different subjects today, a famous and broadly accepted clarification of sustainability acts as introduction into the topic.

“Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs”[183]

With this explanation of sustainability as a part of a report of the United Nations World Commission on Environment and Development entitled “Our common future” the topic of sustainability was established in the scientific area. This report is widely known as Brundtland report, named after the chairperson of the commission. When comparing this definition with the previously introduced concepts of intergenerational efficiency and intergenerational equity sustainability has to be considered as guidance for intergenerational equity. Intergenerational efficiency is seen as a necessary precondition for sustainability by many economists.[184]

When thinking that the basic task of an economy is to meet the needs of the society, it has to be considered which resources the economy respectively society has available for doing that. This is the link to the previous section, which discusses the different input factors in economic production process. Apart from labor, the input factors are usually distinguished between man-made capital and natural capital, which conform to the production factors capital K and resource R in the previously modeled economy. The conclusions drawn from this model in section 4.2.2 are based on the assumption of sufficient substitutability between

---

[182] Hartwick, J. (2009): What Would Solow Say?, in: Journal of Natural Resources Policy Research, Vol. 1, Issue 1, pp. 91–96.

[183] World Commission on Environment and Development and Brundtland, G. H. (1987): Our Common Future. Online, p. 24, http://www.un.org/esa/sustdev/publications/publications.htm, 01.06.11.

[184] Farmer, K./Bednar-Friedl, B. (2010): Intertemporal Resource Economics: An Introduction to the Overlapping Generations Approach, http://dx.doi.org/10.1007/978-3-642-13229-2, January 2011.

these kinds of capital. Under the term of sustainability, there are two opposing paradigms, which deal with the question of substitutability of natural capital.[185]

Weak Sustainability

The concept of weak sustainability assumes that natural capital can be largely substituted by man-made capital. Natural resources are generally handled as economic commodities that facilitate economic respectively human development. Hence, the human use of natural resources is central in this concept. Therefore, this is a mainly anthropocentric perspective. Based on the notion of holding the entire productive capital stock constant, the usage of natural resources requires an increase in man-made capital.[186]

Consequently, the current generation does not owe a share of the deposit of a certain mineral or more general of a certain natural resource to the following generations, but it owes production capacity or eventually the possibility to meet a certain standard of living. So, the generations are at liberty to pass the productive capacity as natural resources, man-made capital or technology and knowledge. The form of the capital is not the most important issue but probably the question which form can be passed most efficiently is crucial.[187]

A more pessimistic view on the substitutability of natural capital is proposed by the paradigm of strong sustainability. This implies that the previously presented conditions or possibilities for ongoing prosperity are seen more critically by supporters of the Strong Sustainability.

Strong Sustainability

The followers of the concept of strong sustainability assume a general complementarily of natural capital and man-made capital and do not consider substitutability of natural capital by man-made capital as a real option. They refer to the finiteness of natural resource, the non-substitutable functions of nature and the uncertainty as well as the irreversibility of the impacts of changes on ecosystems as reason for their attitude. As a consequence, ecological concerns are prioritized to economical interests of individuals.[188]

The assumption of no substitutability of natural capital in general implies the requirement of constant natural capital. Hence, both types of capital have to be separately kept constant for a non-decreasing social welfare. This assumption also results in the requirement that no non-renewable resource is used. Only renewable resources ought to be used within their

---

[185] Grunwald, A. and Kopfmüller, J. (2006): *Nachhaltigkeit,* 1st ed., s.l, p. 37.

[186] Voß, A. and Hirschberg, S. (1999): Nachhaltigkeit und Energie: Anforderungen der Umwelt, p. 2, http://elib.uni-stuttgart.de/opus/volltexte/1999/460, 01.06.11.

[187] Solow, R. M. (1986): On the Intergenerational Allocation of Natural Resources, in: The Scandinavian Journal of Economics, Vol. 88, Issue 1, pp. 141–149.

[188] Voß, A. and Hirschberg, S. (1999): Nachhaltigkeit und Energie: Anforderungen der Umwelt, pp. 2–3, http://elib.uni-stuttgart.de/opus/volltexte/1999/460, 01.06.11.

regeneration capabilities. This might not be very realistic since also the usage of renewable resources is bound to the utilization of non-renewable resources. For example, at least tools like an axe are needed to cut down a tree. But also the assumption of total substitutability of natural capital is unrealistic since nature provides basic life-supporting functions. [189]

However, productive capital assets and technology seem to be much better to provide substitutes for natural resource commodities than for natural resource amenities, which include the mentioned life-support functions.[190]

The concepts of weak and strong sustainability can be seen as extreme positions, as they are in their radical interpretation neither practicable nor realistic. Accordingly, a moderate approach somewhere in the middle between these two concepts might be best. This means a limited substitutability between natural capital and man-made capital is permitted if critical natural capital is preserved. Critical are in particular functions of the nature, which are essential for human life like the breathing air, drinking water and top soils including the underlying natural cycles. So, the inhomogeneity of natural capital has to be considered and substitutability needs to be clarified for each single natural functions. Often limits for the substitutability of each natural resource are considered. However, the total productive capital stock has to be kept constant for a sustainable development. This approach is generally known under the term sensible sustainability.[191,192]

The discussion on the substitutability of natural resources by man-man reproducible capital constitutes the end of the treatise on resource economics within this work. The results obtained within the framework of resource economics are combined with the result of the analysis of the energy system of chapter 3 in order to derive conclusions for the energy sector and in particular for the electric power industry in the next chapter.

---

[189] Voß, A. and Hirschberg, S. (1999): Nachhaltigkeit und Energie: Anforderungen der Umwelt, pp. 2–3, http://elib.uni-stuttgart.de/opus/volltexte/1999/460, 01.06.11.

[190] Krautkraemer, J. A. (2005): Economics of Scaricity: The State of the Debate in: *Scarcity and growth revisited: Natural resources and the environment in the new millennium*, eds. Ralph David Simpson, Michael A. Toman and Robert U. Ayres, Washington, DC, pp. 59–62.

[191] Grunwald, A. and Kopfmüller, J. (2006): *Nachhaltigkeit,* 1st ed., s.l, pp. 38–39.

[192] Fichter, K. et al. (2006): Nachhaltigkeitskonzepte für Innovationsprozesse, pp. 5–6, http://dabei.erfinderforschung.de/fileadmin/user_upload/Bildmaterial/Beucker_Bierter_Fichter_Noack_Springer_2006_a.pdf, 01.06.11.

5 Conclusions for the Electricity Sector

The intention of this chapter is to derive conclusions for the energy respectively for the electricity sector from the insights of the previous chapters. The outcomes of the presented analyses of the energy system of chapter 3 are discussed in combination with the considerations on intergenerational issues of chapter 4. As a follow-up to the deductions of section 3.3 this chapter presents two extended analyses in order to back up the reasoning. The following introduction recapitulates some of the key characteristics of the energy system.

The energy system is characterized by long-term processes. Changes in the energy system are long-time developments. This property of the energy system has not changed since C. Marchetti and N. Nakićenović stated that an energy source needs about 100 years to become major, which means to increase the market share from 1% to 50%.[193] In contrast to the general feeling that the world is speeding up, the analyses of chapter 3 demonstrate that this is not true for the energy system since the average rate of change of the market share of the primary energy sources rather decreased in the analyzed time period after 1950. The fractions of the different energy sources of the primary energy market change more slowly. Accordingly, the long-time character of changes in the energy system is still applicable.

The 1970s with two significant price increases for the most important energy source at that time, petroleum, seem to typify a breakline for the evolution of the energy system as the evolutionary patterns of several energy sources changed in this decade. Coal was subject to a particular conspicuous break in its evolutionary trend in the 1970s. The previous decreasing trend in coal's market share changed to a more or less constant fraction of the primary energy market for coal. The analyses revealed that coal is relatively sensitive to market share peaks of other energy sources. The peak of the market share of an energy source signifies that the growing phase for this energy source ends and the market share decreases subsequently. Consequently, other energy sources take over the market shares. One would assume as C. Marchetti proposed that a new and emerging technology would substitute the old energy technology.[194] Nevertheless, the peaks of energy sources resulted

---

[193] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 7, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

[194].Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

commonly in changed trends for coal's market share, which is the oldest energy technology with a notable market share for the considered time period. The analyses show that coal takes over the market shares of other energy sources after they peaked. Based on this finding, coal is considered to be a kind of "backup" energy source, which fills market shares that cannot be attained by another energy source any more. It seems that this effect also occurred for nuclear energy, which is the newest energy source that achieved a significant market share in the energy system. Hence, a pile out of nuclear energy by coal on global level, which was already considered as an unexpected option by C. Marchetti in 1978, might really happen.[195]

In section 3.3 the situation that coal is almost entirely transformed into another form of energy before provided to the end users is identified as a possible explanation for the intense usage of coal, although coal has drawbacks in comparison to other energy sources since it is less convenient, more polluting and has a lower energy density compared to other energy sources. Overall, the indirect usage of primary energy sources, which means that the energy form that is provided to end users does not correspond to the physical condition of the original energy source, is increasing. On the basis of this result, it is examined in the following, which energy form is provided to the end user and how the energy form that is finally consumed by the end user changes over time.

For this analysis the portion of the major primary energy sources, which is used in its original physical condition is separated from the portion, which is transformed into another form of energy before provided to the end user. So, the portion of coal, which is used in its solid form by the end user, accounts for coal and the portion of coal, which is used to generate electric power, is assigned to electricity. The considered primary energy sources petroleum, coal, natural gas, renewable energy sources and nuclear energy are the same as in the previous analyses. Besides electricity thermal energy, which originates from combined heat and power (CHP) plants and is provided similar to district heating to the process of final consumption to the end use facility, is compared to the usage of the stated primary energy sources in their original physical condition, which is in this work also denoted as direct use. Since the civil use of nuclear energy is practically entirely linked to electric power generation, there is no direct use component of nuclear energy.

In the following, the examination of the energy form of final consumption is performed for the US-American energy market. The US-American energy market is employed as an example since a complete and detailed data-set to conduct this analysis is readily available.

---

[195] Marchetti, C. and Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, p. 25, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

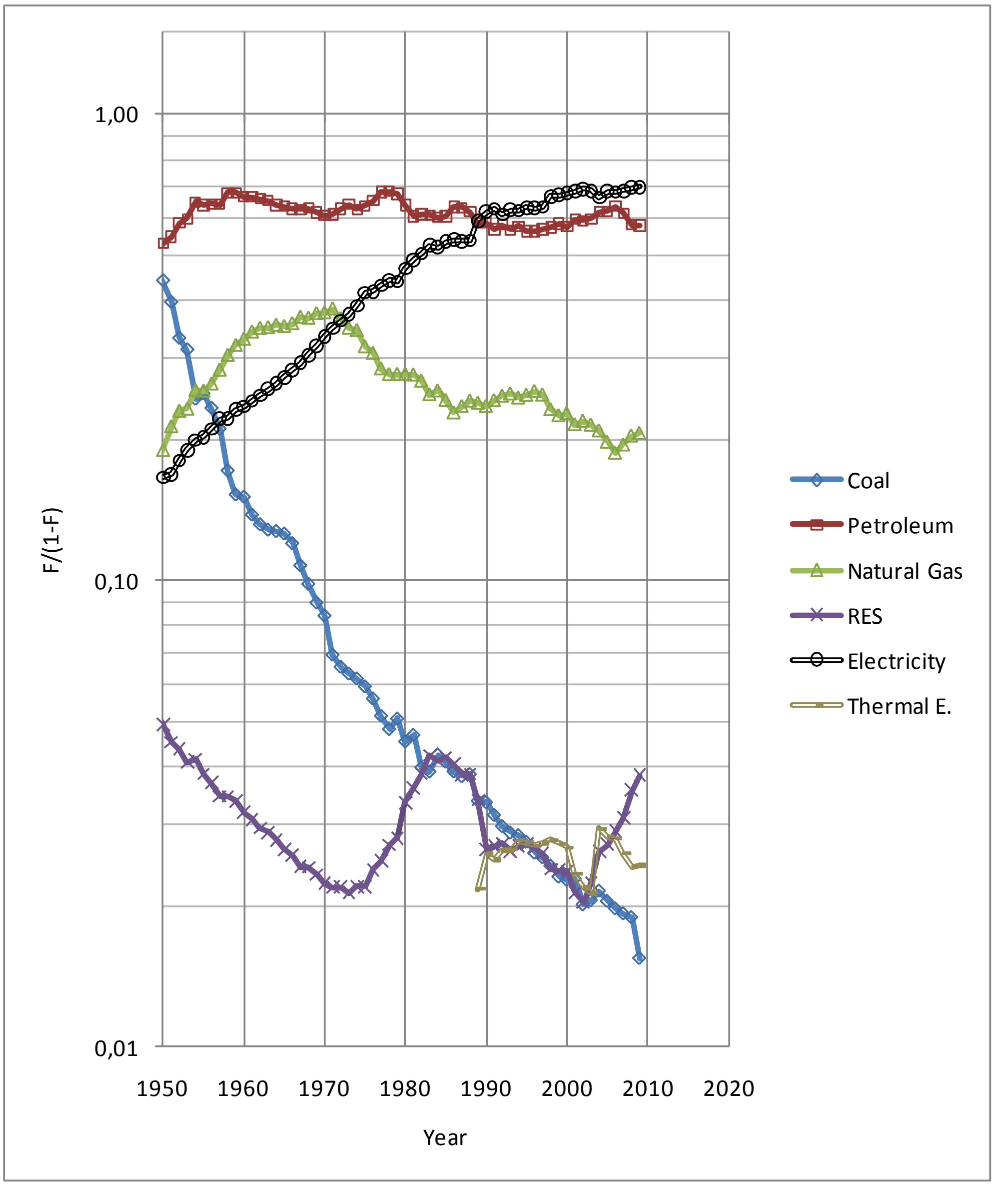


Figure 28: Primary energy sources and electricity USA 1950-2009

Data source: U.S. Energy Information Administration : *Annual Energy Review 2009,* Table 8.4, Table 8.5, Table 8.6, Table 10.1, Table 13.3, Table 13.4, Table 13.5, http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.

For Figure 28 thin double lines stand for the collective portion of all primary energy sources that is used to produce the specified secondary energy form and the thick solid lines denote direct use of primary energy sources.

Nevertheless, the data source does not contain data for CHP plants before 1989. As this would result in a shift of the curves, the collective portion of all primary energy sources, which is used for the production of the thermal energy output of CHP plants is plotted just for information. Actually, the portion for the thermal output of the CHP plants is included in the data for direct use.

The data source contains another inconsistency. For the data after 1989 electric power generation of electric utilities, independent power producers, commercial plants and industrial plants is included in electricity. Prior to 1989 in general only electricity generation of electric utilities is covered by the data for electricity.[196]

The temporal development of the direct use of the primary energy sources in combination with the evolution of energy input to electric power generation is shown in Figure 28. The primary energy input to electricity generation relative to the direct use of the primary energy sources in total has been rising continuously since 1950, which means that the sum of those portions of the primary energy sources, which are used for electric power generation, increased. This means that electricity as energy form became more and more important. According to Figure 28 the entire primary energy input to electricity production exceeds the quantity of energy that is consumed in the original physical condition of petroleum as liquid fuel since 1990.

When comparing the development of the US-American consumption of primary energy sources in total, which is shown in Figure 12, with the course of the primary energy sources in Figure 28, a significant difference in the development paths of coal is identified. This demonstrates the importance of coal for the US-American electricity production since the portion of coal that is used for electricity generation increased notably and the portion of coal which is used directly in its solid form by the end user, declined. The portion of natural gas that is used for electricity generation increased especially the repeal of the Powerplant and Industrial Fuel Use Act in 1987. This development is recognized by comparing the course of natural gas in Figure 12 with its course in Figure 28. When comparing the course of petroleum in these two figures only minor differences can be found. Thus, only a small portion of petroleum flows into electricity generation, as the biggest part of petroleum is used as liquid fuel for transportation purposes.[197]

In the case of renewable energy sources (RES) the previous interpretation of the term direct use does not perfectly fit as there are various renewable energy sources with different

---

[196] U.S. Energy Information Administration : Annual Energy Review 2009, DOE/EIA-0384(2009), Table 8.4, http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.

[197] U.S. Energy Information Administration : Annual Energy Review 2009, DOE/EIA-0384(2009), Table 5.13, http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.

physical properties combined for the aggregate quantity of RES. In Figure 28 the entire portion of renewable energy sources, which is not used to generate electricity, applies to the quantity RES. For example also biofuels, which are not provided in the physical condition of the original source to the end user, are included in direct use of RES. Therefore, it has to be noted that for this analysis RES are determined differently compared to the other analysis since here renewable energy sources, which are not used for electricity generation, are included as well.

The downward trend of RES prior to 1970 was a result of the higher growth of hydro power compared to biomass in this period. In the 1970s the production of biomass for combustion purposes increased significantly, which caused the rising trend for RES. After 1980 new renewable sources like wind, solar and geothermal energy are utilized. They contribute noticeable shares to the total consumption of RES, as shown in Figure 29. Therefore, the derivation of connections between changes in one renewable energy source and the aggregate curve is not that easy. The downward trend of RES after the mid 1980s in Figure 28 suggests that more renewable energy sources for electricity generation are taped than for other purposes. The incline of the curve for RES after the year 2000 in Figure 28 is a result of a considerable increase of biofuel utilization. Despite this increase, more than 50% of the total utilized renewable energy sources are used for electricity generation in the USA in 2009.

Overall electricity is one of the most important energy forms for final consumption and the portion of primary energy sources that is employed to generate electricity is increasing. On the one hand fossil fuels are increasingly employed for the generation for electric power and on the other hand a large share of renewable energy sources are also utilized for electricity generation.

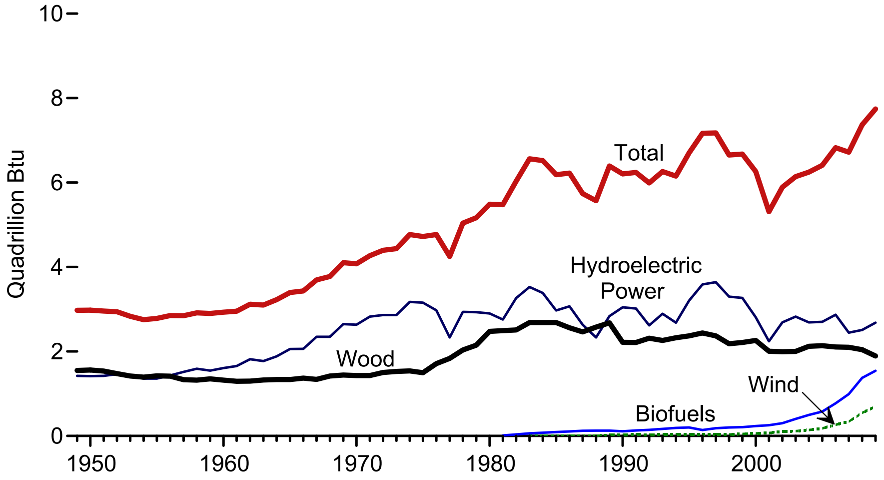


Figure 29: Renewable energy total consumption and major sources USA 1949-2009

Source: U.S. Energy Information Administration : *Annual Energy Review 2009,* p. 282, http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.

In Figure 29 the temporal development of the absolute values of the most important renewable energy sources in the US-American energy system is illustrated. The example of the US-American energy system already shows that renewable energy sources other than hydroelectric power gain importance, but hydroelectric power is still the most important renewable energy source. To accommodate this changed situation and to examine if there are differences in the growth rates for the established hydro power and the new emerging renewable energy technologies, as Figure 29 already anticipates, the development of electricity generation of non-hydro power renewable energy sources on world level is reported separately from the production from hydro power in Figure 30.

The graphical representation of the energy system in Figure 30 is a more detailed version of the data presented in Figure 8. Consequently the compilation of the data follows the constraints that are reported in section 3.1.

Besides the market shares of the primary energy sources coal, petroleum, natural gas, hydro power, nuclear energy and other renewable energy sources Figure 30 includes also a trend line for the market share of hydroelectric power as well as a trend line for the development of the share of the other RES for the time after the year 2000.

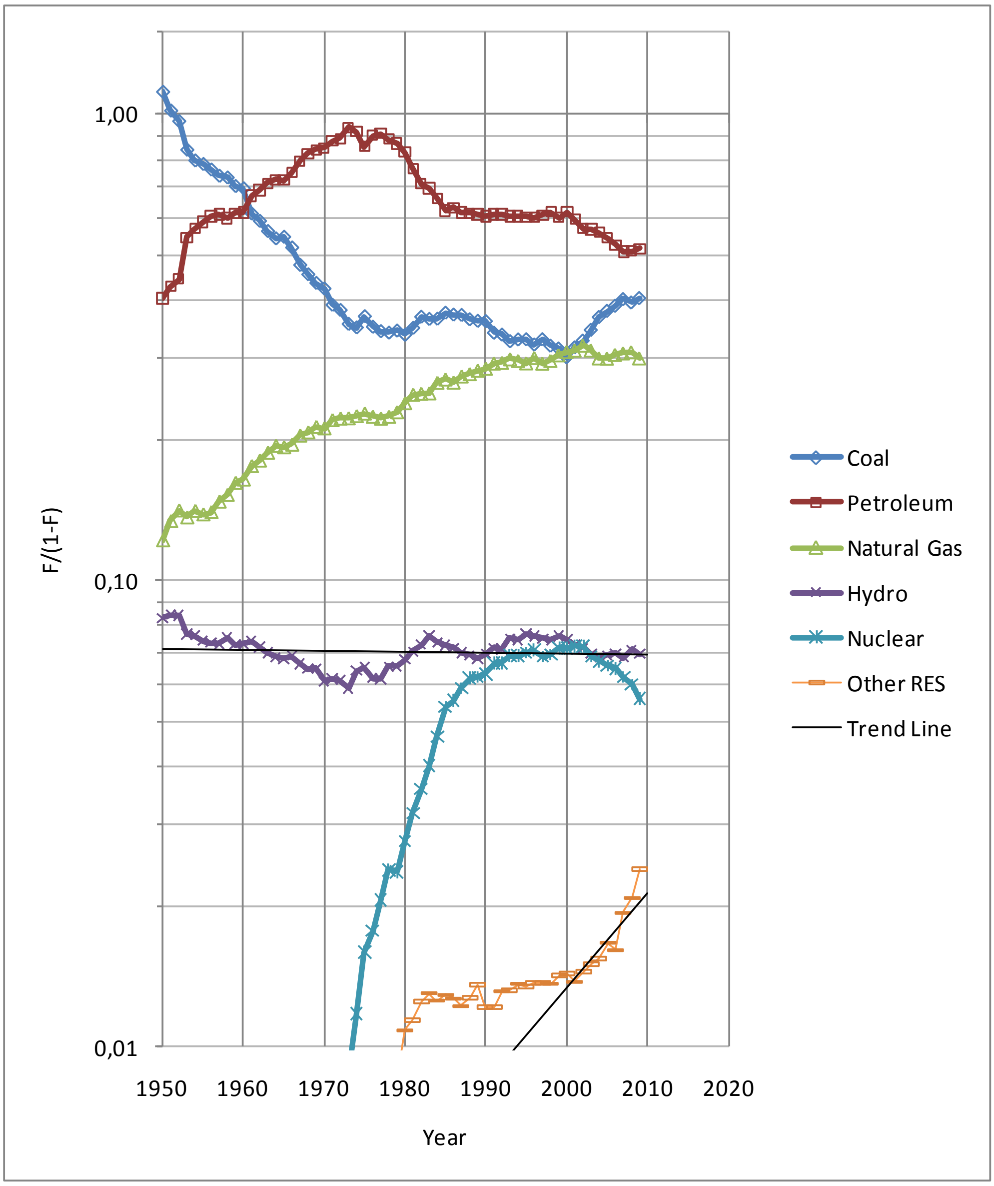


Figure 30: World's energy market and non-hydro renewable energy sources 1950-2009

Data Source 1950-1969: Coal, Crude oil, Natural Gas	Mitchell, B. R. (1993): *International historical statistics: Europe: 1750 - 1988,* 3rd ed., New York, N.Y, pp. 360–380. Mitchell, B. R. (1983): *The Americas and Australasia,* London, pp. 360–380. Mitchell, B. R. (1998): *International historical statistics: Africa, Asia & Oceania, 1750 - 1993,* 3rd ed., London, pp. 360–380, http://www.loc.gov/catdir/description/hol051/00552129.html
Data Source 1950-1969: Hydro Power	Nakićenović, N. (12/1979): *Software Package for the Logistic Substitution Model,* Laxenburg, http://www.iiasa.ac.at/Publications/Documents/RR-79-012.pdf, February 2010.
Data Source 1970-2007	U.S. Energy Information Administration : *Annual Energy Review 2009,*pp. Table 11.1, http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.
Data Source 2008-2009	BP p.l.c. (2010): BP Statistical Review of World Energy June 2010, http://www.bp.com/statisticalreview, February 2011.

Table 1: Data sources for Figure 30

According to Figure 30, the market share of hydro power is almost constant in the time period from 1950 to present, although an approximately six fold absolute increase of the energy production from hydro-electric power is observed in this time frame. So a considerable absolute increase just managed to hold the fraction of hydroelectric power on the global primary energy market constant. In contrary, a remarkable increasing trend for the energy production from non-hydroelectric power renewable energy sources starting around the year 2000 is cognizable. This incline in market share is similar to the growth of the share of nuclear energy in the 1970s, which was followed by a remarkable doubling of the market share in the following decade. Similar to nuclear energy the considered renewable energy sources are used to generate electricity. Though, an energy distribution technology is readily available.

Due to the increasing portion of fossil fuels, which flow into the production of electricity and the large share of renewable energy sources that are utilized through electricity, it is assumed that the importance of electricity increases further. Also developments concerning the consumption process like electric mobility support this assumption. Although the energy distribution technology for electricity is already available, an increased use of electric power requires upgrades and extensions of the electricity infrastructure due to capacity limitations and therefore major investments in infrastructure. Since this energy infrastructure consists of long-living assets and due to the fact that the current energy system heavily relies on exhaustible resources, intergenerational issues need to be considered. In the following considerations, intergenerational issues are discussed based on the scientific insights of chapter 4.

In general, energy resources that are directly related to flow resources like solar energy are less problematic in relation to intergenerational questions. Hence, natural cycles like the water and the wind cycle, which are driven by solar energy, are covered by this notion. Certainly, fossil fuels are principally also based on solar energy, but only indirectly. Therefore, fossil fuels do not apply to this notion since their regeneration period is not relevant for the human scale. In contrary biomass is directly related to solar energy and is covered by this notion, as the regeneration period for biomass is significant for human time spans.

As in chapter 4 in the framework of the Solow-Growth-Model derived, an at least constant consumption over indefinite generations is also possible if exhaustible resources are essential for the economy but offer substitution possibilities. The Hartwick rule defines the preconditions for a constant consumption path in the presence of an essential non-renewable resource as follows.

To achieve a constant consumption path, the economic rent on the extraction of the essential non-renewable natural resource is invested entirely in man-made capital. The resource extraction needs to be done intergenerationally efficient, as described in section 4.2.1. Though, the economic rent develops according to the Hotelling rule. J. Hartwick formulated this rule under the assumptions of no population growth, no technological progress and no capital depreciation. In the case of population growth savings in addition to the economic rents on the exhaustion of the essential non-renewable resource allow a constant per capita consumption if the population does not grow too rapidly, as discussed in section 4.2.2. If depreciation of man-made capital is additionally considered, technological progress is needed to achieve a constant per capita consumption stream. Therefore, to achieve an at least constant consumption for indefinite generations if an essential non-renewable resource is considered for the economy, technological progress is needed to overcome the effects of exponential population growth or depreciation of capital in combination with population growth.

It is assumed, that the importance of energy for the society is not decreasing in the future, since the previous decades and maybe especially the 1970s demonstrated the sensitivity of the economic system on energy issues. Furthermore, the energy consumption increased continuously, which is interpreted as an indication that the significance of energy for the society has rather increased than decreased. Due to the enduring importance of energy for the society, the claim to invest the economic rents on the extraction of exhaustible energy resources according to the Hartwick rule in energy related capital stock seems reasonable since the reduction of energy resources calls for investments in energy infrastructure to meet the future demands if energy holds its key position for society.

By following the Hartwick rule, the entire productive capital stock, which consists of natural capital and man-made capital, persists constant. In this situation the consumption can be interpreted as interest on the productive capital stock.[198] Correspondingly, a raise of the consumption level requires a higher capital stock. To achieve an increased capital stock savings in excess to the economic rents on resource extraction are needed. Whether these additional savings are intergenerational desirable, needs to be clarified with respect to ethical considerations and the concepts of intergenerational equity.

With regard to the efficiency criterion of Kaldor-Hicks a better state can be achieved, if compensation transfers from the beneficiaries to the disadvantaged are employed to make nobody worse off but at least one better off compared to the previous state. In intergenerational terms this may be interpreted as follows. If one generation uses a finite

---

[198] Solow, R. M. (1986): On the Intergenerational Allocation of Natural Resources, in: The Scandinavian Journal of Economics, Vol. 88, Issue 1, pp. 141–149.

resource and therewith reduces the consumption possibilities of subsequent generations, compensation transfers are required to attain efficiency according to the Kaldor-Hicks criterion. Therefore, the generation that gains additional utility from the usage of exhaustible resources needs to provide substitution possibilities to the successors. Thus the generation that uses, for example, fossil fuels as energy source is requested to provide alternatives for the following generations in order that their energy consumption possibilities are not impaired. Consequentially, this implies investments in the energy sector to make alternative energy sources accessible.

As stated before, energy related investments in energy sources that are directly related to a flow resource like solar energy are least problematic in terms of intergenerational issues, since flow resources have the characteristic that their usage now does not affect the future usage.

Overall it can be said that in consideration of intergenerational issues, investments in the energy system respectively in energy related capital stock are required, since currently exhaustible resources are the main primary energy sources.

A key role here plays electricity because the portion of the primary energy sources that is used to generate electricity continuously increased in the past and is currently relatively high, which was assessed on the example of the US-American energy system. The various options to generate electricity with different primary energy sources are one reason for the major role of electric power for energy consumption. Electricity is also important for the utilization of renewable energy sources, which are favorable in intergenerational terms since they are related to flow resources.

A review of these conclusions and the other key results of this work is given in next chapter.

6 Summary

In the following, the key results of this work are described in a brief manner to recapitulate the contents of this work.

The examination of the energy system as a market with different technologies, which are competing for market shares, based on the Primary Energy Substitution Model points out that change processes in the energy system have definitely a long-time character. The growth of major energy sources from market entry to 50% market share is a long-time process and takes about 100 years. The change processes in the energy system cannot be considered to be long-time stable since discontinuities in the development like in the 1970s may occur. The 1970s seem to constitute a breakline in the evolution of the energy system. In this decade almost simultaneously, the market share of petroleum peaked, coal's fraction of the primary energy market left its decreasing path and the market share of natural gas changed the growth rate.

Based on a common pattern of the change processes in the energy system after 1950, coal is assumed to be a kind of “backup” energy source. The recent changes in the global energy system with inclining market share for coal and a decrease of the fraction of nuclear energy may be interpreted as a pile out of nuclear energy by coal as C. Marchetti already considered earlier as an option.

In contrast to C. Marchetti's opinion that the energy system's internal dynamics cannot be significantly changed, external influence on the energy system has to be supposed since consequences of major decisions are cognized. Moreover, the analyses provide no indications that the total availability of a primary energy source has significant influence on the actual development path.

The most important energy sources in all analyzed energy systems are fossil fuels. Since only a finite stock of these exhaustible resources is available for all human generations, intergenerational issues need to be considered. The portion of fossil fuels that is transformed into another energy form before delivered to the end user increases. Electric power gains importance as energy form of final consumption since the portion of fossil fuels that is employed to generate electricity increases and a lot of renewable energy sources are made accessible for the end user through electricity.

The total global market share of renewable energy source related to electricity generation increases slightly, whereas non-hydro RES experience a high growth rate in recent years. Generally, renewable energy sources are directly related to flow resources like solar energy, which are less problematic concerning intergenerational issues since today's usage of a flow resource does not have negative influences on the consumption possibilities of future generations.

In the case of usage of non-renewable resources, the Hartwick rule theoretically suggests investing the entire economic rent on the extraction of non-renewable resources in man-made capital in order to enable a constant consumption stream over time. As a precondition the extraction has to be performed optimally according to the efficiency constraints, in particular conform to the Hotelling rule.

In consideration of the efficiency criterion of Kaldor-Hicks the present generation is required to compensate future generations if currently a higher utility is attained through the usage of exhaustible resources. To compensate the successors for reduced energy consumption possibilities, alternative energy sources need to be made accessible.

If it is assumed that the importance of energy for the society does not decline in the future, the Hartwick rule based investments of the economic rents on the extraction of exhaustible energy resources should also be invested in energy related capital stock to be able to meet future energy needs.

To end this summary a condensed overview of the results obtained in this work is provided in list on the next page.

Key results

- The energy system is characterized by long-time change processes.
- Long-time stability of change processes cannot be supposed.
- Discontinuities in the development may occur like in the 1970s.
- The 1970s seem to constitute a breakline for the evolution of the energy system.
- Significantly, coal's market share does not decrease as before 1970.
- Coal is assumed to be a kind of "backup" energy source.
- A pile out of nuclear energy by coal seems to be under way recently.
- Fossil fuels dominate the current energy system.
- Only a finite stock of fossil fuels is available for all generations.
- Indirect use of fossil fuels increases.
- Electricity gains importance as energy form.
- Renewable energy sources are made accessible through electric power.
- Market share of renewable energy sources increases slightly on world level.
- Renewable energy sources are in general directly related to flow resources, which are less problematic in terms of intergenerational issues.
- Economic rents on the optimal extraction of exhaustible energy resources need to be invested entirely in man-made capital, to secure a constant consumption stream for subsequent generations, according to the Hartwick rule.
- If energy is assumed to be important for the society also in the future, it seems reasonable to invest the economic rents form the extraction of energy resource in energy related capital stock.
- According to the Kaldor-Hicks efficiency criterion investments in energy related capital stock should be promoted to compensate future generations for present utility gains due to the usage or exhaustible resources.

List of Figures

Figure 1: Sample logistic growth curve 10
Figure 2: Transformed logistic curve with semilog y-axes 10
Figure 3: Historical evolution of the world primary energy mix 14
Figure 4: Historical evolution of the world primary energy mix excluding wood 17
Figure 5: Historical Trends in Energy Substitution on world level 1985 20
Figure 6: Global Primary Energy Substitution by V. Smil 2000 21
Figure 7: Historical energy trends for the world by T. Devezas 2008 23
Figure 8: Primary energy substitution global 1950-2009 28
Figure 9: Domestic energy production and primary energy substitution OECD Europe 1950 - 2008 39
Figure 10: Energy consumption and primary energy substitution OECD Europe 1959-2008 40
Figure 11: Domestic energy production and primary energy substitution USA 1950 - 2009 43
Figure 12: Energy consumption and primary energy substitution USA 1950 - 2009 44
Figure 13: Domestic energy production and primary energy substitution China 1952-2008 47
Figure 14: Energy consumption and primary energy substitution China 1952-2008 48
Figure 15: Indirect use of fossil fuels USA 1950-2009 55
Figure 16: Direct vs. indirect use of coal USA 1950-2009 57
Figure 17: Classification of resources 63
Figure 18: Diminishing returns at the extensive margin 69
Figure 19: Production costs and land rent at the extensive margin 70
Figure 20: Hotelling price path 82
Figure 21: Golden rule of capital accumulation 88
Figure 22: Socially optimal rate of extraction 99
Figure 23: Hotelling price and extraction path for a linear demand function 103
Figure 24: Hotelling price and extraction path for an isoelastic demand function 104
Figure 25: Hotelling price path and different extraction costs 105
Figure 26: Hotelling price path disclosure of new reserves 106
Figure 27: Hotelling price path and the discovery of new reserves 107

Figure 28: Primary energy sources and electricity USA 1950-2009 118
Figure 29: Renewable energy total consumption and major sources USA 1949-2009....... 121
Figure 30: World's energy market and non-hydro renewable energy sources 1950-2009 . 122

List of Tables

Table 1: Data sources for Figure 8 28
Table 2: Average annual change of market share per decade on world level 34
Table 3: Slope of the trend lines of Figure 8 as average annual change of market share 34
Table 4: Data sources for Figure 9 39
Table 5: Data sources for Figure 10 40
Table 6: Data sources for Figure 13 47
Table 7: Data sources for Figure 14 48

Bibliography

Aßländer, M. S./Nutzinger, H. G. (2008): John Stuart Mill, In *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall,* edited by Heinz Dieter Kurz. München: Beck.

Bengston, D. N./Iverson, D. C. (2003): Reconstructing Conservation in an Age of Limits: An Ecological Economics Perspective, In *Reconstructing conservation: Finding common ground,* edited by Ben A. Minteer and Robert E. Manning. Washington, DC: Island Press.

Berryman, A. A. (1992): The Origins and Evolution of the Predator-Prey Theory, in: Ecology, Vol. 73, Issue 5, pp. 1530–1536.

BP p.l.c. (2010): BP Statistical Review of World Energy June 2010, http://www.bp.com/statisticalreview, February 2011.

Caspari, V. (2008): Alfred Marshall, In *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall,* edited by Heinz Dieter Kurz. München: Beck.

Chichilnisky, G. (1997): What Is Sustainable Development?, in: Land Economics, Vol. 73, Issue 4, pp. 467–491.

Dasgupta, P. (2005): Three Conceptions of Intergenerational Justice, In *Ramsey's legacy,* edited by H. Lillehammer and D. H. Mellor. Oxford: Oxford University Press.

Dasgupta, P./Heal, G. (1974): The Optimal Depletion of Exhaustible Resources, in: The Review of Economic Studies, Vol. 41, pp. 3–28.

Devezas, T./ Lepoire, D./Matias, J./Silva, A. (2008): Energy scenarios: Toward a new energy paradigm, in: Futures, Vol. 40, Issue 1, pp. 1–16.

Douglas Harper : Online Etymology Dictionary, http://www.etymonline.com, 30.05.11.

Endres, A./Querner, I. (1993): *Die Ökonomie natürlicher Ressourcen: Eine Einführung*, Darmstadt: Wissenschaftliche Buchgesellschaft.

European Commission Eurostat (2009): Panorama of energy 2009 edition, http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-GH-09-001/EN/KS-GH-09-001-EN.PDF,

Farmer, K./Bednar-Friedl, B. (2010): Intertemporal Resource Economics: An Introduction to the Overlapping Generations Approach, http://dx.doi.org/10.1007/978-3-642-13229-2, January 2011.

Feess, E. (2004): *Mikroökonomie: Eine spieltheoretisch- und anwendungsorientierte Einführung*, 3rd ed., Marburg: Metropolis-Verl.

Felderer, B./Homburg, S. (2005): Makroökonomik und neue Makroökonomik, http://dx.doi.org/10.1007/b137628,

Fichter, K./ Noack, T./Beucker, S./Bierter, Willy/Springer, Stefanie (2006): Nachhaltigkeitskonzepte für Innovationsprozesse, http://dabei.erfinderforschung.de/fileadmin/user_upload/Bildmaterial/Beucker_Bierter_Fichter_Noack_Springer_2006_a.pdf, 01.06.11.

Fisher, J./Pry, R. (1971): A simple substitution model of technological change, in: Technological Forecasting and Social Change, Vol. 3, pp. 75–88.

Geraats, P. M. (2006): Intertemporal Substitution and Hyperbolic Discounting, www.econ.cam.ac.uk/faculty/geraats/cons_hyperb.pdf, 30.05.11.

Geyler, S. (2008): *Ökonomisch-ökologische Bewertung von regionalen Trinkwasserschutzoptionen*, 1st ed., Frankfurt am Main, Leipzig: Lang.

Gorostiza, J. L. R. (2002): Ethics and economics: Lewis Gray and the conservation question, Documentos de trabajo de la Facultad de Ciencias Económicas y Empresariales http://eprints.ucm.es/6768/1/0206.pdf,

Gosseries, A. (2008): Theories of intergenerational justice: a synopsis, in: Surveys and Perspectives Integrating Environment and Society, Vol. 1, Issue 1, pp. 39–49.

Griliches, Z. (1980): Hybrid Corn Revisited: A Reply, in: Econometrica, Vol. 48, Issue 6, pp. 1463–1465.

Grübler, A. (1990): *The rise and fall of infrastructures*, Heidelberg: Physica-Verl.

Grübler, A. (1990): Technology Diffusion in a Long-Wave Context: The Case of the Steel and Coal Industries, In *Life cycles and long waves,* edited by T. Vasko. Berlin: Springer.

Grunwald, A./Kopfmüller, J. (2006): *Nachhaltigkeit*, 1st ed., s.l: Campus Verlag.

Hanusch, H./ Kuhn, T./Cantner, U. (2002): *Volkswirtschaftslehre*, 6th ed., Berlin: Springer.

Hartwick, J. (1977): Intergenerational Equity and the Investing of Rents from Exhaustible Resources, in: The American Economic Review, Vol. 67, Issue 5, pp. .

Hartwick, J. (2009): What Would Solow Say?, in: Journal of Natural Resources Policy Research, Vol. 1, Issue 1, pp. 91–96.

International Atomic Energy Agency (2008): Nuclear Power Reactors in the World, Reference Data Series No. 2 http://www-pub.iaea.org/MTCD/publications/PDF/RDS2-28_web.pdf,

Kalmbach, P. (2008): Thomas Robert Malthus, In *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall,* edited by Heinz Dieter Kurz. München: Beck.

Koopmans, T. C. (1967): Intertemporal Distribution and 'Optimal' Aggregate Economic Growth, In *Economic Studies in the Tradition of Irving Fisher:* John Wiley.

Krautkraemer, J. A. (2005): Economics of Scaricity: The State of the Debate, In *Scarcity and growth revisited: Natural resources and the environment in the new millennium,* edited by Ralph David Simpson, Michael A. Toman and Robert U. Ayres. Washington, DC: Resources for the Future.

Kucharavy, D./Guio, R. de Logistic Substitution Model and Technological Forecasting, (2008): http://www.seecore.org/d/200811.pdf, January 2011.

Kucharavy, D./ Schenk, E./Guio, R. de Long-Run Forecasting of Emerging Technologies with Logistic Models and Growth of Knowledge, (2009): http://dspace.lib.cranfield.ac.uk/handle/1826/3730, January 2011.

Kurz, H. D. (2008): David Ricardo, In *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall,* edited by Heinz Dieter Kurz. München: Beck.

Kurz, H. D. (2008): Hermann Heinrich Gossen, In *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall,* edited by Heinz Dieter Kurz. München: Beck.

Kurz, H. D. (2009): Pierro Sraffa, In *Klassiker des ökonomischen Denkens 2: Von Vilfredo Pareto bis Amartya Sen,* edited by Heinz Dieter Kurz. München: Beck.

Kurz, H. D./Salvadori, N. (2009): Ricardo on Exhaustible Resources, and the Hotelling Rule, In *The History of Economic Theory: Festschrift in Honour of Takashi Negishi,* edited by A. Ikeo and Heinz Dieter Kurz. London: Routledge.

Kwasnicki, W./Kwasnicka, H. (1996): Long-term diffusion factors of technological development: An evolutionary model and case study, in: Technological Forecasting and Social Change, Vol. 52, Issue 1, pp. 31–57.

Lee, T./Nakićenović, N. (1990): Technology Lifecycles and Business Decisions, In *Life cycles and long waves,* edited by T. Vasko. Berlin: Springer.

Locatelli, C. (1989): China's Energy Policy: Energy and Economic Development, in: Energy Studies Review, Vol. 1, Issue 2, pp. 144–158.

Mansfield, E. (1961): Technical Change and the Rate of Imitation, in: Econometrica, Vol. 29, Issue 4, pp. 741–766.

Marchetti, C. (1977): Primary energy substitution models: On the interaction between energy and society, in: Technological Forecasting and Social Change, Vol. 10, Issue 4, pp. 345–356.

Marchetti, C. (1979): Energy systems—The broader context, in: Technological Forecasting and Social Change, Vol. 14, Issue 3, pp. 191–203.

Marchetti, C. (1985): Nuclear Plants and Nuclear Niches: On the Genertation of Nuclear Energy During the Last Twenty Years, in: Nuclear Science and Enginieering, Vol. 90, pp. 521–526.

Marchetti, C. (1991): Modelling Innvoation Diffusion, In *Forecasting technological innovation: [based on the lectures given during the Eurocourse on Forecasting Technological Innovation held at the Joint Research Centre Ispra, Italy, October 22 - 26, 1990],* edited by Bernard M. Henry. Dordrecht: Kluwer Acad. Publ.

Marchetti, C. (13.09.1991): *A Forecasting Model for Research and Innovation Activities in Selected Areas: A Support for Strategic Choices*, Venice.

Marchetti, C./Nakićenović, N. (07 / 1978): The dynamics of energy systems and the logistic substitution model: Volume 1: Phenomenoligal Part, http://www.cesaremarchetti.org/archive/scan/MARCHETTI-028_pt.1.pdf, January 2011.

Meadows, D./ Meadows, D./Randers, J./Behrens, W.W (1972): *The limits to growth: A report for the Club of Rome's project on the predicament of Mankind*, New York: Universe Books.

Meyer, P. (1999): A Primer on Logistic Growth and Substitution The Mathematics of the Loglet Lab Software, in: Technological Forecasting and Social Change, Vol. 61, Issue 3, pp. 247–271.

Mitchell, B. R. (1983): *The Americas and Australasia*, London: Macmillan.

Mitchell, B. R. (1993): *International historical statistics: Europe: 1750 - 1988*, 3rd ed., New York, N.Y: Stockton Press.

Mitchell, B. R. (1998): *International historical statistics: Africa, Asia & Oceania, 1750 - 1993*, 3rd ed., London: Macmillan.

Nakićenović, N. (12/1979): Software Package for the Logistic Substitution Model, RR-79-12 http://www.iiasa.ac.at/Publications/Documents/RR-79-012.pdf, February 2010.

Nakićenović, N. (1990): Dynamics of Change and Long Waves, In *Life cycles and long waves,* edited by T. Vasko. Berlin: Springer.

O.E.C.D. (1974): Statistics on Energy 1959–1973,

O.E.C.D. (1983): Energy Statistics 1971-1981,

Oxford University Press. : Oxford Dictionaries, http://oxforddictionaries.com, 30.05.11.

Risse, M. (2002): Harsanyi's 'Utilitarian Theorem' and Utilitarianism, in: Nous, Vol. 36, Issue 4, pp. 550–577.

Santum, U. von (2008): Willian Stanley Jevons, In *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall,* edited by Heinz Dieter Kurz. München: Beck.

Smil, V. (1998): Future of Oil: Trends and Surprises, in: OPEC Review, Vol. 22, Issue 4, pp. 253–276.

Smil, V. (2000): Perils of Long-Range Energy Forecasting Reflections on Looking Far Ahead, in: Technological Forecasting and Social Change, Vol. 65, Issue 3, pp. 251–264.

Solow, R. M. (1956): A Contribution to the Theory of Growth, in: The Quarterly Journal of Economics, Vol. 70, Issue 1, pp. 65–94.

Solow, R. M. (1974): Intergenerational Equity and Exhaustible Resources, in: The Review of Economic Studies, Vol. 41, pp. 29–45.

Solow, R. M. (1986): On the Intergenerational Allocation of Natural Resources, in: The Scandinavian Journal of Economics, Vol. 88, Issue 1, pp. 141–149.

Stiglitz, J. (1974): Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths, in: The Review of Economic Studies, Vol. 41, pp. 123–137.

Ströbele, W. (1987): *Rohstoffökonomik: Theorie natürlicher Ressourcen mit Anwendungsbeispielen Öl, Kupfer, Uran und Fischerei*, München: Vahlen.

Sturn, R. (2008): Adam Smith, In *Klassiker des ökonomischen Denkens 1: Von Adam Smith bis Alfred Marshall,* edited by Heinz Dieter Kurz. München: Beck.

Sweeney, J. L. (2006): Economic theory of depletable resources: An introduction, In *Handbook of natural resource and energy economics,* edited by Allen V. Kneese. Amsterdam: North Holland.

Tietenberg, T. H. (2006): *Environmental and natural resource economics*, 7th ed., Boston, Mass: Pearson/Addison Wesley.

Tsur, Y./Dinar, A. (1995): Efficiency and Equity Considerations in Pricing and Allocating Irrigation Water, http://go.worldbank.org/JLE7Q9NR90, 30.05.11.

Turner, G. M. (2008): A Comparison of the Limits to Growth with Thirty Years of Reality, Socio-Economics and the Environment in Discussion (SEED) Working Paper Series 2008-09.

U.S. Energy Information Administration : International Energy Statistics, http://www.eia.gov/countries/data.cfm, 10.04.11.

U.S. Energy Information Administration : Major Legislative and Regulatory Actions (1935 - 2008), http://www.eia.gov/oil_gas/natural_gas/analysis_publications/ngmajorleg/ngmajorleg.html , 01.06.11.

U.S. Energy Information Administration : PETROLEUM CHRONOLOGY OF EVENTS 1970 - 2000, http://www.eia.gov/pub/oil_gas/petroleum/analysis_publications/chronology/petroleumchronology2000.htm, 01.06.11.

U.S. Energy Information Administration (2010): Annual Energy Review 2009, DOE/EIA-0384(2009) http://www.eia.doe.gov/totalenergy/data/annual/pdf/aer.pdf, April 2011.

U.S. Energy Information Administration (2010): International Energy Outlook 2010, http://www.eia.gov/oiaf/ieo/pdf/0484(2010).pdf, 01.06.11.

Voß, A./Hirschberg, S. (1999): Nachhaltigkeit und Energie: Anforderungen der Umwelt, http://elib.uni-stuttgart.de/opus/volltexte/1999/460, 01.06.11.

Wacker, H./Blank, J. E. (1999): *Ressourcenökonomik: Einführung in die Theorie erschöpfbarer natürlicher Ressourcen*, München, Wien: Oldenbourg.

Wagener, H.-J. (2009): Vilfredo Pareto, In *Klassiker des ökonomischen Denkens 2: Von Vilfredo Pareto bis Amartya Sen,* edited by Heinz Dieter Kurz. München: Beck.

World Commission on Environment and Development/Brundtland, G. H. (1987): Our Common Future. Online, http://www.un.org/esa/sustdev/publications/publications.htm, 01.06.11.

World Nuclear Association (April 2011): US Nuclear Fuel Cycle, http://www.world-nuclear.org/info/inf41_US_nuclear_fuel_cycle.html, 01.06.11.

World Nuclear Association (April 2011): World Uranium Mining, http://www.world-nuclear.org/info/inf23.html, 01.06.11.