# Sustainable Raw Materials Management – An Interdisciplinary Approach

Dissertation

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To my parents

This is just one example of the many ways
you are damaging and depleting your Mother,
the Earth, the giver of all life, out of a complete disregard
for her needs and natural processes.

You are concerned
about little on your planet except
the satisfying of your own passions,
the meeting of your own immediate (and mostly bloated) needs, and
quenching the endless human desire for Bigger, Better, More.
Yet you might do well as a species to ask,
when is enough enough?

Neale Donald Walsch
Conversations with God
Book 2, Chapter 16

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# Sustainable Raw Materials Management – An Interdisciplinary Approach

## 1 Introduction

### 1.1 The Dependency on Finite Raw Materials

The manufacturing sector is the backbone of many developed economies. By knowledge- and technology-based processing of mostly imported raw materials to high quality products a great value added is reached, which is the basis for material wealth especially in the Western world. Since many countries (e.g. the EU, the USA or Japan) have no or only very limited own reserves of raw materials on their own territory, resources[1] must be imported to a large extent. This is the case for both energy and non-energy raw materials. To mention a few examples, 95% of the world's rare earths are currently mined in China; the entire world production of niobium originates from Brazil (90%), Canada (9%) and Australia (1%); Gallium can only be imported from China (83%) or Japan (17%), Germanium either from China (79%), the USA (14%) or Russia (7%) (Koren et al. 2012, p. 42). The import share of the EU for additional important raw materials such as antimony, cobalt, molybdenum, niobium, platinum, tantalum, or titanium is 100% (Koren et al. 2012, p. 14). In sum, the global resource trade (whose scope has more than tripled over the last decade) amounts to app. $5 trillion in 2010 (Lee et al. 2012, p. 4). Since raw materials costs constitute the largest cost factor for manufacturing companies (e.g. 43% in Germany; Angerer et al. 2009, p. 2), and since prices for raw materials are subjected to severe short and long term fluctuations, the (long-term) supply of raw materials represents a significant risk.

[1] In this work, the terms "raw materials" and "resources" are used synonymously. We always refer to (non-renewable) *natural* resources. Other resources like financial, personnel or other resources a company also requires are not considered here.

## 1.2 The Need for Sustainable Raw Materials Management

Basically, it is the resource-poor *economies as a whole*, which are affected by the above-mentioned dependence on raw materials. The effects arising from the scarcity and finiteness of many raw materials are therefore originally an object of study *in economics*. In this thesis, however, the subject area will be examined primarily from a *business perspective*, i.e. from the perspective of a single company.

As part of the thesis, in particular companies in the manufacturing industry take center stage, as they particularly require a secure supply of raw materials. So, the core question a company in the manufacturing sector faces in this context is: *How can a company sustainably manage its short-, medium-and long-term raw materials requirement?* If this question is examined in more detail, it can be divided into four dimensions. The first dimensions refer to the three established aspects of sustainability, so the *economic*, *environmental* and *social* perspective (Brundtland et al. 1987; Küng 1996). Each of these aspects also carries specific risks, which need to be considered as part of a sustainable management of non-renewable raw materials.

Considered in an abstracted way, it is the core purpose of companies in the manufacturing sector to refine raw materials into high-quality products. To accomplish this, specific technical skills are additionally required. To manage the demand and the consumption of raw materials in a sustainable way, it is also required to consider the *technical* dimension (Weizsäcker 2006). From our interdisciplinary perspective, technology can be considered to be the fourth driving factor of sustainability. This represents an extension of the established approach of sustainability. Thus, the present work contributes to answer the following *meta-question*:

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| How can a company in the manufacturing sector manage its demand for non-renewable raw materials – and the associated risks – considering technological and economic, as well as environmental and social objectives? |

As it seems fundamentally questionable whether this question can be fully answered, and as this would – in any case – by far exceed the framework of one scientific publication, the present work only responds to *individual aspects* of this complex issue. Therefore, this thesis only aims to find answers to *partial questions* arising from the meta-question. Doing so, we want to make a small contribution to get *closer to a complete answer* to the m eta-question.

If the meta-question is considered from the aforementioned dimensions, it is possible to derive *partial questions.* The following partial questions, which are of interest primarily to companies in the production sector, are focused:[2]

### 1.2.1 Economic Aspects

To protect against the before mentioned *economic* risk related to the consumption of non-renewable raw materials in a suitable manner, companies especially in the manufacturing sector therefore need to deal with the following partial questions:

- Is it possible to *identify drivers*, from which long-term *price changes* of raw materials can be deduced?
- Is it possible to *identify drivers*, from which short-term price *fluctuations* of raw materials can be deduces?
- How to *include risks* arising from the dependence on raw materials into the decision calculus of a company?
- To what extent it is possible to *protect against price increases and volatilities* of raw materials relevant for the company?

### 1.2.2 Ecological and Social Aspects

Apart from this purely economic perspective, mining and use of raw materials are very important for two other 'stakeholders': On the one hand a large number of people (especially in developing countries) is involved in the extraction of raw

[2] Besides these application-oriented *partial questions*, also theoretical *research question* are focused. Research questions are primarily addressed in Section 1.3 and Section 1.5 as well as in the main part of the thesis (Section 2 and Section 3).

materials. On the other hand, raw material extraction and processing have a major impact on the environment. Thus, also the following question must be answered:

- What is the *impact* of the use of raw materials on the *people involved* in the mining process (*social perspective*) and the *natural environment* (*ecological perspective*)?
- What *amount* of non-renewable raw materials is available worldwide and which *criticalities* result from this?
- Which opportunities are available to a company in the industry sector to *reduce* the environmental and social *risks* arising from the use of non-renewable raw materials?

Although these external effects do – caused by market failures – not directly affect raw materials prices in the short term, it is important for a sustainable company to consider these aspects, too. These "soft factors" can both be relevant for image reasons (to avoid e.g. negative press or a negative corporate image). Moreover and particularly, a company should also look at these aspects in an honest sense of responsibility towards these two 'stakeholders'.

### 1.2.3 Technological Aspects

The decision of which raw material will be used in a product (and the implicit decision, which amounts of raw materials are required for the entire product life cycle) is already made in the development phase. As part of a purely technical materials selection, the specific material properties of the relevant raw materials are at the spotlight. Insofar as a raw material – as part of a sustainable consideration – turns out to be critical (for example, i.e. *expansive* in economic terms, *polluting* in ecological terms, or sourced from war zones and so *unethical* from a social perspective), it may be useful to substitute this critical raw material by a another one with identical or similar material properties, which is less critical. It is also possible that – due to technological progress – there are changed in the quality or the properties of raw materials or precursors. From this, the following partial questions arise with a technical focus:

- To what extent is it possible already in the phase of R & D to make sustainable *selection decisions* regarding the use of raw materials?
- Is it possible to *substitute* a (possibly critical) raw material by a less critical one that has similar material properties?
- What is the impact of *technological progress* on the raw materials required for the manufacturing of products?

### 1.2.4 Introductory Overview of the Main Topics

Approaches towards a sustainable use of raw materials are focused in this thesis. As the current price, at which a raw material can be purchased, as well as its future development are of primary relevance for a company in the production sector, raw materials *prices* are focused in the first half of the thesis (Section 2). Here, it can be shown that medium and long-term explanations of the influence of different drivers and predictions about the development of raw materials prices are subject to large uncertainties. Moreover, the only consideration of raw materials *prices* would – as already mentioned – ignore external effects (which are caused by market failure) and therefore would result in incomplete conclusions. For these reasons, we will develop interdisciplinary protection strategies against raw materials risks in the second half of the thesis (Section 3). Based on these strategies, companies in the production sector can better protect or even immunize themselves against raw material price increases and volatilities.

## 1.3 Drivers of Resource Prices

As shown in the previous section, is the *price*, which plays in an important role as part of an economic view. To better understand the pricing of a non-renewable raw material and its price development, we first of all have to identify price *drivers* and study their mode of action in more detail. For companies in the manufacturing sector, which are highly dependent on raw materials, this knowledge is of great relevance.

To better understand and explain the pricing of non-renewable raw materials, it is useful to focus first of all on their historical trends. On the one hand, the consideration of *long-term* price *trends* is to be considered (Section 1.3.1); on the other hand, *short-term* price *fluctuations* (volatilities) may also be of interest (Section 1.3.2). In addition, most raw materials – in contrast to shares, bonds or renewable resources (such as wood, food or energy from plant resources) – are available only in a finite extent. This requires a specific study of their price development.

## 1.3.1 Price Development in the Long Term

If the long-term price development of raw materials is considered irrespective to scientific approaches just by taking a look at the price chart of energy and non-energy raw materials shown in Figure 1, one might simplified conclude that raw materials prices increase exponentially in the long-range.

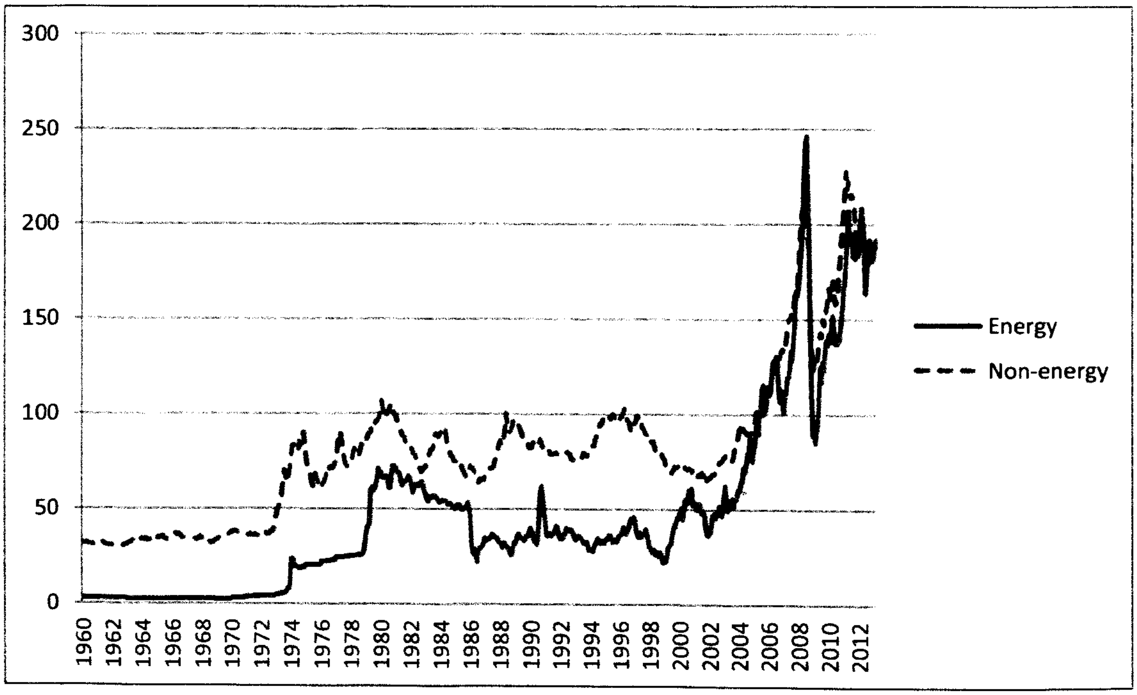


**Figure 1** Development of energy and non-energy raw materials prices (01/1960 - 02/2013) based on nominal US$, 2005 = 100; own chart with figures from Word Bank (2013)

In a more detailed consideration, however, it quickly becomes clear that this increase is partly due to the simple fact that, according to standard practice,[3] the chart is based on *nominal* prices (i.e., prices are not adjusted for inflation). It is also obvious that there were longer periods with almost unchanged (nominal) prices (from 1960 to 1973 and from 1974 to 2005). In contrast relatively short periods can be observed with enormous price volatilities (1973/74 as well as from 2006 onwards). Moreover, it can be seen that prices of energy and non-energy raw materials are positively correlated most of the time; but in contrast, there are also periods when the prices of both raw material classes developed in different ways.

For a better understanding of long-term, historical raw materials prices, it is therefore not sufficient to only conduct some 'chart analysis'. To identify and better understand drivers and their influence on the historical price trend of non-renewable resources, relevant scientific literature is to be studied first, which is the basis for our scientific work.

Scientific studies related to the scarcity of resources and the resulting consequences for the economy and society rich go back to the 18th century. Until then, the idea had prevailed that a growing population is positive as it was simultaneously leading to a greater economic productivity. In 1798, Malthus contradicts this paradigm. In his purely qualitative essay, he relates the already observable *exponential* increase in population to the increase in food production only *linearly* increasing over time (Malthus 1798). From this he concludes limited availability of food and resulting shortages, which are leading to a rise in food *prices*. Moreover, he concludes that the scarcity of the *production factor land* has a limiting effect on the population. This prediction is referred to as 'Malthusian crisis' or 'Malthusian nightmare' in literature.

Besides the production factor land, Ricardo (1817, chapter 4) additionally includes the production factors *labor* and *capital* when he conducts his also purely qualitative research "On Natural and Market Price". Barnett and Morse (1963)

[3] Cp. World Bank Commodity Price Data (2013): "monthly series are available only in nominal US dollar terms"

empirically test the long-term trend of commodity prices and note that "the long-run scarcity of natural resources can best be assessed by looking at economic indicators" (Norgaard 1990, p. 20). Hotelling (1931) relates different economic indicators into a self-contained, model-theoretic approach, which is discussed in detail in Section 2.1. On this basis he derives the prediction the price of non-renewable resources over time increases exponentially (cp. Krautkraemer 1998, p. 2066). Other authors also examine the long-term price development of non-renewable raw materials – partly on the basis of theoretical considerations, partly on the basis of empirical studies – but draw other conclusions, which are highly contradictory: Pindyck (1978) and Slade (1982) for example discover U-shaped price curves. According to McRae (1978) raw materials prices are characterized by a 'random walk'; Smith (1979) observes a predominantly negative price trend. In contrast, Lee et al. (2006, p. 369) come to the conclusion that prices of finite raw materials are "stationary around deterministic trends with structural breaks". These highly contradictory results can be explained in part by the fact that the studies are based on *different study periods*. Another reason is that price developments of *different raw materials* or classes of raw materials were examined.

Thus, the following research questions are central: What are the long-term drivers for raw material price changes? Is it possible to identify them and their impact either on the basis of already existing theoretical models or based on empirical literature? Due to the fact that existing literature mainly focuses on only one or few specific drivers and analyzes their specific impact in isolation, we will focus on the development of an approach serving as a basis for the *simultaneous* integration of several relevant drivers.[4]

However, it becomes evident that general conclusions about *long-term* raw materials price trends are *not* possible. On the one hand this is due to the large number of drivers and the difficulty to reflect their specific individual influence on the total price. Moreover, only the study of long-term drivers would be insufficient

[4] For the most part, the following section is based on the research paper "What drives resource prices? – A literature review with recommendations for the further development of the Hotelling model" (Gaugler 2012a). A German language version of this paper is accepted with minor revisions to be published in Zeitschrift für angewandete Umweltforschung.

for a company's need. As also short-term price fluctuations are of major importance for the strategic and operational purchasing of a company (especially for the further production of established products), we will study them more detailed in the following section. As it additionally becomes clear in the course of our studies that more resilient predictions about the development of raw materials prices can only be made raw material-specific, we will subsequently focus on *short term* fluctuations of *individual* raw materials.

## 1.3.2 Price Volatility in the Short Term

Analyzing short-term price developments of individual raw materials it becomes evident that prices are subject to considerable volatilities. For example, while the one-year volatility of Euro-Dollar exchange rate is just under 10% and the volatility of interest rates is less than 20%, it is between 20% and 30% for all quantitatively important industrial metals (Commerzbank 2013). In addition, an increase in volatility can be observed on the commodity markets, which rose from 4,1% (in the period 1980 - 2012) to 15,1% (in the period 2005 - 2012) (Lee et al. 2012, p. 59, p. 177).[5]

Since these price changes represent a big risk for manufacturing companies, it is also advisable – from a practical as well as a scientific perspective – to analyze these (short term) price fluctuations in detail. Again, we therefore aim to identify and analyze *drivers* that are causal for the price fluctuations. It is elaborated and becomes clear in Section 2.2 that these drivers differ from the long-term drivers discussed in Section 2.1. Thus, the following research questions are focused: Is it possible to explain short-term changes in raw materials prices, which are exemplarily identified considering the three metallic materials neodymium, indium and gallium, by fundamental factors or are these changes random in nature? To find answers on this question, an empirical analysis on the basis of a raw material-specific event study was carried out.[6]

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[5] Lee et al. (2012) define volatility as standard deviation of *monthly* International Monetary Fund (IMF) commodity price indices from annual averages.

[6] For the most part, the following section is based on the research paper "Determinants of the Price of Non-Renewable Resources: An Event Study for Scarce High-Tech Metals" (Wanner,

In the first part of Section 2, we study *long-term* price drivers like mining costs, technical progress, ore quality, market structure, existence of risks, backstop technologies, recycling as well as changes in demand on an abstract level. In contrast to these often simultaneously arising long-term drivers, it is easier to differentiate the specific effect of single drivers in the *short term.* Doing so in the second part of Section 2, some valid explanations of the effects of individual drivers on the price of a non-renewable resource can be made on a raw material-specific basis. Nevertheless, a number of uncertainties still remain.[7]

On the basis of the scientific approaches presented and extended in this thesis it is thus *not* possible in the long term and only *partially* possible in the short term to explain current prices of raw materials from the analysis of various drivers. It is also not possible in the framework of the models elaborated in Section 2 to make prediction of long- and short-term price trends in the raw materials sector.[8] Against this background, measures and strategies to *protect* a company in the manufacturing sector against risks arising from the dependence on raw materials take center stage in the second half of the thesis.

## 1.4 The Need for Interdisciplinary Research

The selection of raw materials, which already is made already in the development and design phase, makes a company dependent on the supply of these raw materials for the entire production period and life cycle of the product (or even a complete product line). Thus, it would fall short to consider economic, environmental and social factors only from a current perspective. Rather, the need for raw materials – as well as the material flows and risks related – are to be examined throughout the entire life cycle of the product. A sustainable company must additionally

Gaugler, Gleich, Rathgeber 2012), working paper, University of Augsburg, which is currently under review.

[7] It should be noted that in addition to the previously discussed short- and long-term drivers and dependent on the production site(s) of the company, *exchange rates* also play a significant role.

[8] This statement may be disappointing at first sight. If it is set in relation to research in the area of the entire financial sector, it is clear that valid statements about future prices (such as shares, bonds or their indices) are similarly and generally difficult.

analyze the mining and processing of the raw materials required for the production of primary products already in an early stage. It also should be clarified already in the development and design phase whether the product can be re-used as a whole after the end of its usage phase, whether it can be partially re-manufactured, whether it can be re-cycled on material level, or how the disposal of the product can alternatively be accomplished (Reller and Meißner 2012, cap. 1, p. 4).To meet current economic, environmental and social criteria and to satisfy these requirements for the complete resource usage phase, an interdisciplinary approach is required. This is the case both from a company and a scientific perspective. The present thesis therefore aims to develop a sustainable raw materials management, which meets these requirements. In this respect, the following areas will to be focused in detail in Section 2 and Section 3:

- The perspective of *resources strategy ("World of volume units"):* In this area, it is about the (current and future) physical, *quantitative availability* of raw materials. Thus, the following thematic areas are studied by resource strategist: The global geological conditions, which imply whether a raw material is available in sufficient quantities and the study of supply risks; the localization of mineral deposits and their size; the assessment of (geo)political instability in resource-rich countries and regions; the assessment of social or environmental risks related to the extraction of raw materials; the assessment of the time when finite raw materials are running low.
- The perspective of *materials science and engineering ("World of* physical *units"):* In this area, it is about the *technical material properties*, which characterize specific raw materials. In the phase of sustainable development and design of a new product, the following issues are to be considered: The technical requirements of a (raw) material that it can be used in a particular component and the specific material properties (e.g. electrical conductivity, requirements in terms of weight, corrosion resistance or security). It also should be assessed whether a (from a resource strategy perspective) *rare* or (from an economic perspective) *expansive* raw material can – with respect to the required material properties – be substituted by another, less critical and/or cheaper material.

- The perspective of *economical* resource management *("World of monetary units"):* In this area is about the *monetary valuation* of the raw materials required in the entire supply chain. Thus, it is first of all the current price of specific raw materials, which is in the focus in this area of sustainable resource management. In addition, it is important to economically quantify resource strategic and technical *risks* that are necessary for the estimation of future price developments. Based on this, it is necessary to find answers to the question whether it is economically favorable e.g. to carry out the (technically possible) substitution of a raw material classified as 'rare' from a resource strategic perspective by another raw material, which is available in sufficient quantity.

To establish a sustainable raw materials management, novel methodologies are required allowing an interaction of these three perspectives. For this reason, interdisciplinary research approaches take center stage in this thesis. This firstly becomes apparent in Section 2, when price drivers of non-renewable raw materials and resulting risks from all three areas are included in the study. Secondly, the approaches for a sustainable management of non-renewable raw materials developed in Section 3 are thoroughly interdisciplinary by nature.

## 1.5 The Protection against Raw Materials Risks

If a company seeks to protect against *economical* raw materials risks (i.e., in particular long-term commodity price increases, short-term fluctuations or availability risks) and wants to institutionalize a sustainable resource management (also from a sense of responsibility to all the *people* involved in the mining of raw materials as well as to the natural *environment* as it was already discussed in Section 1.1), a variety of measures and strategies are available. These measures and strategies will be discussed in more detail in the following three sections: At first an 'ad hoc' protection strategy (i.e. an immediately usable way to implement sustainable raw materials management) is exemplarily presented. In contrast, example 2 and 3 will refer to forward securing strategies with respect to the development of new materials and products.

### 1.5.1 An Example for Sustainable Ad Hoc-Protection

In developed countries, 20 - 40 % of the *energy consumption* is caused by residential and commercial buildings. Thus, energy demand of buildings is even bigger than the demand of industrial or transportation (Pérez-Lombarda et al. 2008). In addition, measures to increase energy efficiency of buildings ("building energy efficiency") promise the world's by far biggest saving potentials and are estimated to amount to a value of 800 trillion $ p.a. in 2030 (Lee et al. 2012, p. 113; The Climate Group 2008; WBCSD 2009). In this context, a mathematical model will be presented in Section 3.1, by means of which the optimal level of investment in 'Smart Houses' can be determined. Following the approach of sustainable resource management, not only the economical but also the ecological perspective of this measure are examined and illustrated by a numerical example. Thus, we focus on the following research questions, which will be answered on the basis of valid assumptions: How to evaluate investments in "Intelligent Houses" in an economically appropriate way? And, on this basis: Is it possible to use information systems (IS) to harness both the economic *and* ecological potential of investments in energy efficiency measures?[9]

### 1.5.2 An Example for Sustainable Basic Research

Many future technologies are highly dependent on the availability of finite raw materials (Angerer et al. 2009; Koren 2012). This dependence on the one hand refers to the quantitative availability of certain raw materials, which are required for the production of a new product throughout its complete life cycle. On the other hand, the number of required elements characterized by their specific technical properties, increased from about 25 in the 1970s to more than 70 in the meantime (Achzet et al. 2011, p. 11). Since many of these elements are scarce

[9] For the most part, the following section is based on the research paper "Determining the Optimal Investment Amount of an Intelligent House – Potentials of Information and Technology to Combine Ecology and Economy" (Buhl, Gaugler, Mette 2011), which was presented at the 19th European Conference on Information Systems (ECIS), Helsinki, Finland, 2011.

(EU 2010), but as their long-term availability is required especially for new products and materials (Buhl, Reller, Horn 2010), it is important already in the phase of basic research to identify future raw materials risks and to reduce them. Using an example, which refers to basic research in the development of novel materials for the semiconductor industry, these raw materials risks are examined in more detail in Section 3.2. Here, the three classes of material barium-titanate (BTO, which is doped with rare earth), calcium-copper-titanate ($CaCu_3Ti_4O_{12}$, CCTO), and lanthanum-strontium-nickelate ($La_{15/8}Sr_{1/8}NiO_4$, LSNO) are compared by means of a qualitative combination of interdisciplinary research. Here, the following research question is in the foreground: What are the implications for basic research with respect to the development of novel materials, if – in addition to a purely technical consideration – also resource-strategic considerations (keyword: 'availability' of raw materials) and economic aspects are considered?[10]

### 1.5.3 An Example for Sustainable New Product Development

In the previous example of basic research, the focus was mainly on the techno-economic and resource strategic area. In Section 3.3 this focus is extended to social and environmental factors. Raw materials risks are discussed in an application-oriented way using the example of cobalt, which is increasingly required for the development and production of Lithium-ion based high-power batteries (Angerer et al. 2009, p. 173). The research question "Which raw material risks can occur in new product development if economic, environmental as well as social issues are considered and to what extent it is possible to reduce these risks?" is again studied using a combination of qualitative interdisciplinary research areas.

[10] For the most part, the following section is based on the research paper "The Route to Resource-Efficient Novel Materials" (Krohns, Lunkenheimer, Meißner, Reller, Gleich, Rathgeber, Gaugler, Buhl, Sinclair, Loidl 2011), which is published in Nature Materials. This work was supported by the Deutsche Forschungsgemeinschaft via the TRR80.

Within this research project a roadmap towards an interdisciplinary resource management is developed, by means of which price-related risks as well as negative environmental and social impacts of cobalt mining can be assessed and reduced.[11]

## 1.6 Structure of the Thesis

As already shown in the introduction, companies in the manufacturing sector depend on finite resources to a large extent. To ensure the availability of these raw materials in the short, medium and long term, a sustainable management of raw materials is required. In this context it is important to consider price and availability risks as well as social and environmental impacts of raw materials extraction.

In the first part of this thesis we mainly focus on the impact of different drivers on the development of raw materials *prices*. Here, we can distinguish between long-term (fundamental) drivers (Section 2.1) and short-term drivers, which are considered in Section 2.2. Based on this analysis it is possible to better understand the impact of different drivers on the prices of finite raw materials. Nevertheless, it is and will not possible to precisely explain current price of raw materials on the basis of the drivers studied in our scientific work.

Thus there is an evident need for a sustainable company to *secure* against raw materials price increases and volatilities in an appropriate manner. Therefore, we will present and evaluate different interdisciplinary securing strategies in the second half of the thesis. In a first step a strategy to secure against energy price changes, which can be implemented in the short term, will be presented (Section 3.1). Subsequently, we introduce an interdisciplinary material selection decision, which can already be applied at the stage of basic research (Section 3.2). Finally, an application-oriented measure is presented to ensure sustainable resource management for the case of cobalt (Section 3.3). Depending on the application context, each of these measures and strategies can help to set up a more sustainable

[11] For the most part, the following section is based on the research paper "Nachhaltige Neuproduktentwicklung – ein interdisziplinärer Ansatz zur Identifikation von Rohstoffrisiken am Beispiel von Kobalt" (Gaugler 2012b), which is published in UmweltWirtschaftsForum, DOI 10.1007/s00550-012-0260-1.

use of scare raw materials. This structure is further illustrated graphically in Figure 2.

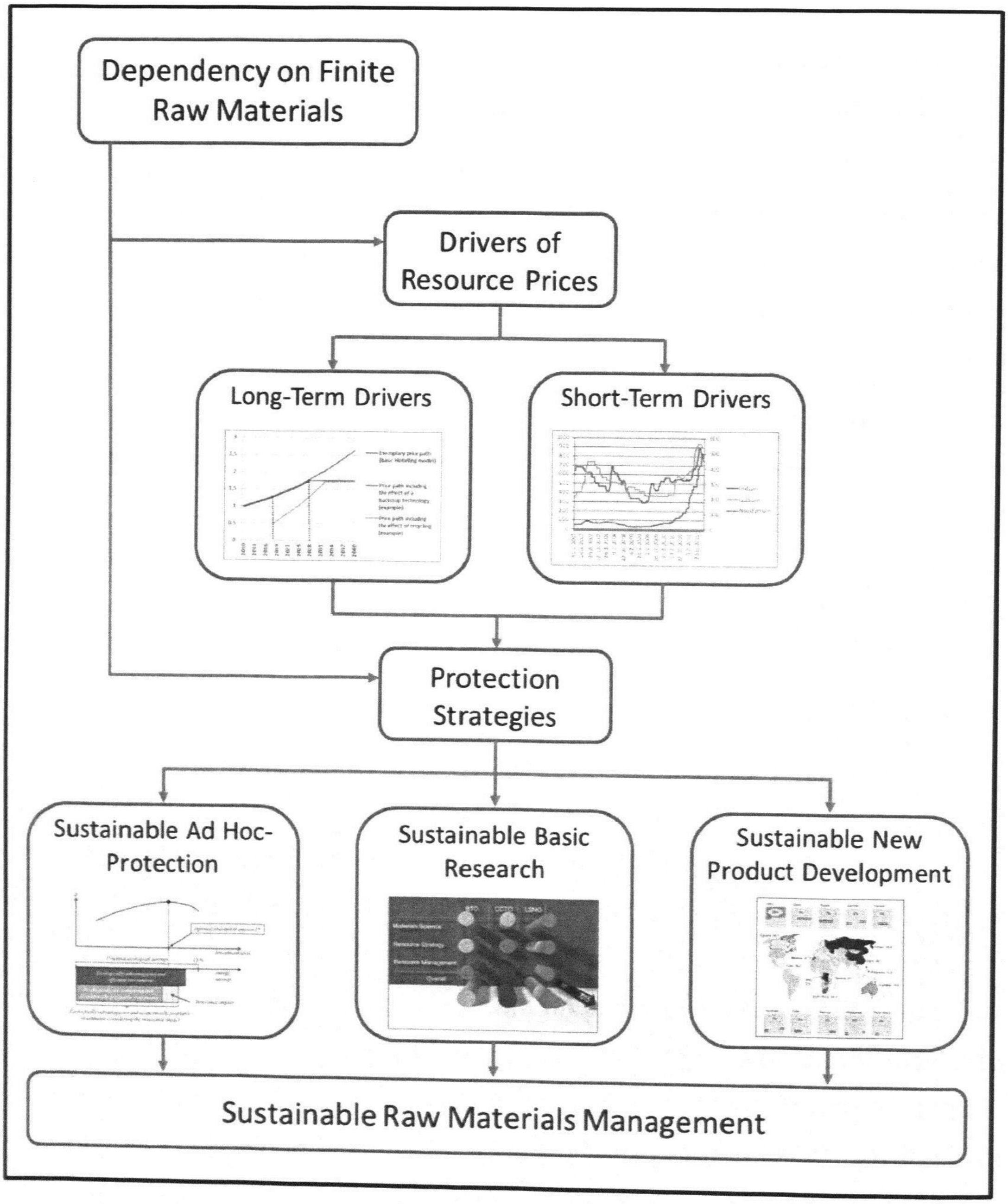


**Figure 2** Structure of the thesis

# 2 What Drives Resource Prices?

## 2.1 What Drives Resource Prices in the Long Term?

As described above, companies in the manufacturing sector are heavily dependent on raw materials. Therefore, explanations of the effects of different drivers on the pricing of raw materials – and, based on this, predictions about the future development of commodity prices – are important to them.

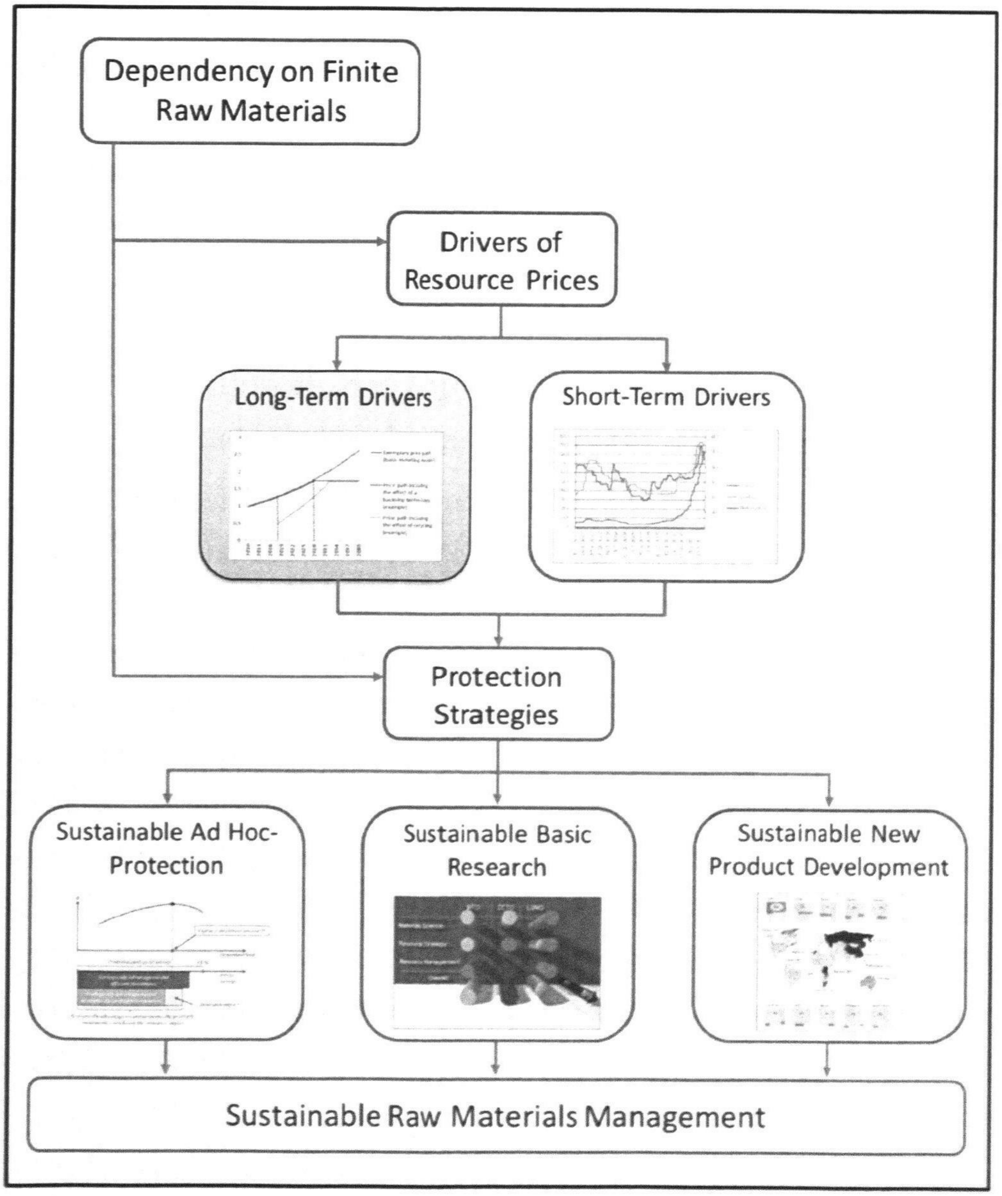


**Figure 3** Structure of the thesis: Long Term Drivers

The following section will examine to what extent it is possible to make statements about the long-term price development (cp. Figure 3) from a purely scientific point of view. Based on a literature review, this issue is first of all considered from a model-theoretical perspective. Here, the model of Hotelling (1931) serves as base. Secondly, results of existing empirical studies are examined in the following. Based on these (partly contradictory) results, recommendations for the further development of the Hotelling model are developed and tested. Thereby, the following already mentioned partial questions are at the center of the next section: Is it possible to *identify drivers*, from which long-term *price increases* raw materials can be deduced? How to *include risks* arising from the dependence on raw materials into the decision calculus of a company? And, in addition: Is it also possible to integrate technically related drivers (such as the possibility of *substitution* or *technical progress*) in an economic model to forecast price developments of raw materials?

### 2.1.1 The Need for Research on Long Term Resource Price Trends

As already sketched in the Section 1.1, many developed regions like the EU, US and Japan owe their economic prosperity in large part to their ability to export high-value goods. At the same time, they often have only few own natural resources and are heavily dependent on importing energy and non-energy raw materials (EU 2010). As the earth only has a limited amount of finite resources, the fair distribution of these resources is a generally-accepted goal, but this is difficult to achieve in practical terms. When it comes to the use of natural resources, it is a matter of trying to balance conflicting economic, environmental and social interests. To what extent is it possible, bearing in mind our responsibility for the welfare of future generations, to maximise the living standards of today's generation throughout the world, including in those countries that export raw materials? To what extent is it possible to effectively control air and land pollution linked to the consumption of raw materials?

Whether we like it or not, it is the *price* of finite resources that is the key driver in determining the answer to these questions. Supported by the de facto absence of statutory regulation of international raw materials extraction and trade, prices have been driven by the market alone and have had a tendency towards encouraging maximum consumption by today's prosperous nations, while shifting the associated negative effects of this consumption onto the environment itself and onto future generations. In a market economy, irrespective of the country's statutory legislation, price represents the only central tool for controlling the efficient use of finite resources in terms of economic, environmental and social interests. To compensate for market failures, it is incumbent upon state entities to ensure that there is a fair distribution of finite resources by influencing the price. To do this it is necessary to have a clear understanding of raw materials markets and the market drivers that influence prices. Using various practical and scientific methods, an attempt will be made to better understand the influences and issues that impact the price of raw materials.

One pragmatic approach to evaluating which drivers influence prices relative to the risks that arise from the extraction of finite resources, involves measuring criticality, which is carried out separately for each individual raw material. Only using the criteria 'economic importance' and 'supply risk' European Commission (EU 2010, p. 6) tries to identify the criticality of an individual raw material: If a raw material has high values on both criteria, this is automatically considered 'critical'. Rosenau-Tornow et al. (2009) aim to identify long-term supply risks for mineral raw materials. Based on a combined evaluation of past and future supply and demand trends they are developing a nine-stage scoring-model and thus assess the criticality of different materials. With a similar goal, Graedel et al. (2012) examine the criticality of metals. They develop a sophisticated scoring model based on the main criteria 'supply risk', 'environmental implications', and 'vulnerability to supply restriction'. On this basis, metals are divided into four groups of different criticality. From an economic perspective, the broad concept of criticality can be split up into two components: One is the *measurable* aspect – also referred to as scarcity – that leads to measurable change of *prices* (either caused by an increase in demand or reduced supply) and thus to an increase of risk for a supply company. Secondly, also *non-measurable* aspects such as company-specific or aggregated demand elasticities as well as soft factors are studied as part of general research on criticality (Gleich et al., 2013).[12] Classic economic theory has always included studies on the scarcity and effect of resources and general production factors. As long ago as 1798, Malthus demonstrates in a qualitative study that an exponential growth in the population, accompanied by limited availability of the production factor land, would lead to a shortage of food in the long term. Ricardo, on the other hand, (1817, section 5.21) relaxes the assumption of absolute scarcity and assumes that there will be a "decreased rate of production" from land available for food production, but still comes to the conclusion that the growth of a society will come to a standstill in the absence of resources. From a neo-classical perspective, Gray (1914) refers to Ricardo several times in his article "Rent Under the Assumption of Exhaustibility", takes on board his views on the extraction of finite resources and, by looking at one individual mine, comes to the same general conclusion as the one Hotelling (1931) makes in his basic model on raw materials supply: the price of a finite resource grows in line with the rate of interest (cp. Krautkraemer 1998, p. 2066). In contrast, Pindyck (1978) concludes from his theoretical analysis that raw materials prices follow a U-shaped curve. He surmises that the initial price drop is the result of the large quantity of raw materials initially found, but that the price trend later changes direction as these materials are extracted and exploration efforts are both undertaken and successful. In summary, it is clear that, on the basis of theoretical research alone, only partial assumptions can be made, and at first glance it does not appear possible to draw firm conclusions about actual price movements for finite resources.

Published empirical studies that examine resource price movements are often fundamentally contradictory in their conclusions. For example, an examination of the prices for finite resources during the period 1940 - 1976 suggests that raw materials prices do increase, but that the amount by which they should increase differs greatly, depending upon which modelling approach is taken (Berck and Roberts, 1996). However, raw materials prices can also change on a largely random basis (from 1922 to 1974) and are described by McRae (1978) as a random walk. In

[12] In the following quantitative study, we primarily focus on scarcity, i.e. measurable aspects. In contrast, qualitative (ecological and social) aspects are additionally studied in the second part of the thesis.

contrast, Smith (1979) observes that, in the period examined from 1900 to 1973, the price trends for natural resources were predominantly negative, while Slade (1982) in her much-referenced study comes to the conclusion that the price of many raw materials during the period 1870 to 1978 went down initially, only to go up again, and that, overall, prices follow a U-shaped curve. Lee et al. (2006, p. 369) determined from a study of finite resource prices from 1870 to 1990 that prices for finite resources are "stationary around deterministic trends with structural breaks" (cp. Section 1.3.1).

Moreover, a number of meta-analyses examining the development of commodity prices and their drivers are based on individual studies on the model of Hotelling. Comparing four different tests, Chermak and Patrick (2002) come to the conclusion that two of them confirm the validity of the theory of Hotelling, while the other two come to the opposite conclusion. In an extensive meta-analysis of empirical studies based on Hotelling, Slade and Thille (2009) concluded that it is not possible to confirm the general validity of the basic Hotelling model. Krautkraemer (1998) starts his review article with the basic model of Hotelling and expands it gradually. He introduces the drivers 'exploration', 'capital investment and capacity constraints', 'ore quality' as well as 'market imperfections' and explains – largely non-formal – the effects of these drivers on the price development of a finite resource; however, without making clear statements about the effects of the individual drivers.

These meta-analyses are a basis for further investigation of commodity price developments. Nevertheless, existing meta-analyses are mostly based on studies testing the basic Hotelling model or extend it only in terms of single drivers (Chermak and Patrick, 2002; Slade and Thille, 2009). Probably due to this limitation, these studies usually come to the conclusion that the validity of the (basic) model cannot be confirmed. Although Krautkraemer (1998) presents well derived starting points for an extension of the basic Hotelling model, these proposals are of limited use, since their implications are derived in mainly qualitative manner; despite the fact that the article was published already a quite long time ago. Overall, it can be seen from this short overview of the relevant literature that it is not possible to draw a generally valid conclusion on price trends for finite resources from existing literature alone. In order to find a more valid and reliable answer to the question "What drives resource prices?" we therefore need to take a more comprehensive, theoretical approach. As part of this study we will, therefore, analyse the results of established and current studies, while taking current developments in the raw materials markets into consideration, in order to identify those points – from a scientific perspective – for which it is possible to find valid answers and those points for which answers cannot be found, or only to a limited extent.

Motivated by the weak results provided by (meta-)analyses of Hotelling's basic model and its already existing extensions, we are expanding Hotelling's model by a simultaneous approach including additional drivers such as backstop technology and recycling. In addition, drivers integrating changes in the demand side are integrated into the model. Last but not least, we introduce an approach to distinguish between short- and the long-term effects of different drivers on the evolution of commodity prices.

A better understanding of these drivers and the way they work together can help in the quantification of raw materials price determinants and availability risks, which can then be used in the implementation of appropriate governance strategies, especially those aimed at a fairer international and inter-generational distribution of finite resources.

Firstly, the principles of the Hotelling model are presented, followed by approaches designed to expand the model into a more comprehensive overall model. After deductions are made from the Hotelling model, these are then further expanded by cet. par. consideration of the determinants extraction costs, technical progress, degradation, market power, risk, recycling and the existence of a backstop technology. It is then demonstrated how these drivers can be simultaneously incorporated into the model. The necessity of incorporating growing demand into the Hotelling model is discussed, along with the attendant difficulties and the need for additional research.

## 2.1.2 The Basic Hotelling Model – a Theoretical Approach to the Price Development of Finite Resources

As the model proposed by Hotelling (1931) presents the theoretical basis for this more detailed examination of the drivers of resource prices, we should first look at his underlying assumptions. Hotelling assumes a fixed start point in time $t = 0$ and a quantity based on the known stock of raw materials $\bar{y}$, where raw materials suppliers, who each have an identical cost structure, maximise their net present value by selling their raw materials. Assuming a polypolistic market structure, an end point in time $T$ for the extraction of the stock, complete information, decisions under certainty (= absence of risk) and a lack of state interference, then continuous modelling gives the following profit function, in which $p(t)$ stands for the price of the resource at point in time $t$, $y(t)$ for the quantity sold in in $t$ and $\gamma$ for the constant discount rate (cp. Feess 2007, p. 350):

$$G(y(t)) = \int_{t=0}^{T} \frac{p(t)\,y(t)}{e^{\gamma t}} dt = \int_{t=0}^{T} L(y,t)dt$$

In order to solve the equation – with the constraint of the resource's finiteness – the following simplified variation problem (cp. Kielhöfer 2010, p. 79)

$$L(y,t) = \frac{p(t)\,y(t)}{e^{\gamma t}}$$

can be set up including the isoperimetric constraint

$$\bar{y} = \int_{t=0}^{T} y(t)dt$$

or

$$K(y,t) = \bar{y} - \int_{t=0}^{T} y(t)\,dt = 0.$$

This must satisfy the simplified Euler-Lagrange equation with isoperimetric constraint

$$\frac{\partial L(y,t)}{\partial y(t)} + \lambda \frac{\partial K(y,t)}{\partial y(t)} = 0$$

$$\frac{\frac{\partial p(t)}{\partial y(t)} y(t)}{e^{\gamma t}} + \frac{p(t)}{e^{\gamma t}} - \lambda = 0$$

and must satisfy the initial value condition on $p_0$

$$\frac{\partial p_0(y_0)}{\partial y_0} y_0 + p_0(y_0) - \lambda = 0,$$

which sets the price $p_0$ as the starting price for the time $t = 0$. Provided the continuous differentiability of $p(t)$ and $y(t)$, the solution

$$p_0 = \lambda = \frac{p(t)}{e^{\gamma t}}$$

is obtained, resulting from the simplified Euler-Lagrange equation under constraints. From this it can be seen that the discounted price must be the same in each period in order to ensure profit-maximizing resource extraction. Transformed, this results in the price path of a finite resource:

$$p(t) = p_o e^{\gamma t}$$

For completeness, we set up the second variation $\delta^2 G(y,t)$. As it holds

$$\delta^2 G(y,t) = \int_{t=0}^{T} 0 \cdot h^2 dt \leq 0 \; \forall \; h^2 > 0,$$

$G(y(t))$ is the *maximum* of the profit.

Hotelling's rule in its original form states that the price $p$ of a finite resource must rise with the rate of interest $\gamma$ and is synonymous with the statement that the prices of finite resources rise exponentially. Applying this to a numerical example, we assume a current price $p_0$ of \$1.00 per pound (1 pound equals 0.4536 kg) and an interest rate $\gamma$ of 3.24%[13] results in the long-term price path using Hotelling's rule visualized in Figure 4.[14]

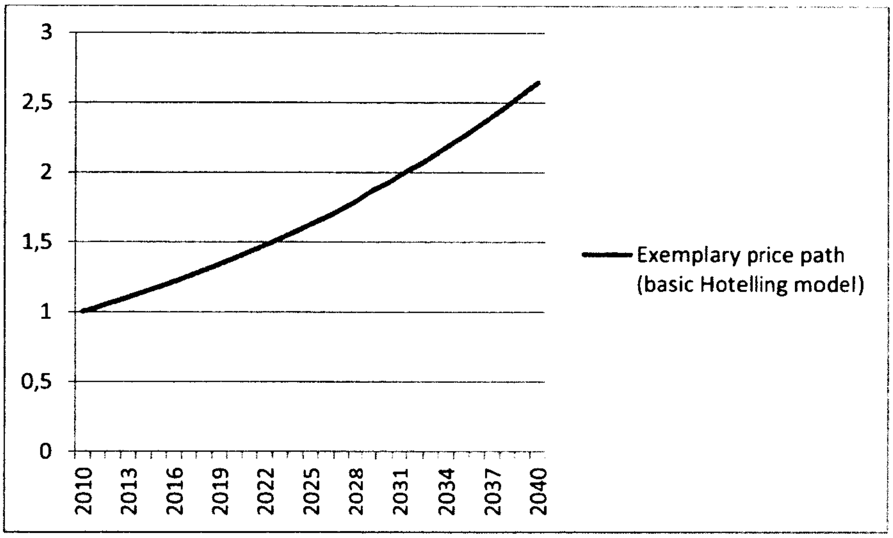


**Figure 4** Exemplary price path in accordance with basic Hotelling model

Raw materials suppliers who wish to maximise their profits are, therefore, not concerned whether they sell their raw materials at the point in $t_0$ at the price $p_0$ or at a later point in time $t$ at the higher price $p_t$. We can therefore derive the following theory-based hypothesis from the basic Hotelling model:

**Hypothesis H1:** The later a raw material is extracted and the higher the underlying rate of interest, the higher its price.

A study of the empirical literature that examines the development of raw materials prices and relates them to Hotelling's rule, reveals no clear picture: in examining the market for old growth timber (which can be considered to be de facto a finite resource on account of its extremely slow growth) Livernois et al. (2006, p. 183)

[13] In line with Krautkaemer (1998 p. 2090, footnote 18), among others, the real interest rate is based on the US Consumer Price Index (CPI). Own calculation based on data from the Bureau of Labor Statistics (2011): 1913 - 2010).

[14] Even though the rate of interest in the original version of the Hotelling model is not specified in detail, this paper deals with real prices, in accordance with other literature that is based on Hotelling.

come to the conclusion that their results are probably the clearest confirmation of the basic Hotelling model to found in the literature to date. In contrast, Farrow (1985), who also tested the Hotelling model, concluded that: "The results reject the hypothesis that the data are consistent with the theoretical model." In his empirical study of resource prices, Heal (1981) discovered that it is not possible to confirm the hypothesis of rising resource prices that underlies Hotelling's rule.

As the Hotelling model in its original form simply provides "some basic implications for how the finite availability of a non-renewable resource affects the resource price" (Krautkraemer 1998, p. 2065), the following sections show how the restrictive assumptions of the basic Hotelling model described above can be relaxed. The resulting changes to the price path will then be presented on this basis. These will initially be discussed in a cet. par. examination and then using a combination of drivers. Economic interpretations will also be explored and illustrated using a numerical example, before further general theory-based hypotheses are put forward and tested.

## 2.1.3 Extensions of the Basic Hotelling Model

### 2.1.3.1.1 Extraction Costs

Extraction costs are not considered in the basic model. If we include these in the Hotelling formula with the designation $c$, we get the following adjusted price path (cp. Krautkraemer, 1998):

$$p(t) \; = p_0 e^{\gamma t} - c_0 e^{\gamma t} + c(t)$$

With a positive discount rate $\gamma$ then $c_0 e^{\gamma t} \geq c_0$ always applies due to $c_0 e^{\gamma t} > 0$ with the result that there is a constant downward price path due to the positive extraction costs $c_0 > 0$. If we assume constant extraction costs of $c_0 = c_t = 0{,}5$ then the price path has the following progression, which deviates from the basic model.

The resource price therefore rises cet. par. *more slowly* than in the original case without extraction costs (large arrow in Figure 5). Based on the fact that the raw materials price is relatively lower in the future than it was the case in the initial case, a larger quantity of the raw material will not be sold until a later point in time.

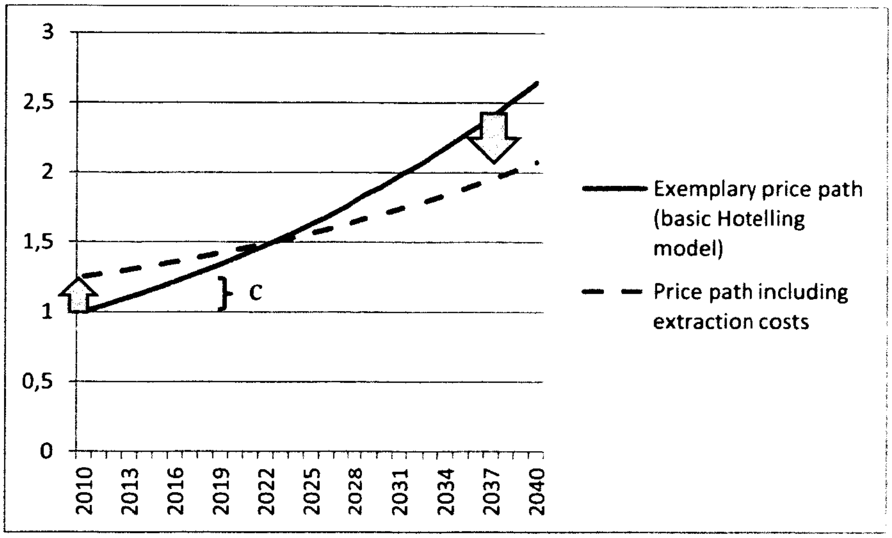


Figure 5 **Exemplary price path in accordance with the basic Hotelling model including extraction costs**

The original model is now to be extended to an analysis of the market side. The impact of this hypothetical consideration to the price path is an abrupt increase of the price at time $t = 0$. This ad hoc effect stems from the fact that each resource provider, who is setting its price based on its marginal cost in a polypole market structure, has to increase the price of its mined resource by the level of resource extraction costs $c$ (small arrow in Figure 5).

Because – if we follow the reasoning of Slade (1982) – extraction costs can be broken down by technical progress on the one hand and degradation (i.e. the over time diminishing quality of ore; cp. Gaudet 2007) on the other, both drivers and their differentiated effects on the price path are considered in more detail now.

#### 2.1.3.1.2 Technical Progress and Degradation

Slade (1982) maintains that extraction costs are negatively dependent on technology-driven, exogenous improvements to extraction methods, and positively dependent on endogenous degradation, which leads us to an expansion of the basic Hotelling model. If this is incorporated into the Hotelling formula, with technical progress represented by $tp$ and degradation by $dg$, this results in the following induced deltas to the original cost trend:

$$-\Delta c(tp)_t = tp_0 e^{\gamma t} - tp(t)$$

and

$$-\Delta c(dg)_t = -dg_0 e^{\gamma t} + dg(t)$$

As there is no publicly-available valid quantification of these drivers, their impact on the price path is presented simply as an example in Figure 6: While the impact of degradation is therefore similar to that of extraction costs, as shown above, in that it pushes the price path down, technical progress has the opposite effect (cp. large arrows).

Considering the impact of technological progress, a short-term effect may also occur, which moves the price path down at time $t = 0$ (cp. small arrow in Figure 6). This is the case when a novel mining method is available, which abruptly gives the opportunity to mine of a resource in a cheaper way.

In contrast, degradation is a slow and planable process. Thus, there is no short term effect and no price jump is expected.

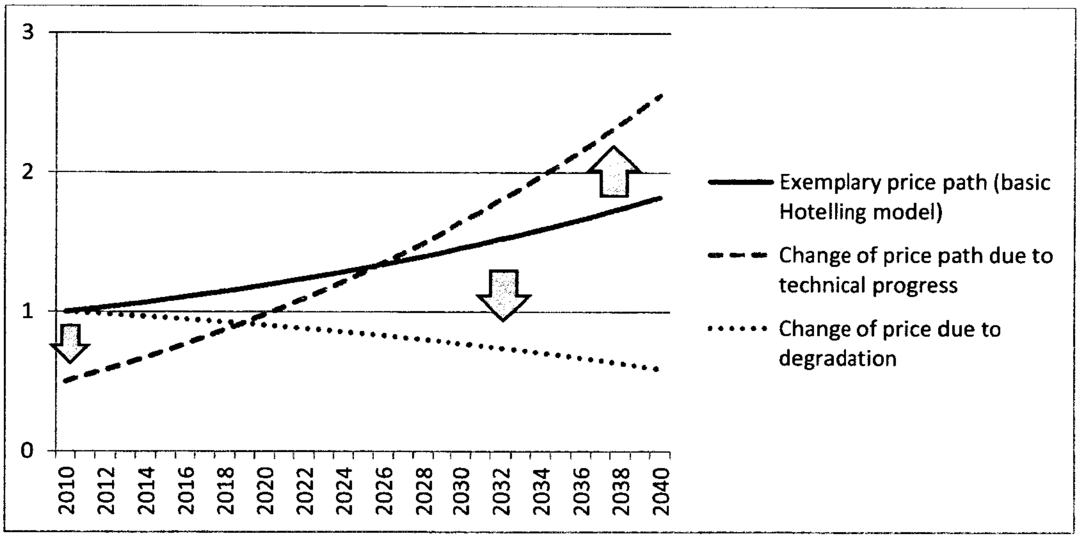


Figure 6 **Example of effect of technical progress and degradation**

On the basis of the considerations presented here we can construct the following hypotheses and relate them to empirical observations:

**Hypothesis H2:** The greater the influence of technical progress on the extraction of a finite resource, the higher its price will be in future.

If we test this hypothesis against the results to be found in empirical literature, we can see the following: Lasserre and Ouellette (1988) concluded from their examination of the effects of technical progress on the extraction of asbestos in Canada that this had a negative effect on the price path and led to a 76% reduction in prices during the period observed from 1953 to 1982. In their study on the effect of technical progress in the years 1967 to 1990, Cuddington and Moss (2001 p. 1144) discovered that this had a significant effect on reducing exploration costs for natural gas and crude oil (though the significance of the effect was less marked for crude oil) and found, for example, that exploration costs for natural gas would have gone up by around 22% per annum if they had not been reduced by the effect of technical progress to the actually observed figure of around 2.7%. A further study on the effects of technical progress was carried out by Schmitz (2005), who measured the increase in "total factor productivity" (which includes labour productivity and capital productivity) in the iron ore industry in Canada and the

USA and found that during the period 1981 - 1995 this went up by 51%. These empirical findings lead to the result that hypothesis H2 must be rejected.

**Hypothesis H3:** The greater the influence of degradation on the extraction of a finite resource, the lower its price will be in future.

In examining global nickel prices, Stollery (1983) establish that degradation (sometimes referred to as 'depletion' or 'reduction of ore quality' in literature) represents an important determinant of price and that the validity of the basic Hotelling model is significantly improved by relaxing the assumption of a "fixed homogeneous reserve stock" (p. 163 et seq.). In addition to studying the effects of technical progress, as described in the last section, Lasserre and Ouellette (1988) also look at the influence of degradation and come to the conclusion that in the period 1953 to 1982 this resulted in a reduction in factor productivity of 63%. These results from studies on the influence of degradation would suggest that hypothesis H3 can also not be proven.

#### 2.1.3.1.3 Combined Examination of Technical Progress and Degradation

Both literature on theoretical models and empirical studies agree that technical progress and degradation affect extraction costs in opposite directions. As to date no conclusion has been drawn as to which of the two drivers has the strongest impact on extraction costs, and which, therefore, over time produces a generally rising or falling price path, the following hypothesis is set and tested using empirical analysis:

**Hypothesis H4:** The later a raw material is extracted, the lower its extraction costs.

In their study of the extraction costs of a range of different raw materials during the period 1870 to 1957, Barnett and Morse (1963) observe a clear fall in extraction costs for minerals, with these overall costs falling steadily by more than 75%. In contrast, Slade (1982) conducts an empirical study of raw material price development between 1870 and 1978 and comes to the conclusion – as discussed in the introduction – that eleven of the twelve raw materials prices studied have a U-shaped curve. She identified technical progress as the first predominant driver that initially leads to falling prices, but in time this is overlaid by the reduction in ore quality and ensuing price increases. According to the study by Lasserre and Ouellette (1988) mentioned previously, with a figure of 76%, technical progress has a stronger price-lowering effect than the price increases caused by degradation, which leads to an overall net lowering of the price by 13%. In his study of copper prices (2002), Buñuel comes to a more differentiated conclusion about the respective strengths of the two drivers, saying that whereas until the end of the 1930s technical progress had been the dominating driver and hence led to a drop in prices, this changed to a positive trend in the years 1938 to 1976, and then once again experienced a clear downturn in the years that followed. So when considering the effects of extraction costs on the price of finite resources, we are faced with a mixed picture, meaning that, overall, the general validity of hypothesis H4 can not be confirmed.

### 2.1.3.1.4 Market Power

Another driver that influences the price of finite resources is the structure of the supply-side market. Unlike in previous models that were based on the case of atomistic competition, in extreme cases a monopoly can arise, whereby the raw materials are extracted by a single producer who can then set the price and control supply in order to maximise its own profits. In contrast to a polypoly situation, the holder of the monopoly can vary the quantities supplied and affect the price trend, which can be shown as

$$p_{(Monopol)}(t) = p_0(y_0)e^{\gamma t} + y_0 \frac{\partial p_0(y)}{\partial y_0} e^{\gamma t} - y(t)\, \frac{\partial p(y,t)}{\partial y(t)},$$

where the price function $p\,(y,t)$ must satisfy certain conditions (cp. Krautkraemer, 1998). If we assume a demand function expressed as $p(t) = 100 - 0.5\,y(t)$, an extraction quantity of $y_0 = y(t) = 1$ that is constant over time and a start price of $p_0(y_0) = 1$, this will be shown diagrammatically in the case of a monopoly, and in turn compared to the polypoly situation that has previously been studied (Figure 7).

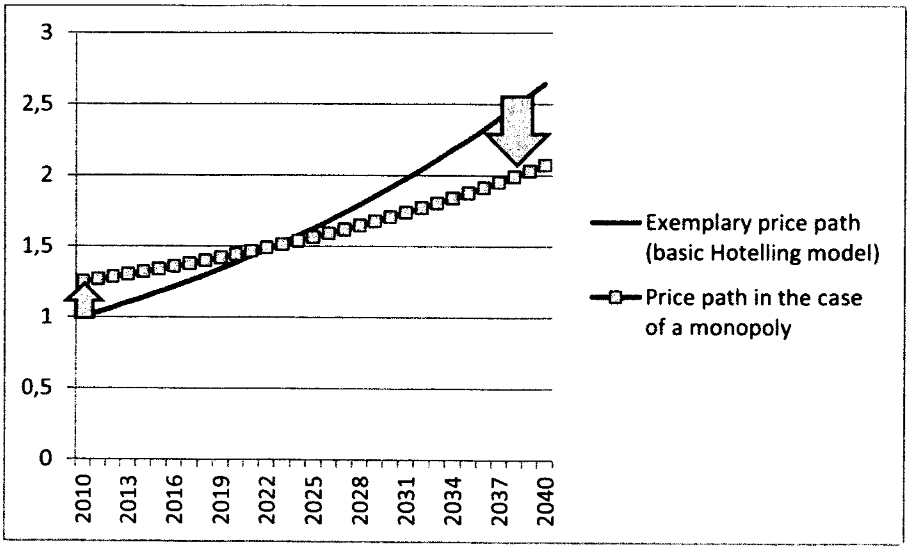


**Figure 7** Exemplary price path (basic Hotelling model) vs. monopoly situation

It becomes apparent that in a monopoly situation the price path is cet. par. flatter than in a competitive situation and hence the extraction of resources occurs more slowly (cp. large arrow in Figure 7). This can be explained formally, as $\frac{\partial p_n}{\partial y_n}$ (i.e. the gradient of a (normal) demand function) is always negative, the expression $e^{\gamma t}$ – due to a positive interest rate – is always greater than one and hence $y_0 \frac{\partial p_0}{\partial y_0} e^{\gamma t}$ is (in terms of the absolute value) always greater than $y(t) \frac{\partial p(t)}{\partial y(t)}$ (Stiglitz 1976, p. 657). If one compares a polypole market structure and a market structure affected by market power, a short-term effect also occurs in this case: An ad hoc increase in market power – for example, because of the merger of companies or caused by the formation of a cartel – leads to a sudden price increase. Its effect is shown by the little arrow in Figure 7. If one examines mining of finite resource and its trading, oligopolistic market structures are often observed (e.g. OPEC in the oil market; Achzet et al. 2011). In this case it should be assumed that the correct price path lies in the range between the extremes of polypoly and monopoly.

If we integrate market power into the basic Hotelling model, then hypothesis H5 can be derived and studied in relation to how it fits in with empirical studies.

**Hypothesis H5:** The greater the supplier-side market power, the flatter the price path.

When reviewing the literature on the development of raw materials prices in relation to Hotelling's rule, it becomes clear that firm empirical studies on the effects of market power that establish a relationship with Hotelling's rule are few and far between (Devarajan and Fisher 1981, p. 68). This is due to the difficulty of finding a valid data set that can be used to separate the effects of market power on price paths. Although theoretical studies provide plenty of evidence for the validity of hypothesis H5, (e.g. Lewis et al. 1979, p. 227, which refer to the Stiglitz and Solow models, among others), it cannot be proven or disproven because of the lack of empirical validation.

#### 2.1.3.1.5 Risk

In line with the assumptions presented in the beginning of Section 2.1.2, it is henceforth assumed that the raw materials suppliers have all the information they require and are in a position to make their extraction decisions under certainty. As this simplified view does not correspond to the uncertainties that plague decision-making situations in the real world, the following will show how the basic Hotelling model can be expanded to include the risk drivers and how to approach the implications of this expansion. In order to achieve this, the interest rate $\gamma$ used by the basic model must be varied so that it contains a risk premium alongside the risk-free market rate of interest and thus present a risk-adjusted discount rate $\gamma_{ra}$ (Copeland et al. 2005, p. 157) with the condition that $\gamma_{ra} > \gamma$. In mining projects, raw material risk represents the main form of risk for the whole project, so only this aspect is considered in the following discussion. This, cet. par., results in the following, risk-adjusted price path:

$$p(t) = p_o e^{\gamma_{ra} t}$$

Different risk drivers can be considered to determine the specific risk related to a finite resource. They can be identified as imponderables relating to the producing countries and concentration, along with political risks and the future importance of a non-renewable resource. So if, based on the above, we now use an exemplary risk-adjusted interest rate $\gamma_{ra}$ of 5% instead of the real interest rate that is used in the basic model based on the US consumer price index (CPI), which at times, with its average rate of 3.24%, insufficiently incorporates an appropriate risk premium, this has a clear effect on the predicted trends in raw materials prices based on the theoretical model.

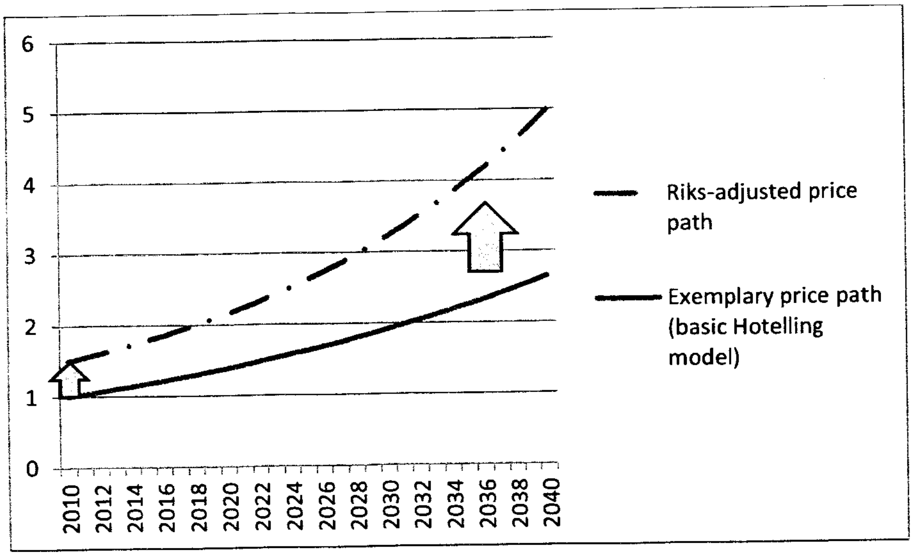


**Figure 8** Example of effect of risk-adjustment

Both the description and the chart show how even a small adjustment to the interest rate have a major effect on the price path (Figure 8). As the risk-adjusted discount rate is higher than the interest rate used in the basic model, the price path is steeper than in the original scenario. Unlike the above-discussed cases of mining costs, technological progress and market power (where one can distinguish between a short-term and a long-term effect) and unlike the case of degradation (only characterized by a long-term effect), in case of risk, both the previously shown long-term effects as well as an additional short-term effect change of the price path in the *same* direction. This ad hoc effect can be explained by the fact that increasing interest rate lead to an increase of mine operators' capital cost. As a result, all mines not having a positive net present value after the increase of interest rates, drop out. As a consequence, there is a price jump is at the beginning of the period, which is shown by the small arrow in Figure 8.From this, it can be deduced that the resource is extracted more rapidly, which leads on to the following assumption:

**Hypothesis H6:** The higher the level of raw material risk, the steeper the price path will be.

Many empirical studies are based on the interest rate used in the Hotelling model. So, for example, Svedberg and Tilton (2006) use the example of copper (during the period 1870 to 2000) to show that the normally-applied real interest rate such as that based on the US consumer price index or the US producer price index overestimates the effect of actual inflation by 0.9% to over 2.0% p.a., and hence the interest rate used in the basic Hotelling model also has to be adjusted. Livernois et al. (2006) test Hotelling's rule using the example of tropical timber, and come to the conclusion that theoretical and empirical observation are only congruent if the interest rate is adjusted to 8.6%, whereby this figure can be construed as a scarcity rent and therefore not as a risk premium in the sense of hypothesis H6. Young und Ryan (1996) expanded the Hotelling model with regard to risk, and in their study of various metal raw materials they established positive risk premiums for copper and zinc. Although this study looked at the possibility of incorporating raw materials risk into the Hotelling model, no inferences were drawn about the validity of the hypothesis. And as theoretical literature also provides contradictory conclusions in relation to the effects of risk on the extraction of raw materials (Farzin 1984, p. 841; Gibert 1979, p. 47; Kumar 2002, p. 852; Pindyck 1980, p. 1203, p. 1217), based on papers that have been published to date, it is not possible to either prove or disprove hypothesis H6 . This is partly due to the fact that this analysis of the interest rate does not distinguish between the proportion that is purely inflation-related, the risk-free interest rate and an appropriate risk premium.

### 2.1.3.1.6 Backstop Technology and Recycling

So called backstop technologies $bs$ as well as recycling $re$ can be identified as additional drivers having an impact on the price development of finite resources. Since it can be demonstrated in the following that both drivers have similar effects on the basic model of Hotelling, they are discussed together in this section.

A backstop technology can be defined as an ultimate technology resting on a very abundant resource base (Nordhaus et al. 1973, p. 532). In contrast to the basic model of Hotelling the price increase comes to an end as soon as the use of a backstop technology is technically feasible and economically viable (Heal, 1976). This leads to an adjustment of the price path, which is now extended to the backstop technology $bs$:

$$p(t) = \min(p_o e^{\gamma_{ra} t}; p_{bs})$$

If it is possible to recycle the complete amount of a finite resource required for new products from unneeded old products, the costs resulting from this are cet. par. the maximum price limit. Thus, assuming that the entire demand for a finite resource can be met by recycling, this driver recycling also leads to a cap on the price path and thus is identical to a backstop technology in its long-term effect (see large arrow in Figure 9).

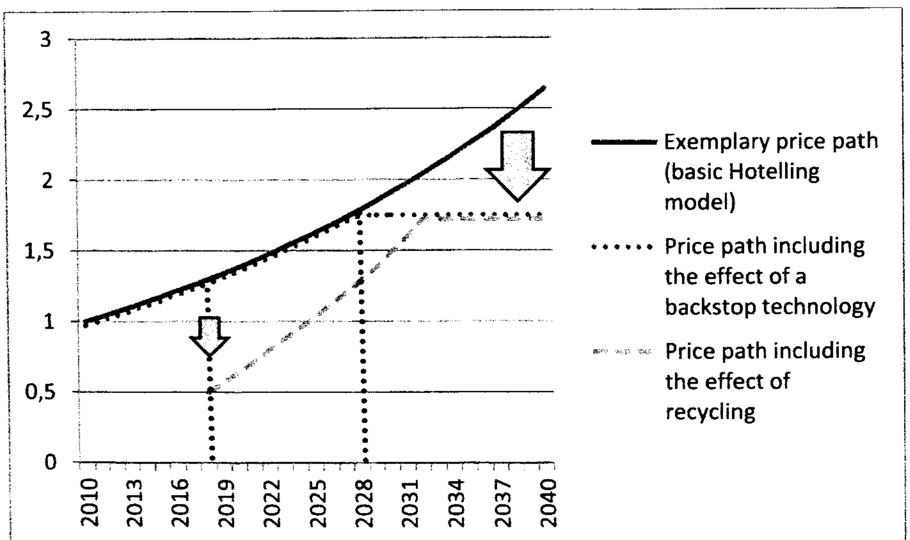


**Figure 9** Example of the effect of a recycling or backstop technology

Additionally, the short-term impact of a mandatory recycling, if it is introduced ad hoc due to legal requirements e.g. in 2018, is also shown in Figure 9. As the raw material re-enter the production cycle in this case, a hypothetical drop in the cost can be observed, as market side is additionally taken into account now. The extent of the decline, however, is dependent on the amount of recycling. On the one hand, this effect (its mode of action is just opposite to the above illustrated case including mining costs) causes an immediate price jump down (cp. small arrow). On the other hand, the price path hereafter rises more steeply than in the original case.[15]

In contrast, if only a very small amount of the resource requirement can be met by recycling, this has no effect on the price path: In this case recycling (and the resulting amount of raw material recovered) can be modelled as a newly developed mine and has no influence on the price (analogous to the case of atomistic market structure discussed in the above passage). However, if a larger part of the demand can be met, it is likely that this cet. par. weakens the increase of the price path. As a result, the price path – depending on the amount of raw material provided by recycling – now runs between the two extreme forms shown in Figure 9. Analogous effects can be identified, if *one* single backstop technology does not have an *immediate* effect, but if a *flow* of innovations characterized by *gradually* effects. Based on these considerations, the following two hypotheses can be derived.

Hypothesis H7 refers to the backstop technology and can be formulated so follow:

**Hypothesis H7:** If a backstop technology exists, the price of an affected finite resource does not exceed the price of the backstop technology.

Although the effect of a backstop technology on the price of finite resources has been studied in several model-theoretic articles (Heal 1976, p 373; Dasgupta and Stiglitz 1981, p. 88; Krautkraemer 1986), there are no empirical studies available

[15] By contrast, the following case would be possible as well: If, because of a legal requirement, mandatory recycling of a non-renewable resource is introduced and the cost of recycling is *higher* than the cost of mining the resource, this would cause a hypothetical price jump *upwards*.

on how backstop technologies affected the Hotelling price path in the past. Nevertheless some studies that are directed toward the future, describe the effects of a backstop technology. For example, Yaksic and Tilton (2009) describe that the extraction of lithium from seawater can be seen as a backstop technology. Based on a their study on the price and quantity structure, they come to the conclusion that the price of lithium carbonate even in worst scenario will never rise for about U.S. $10 per pound in the long term, which – compared to baseline in 2008 – corresponds to a maximum possible price increase by a factor of 10 (Yaksic and Tilton 2009, p. 190). Starting at this price level, the backstop technology (i.e. the extraction from seawater) comes to use in unlimited quantities.

Also focused on a future model Chakravorty et al. (1997) study backstop substitutes for finite resources and draw their attention to the production of electricity. They come to the conclusion that the conventional energy sources such as coal, oil and natural gas will be replaced within an observation period of about 20 years by photovoltaic technologies, since they can be seen as backstop technology because of their over time decreasing cost (Chakravorty et al. 1997, p. 1218).

While both of these studies suggest that the price path is capped if a backstop technology is available and thus support hypothesis H7, the following observation suggests rejecting it: Since the year 1925 the so-called Fischer-Tropsch (FT) process is available to produce oil from coal in industrial scale (Dry 2002). Since the availability of coal – unlike oil – is secured for centuries, this process is a backstop technology theoretically limiting the maximum oil price to the expense of the FT process. The process is already used profitably at a price of about $40 (Bloomberg 2009). In contrast, the oil price moves far beyond this price level and is also characterized by strong volatility (Narayan and Narayan 2007). This contradicts the model-theoretic considerations to backstop technologies and does not support hypothesis H7.

On the basis of the existing empirical literature and the examples presented above, it is therefore not possible to confirm hypothesis H7, nor to reject it.

With regard to the effect of recycling the following hypothesis can be formulated and examined:

**Hypothesis H8:** The higher the recycling rate of a finite resource, the flatter is its price path.

Beginning in the early 1970s, the trade-off between economic growth and environmental quality has been scientifically studied (d'Arge 1971; Skinner 1989). Against this background, first model-theoretic approaches have been developed with the aim to reduce the negative impact of economic growth on the environment by recycling and to reduce the costs resulting from pollution (Weinstein and Zeckhauser 1974; Hoel 1977, p. 232; Huhtala 1999). Empirically studying the effect of recycling on the development of commodities prices, Di Vita states the common problem that "data on recycled waste prices are not easy to find" (Di Vita 2007, p. 148). He therefore merely refers to Berglund and Söderholm (2003), who empirically examine the relation between economic growth and recycling using the example of waste paper but cannot derive any conclusions about the effect of recycling on the resource price.

Since there are no empirical studies that provide a direct link between recycling and resource, the results of several publications will be considered in combination in the following section: They in turn relate to the market of wastepaper.

Since the 1940s, the rate of recycling of paper is constantly increasing (Berglund and Söderholm 2003, p. 434) and has reached a worldwide share of 56% (as of 2009). In some developed countries (such as Sweden and Germany) it is over 80% (The Swedish Forest Industries Federation 2011, p. 50). In contrast, if we examine the development of the price, an enormous volatility can be observed on the one hand (e.g. a sharp rise in cardboard prices by a factor of 6 between January 1994 and April 1995, which is even exceeded by the increase in prices for newspaper paper in the same period of time (Ackerman and Gallagher 2009, p. 278)). On the other hand, however, it is not possible to make a statement about the impact of rising recycling rates on the development of the price path. As a flattening of the price path is not evident, it is not possible to confirm hypothesis H8.

In addition, we will focus on the recycling of mass-produced metals. Since the mid-1970s the rate of recycling of metal has been rising steadily (for example, in Germany from 33% to a current value of 57% (WirtschaftsVereinigung Metalle

2010, p. 3). The investigation of metal prices, however, shows that a flattening of the price path is not recognizable. Instead, only high volatility can be observed, which is also independent of the increase in the recycling rate. Rather, the prices of the relevant metals are each increased (cp. e.g. LME 2012a) and hypothesis H8 can not be confirmed by the investigation of metals either.

The case of Titanium will be discussed in a next step, since the recycling rate for this special metal shows the highest percentage increase: While recycling rate in 1993 was still very low (e.g., only 1% in the U.S., which is the lowest recycling rated tested by Sibley and Butterman 1995, p. 266), the rate nowadays has risen to over 50% (which makes Titanium one of the elements with the highest recycling rate) (United Nations Environmental Programme 2011, p. 26). When considering the price for the same period it is clear that on the one hand a flattening of the price path is not visible (USGS 2011a; Metalprices 2012) (cp. Figure 10). On the other hand the price changes are not related to the enormous increase of the recycling rate by the above-mentioned factor of 50.

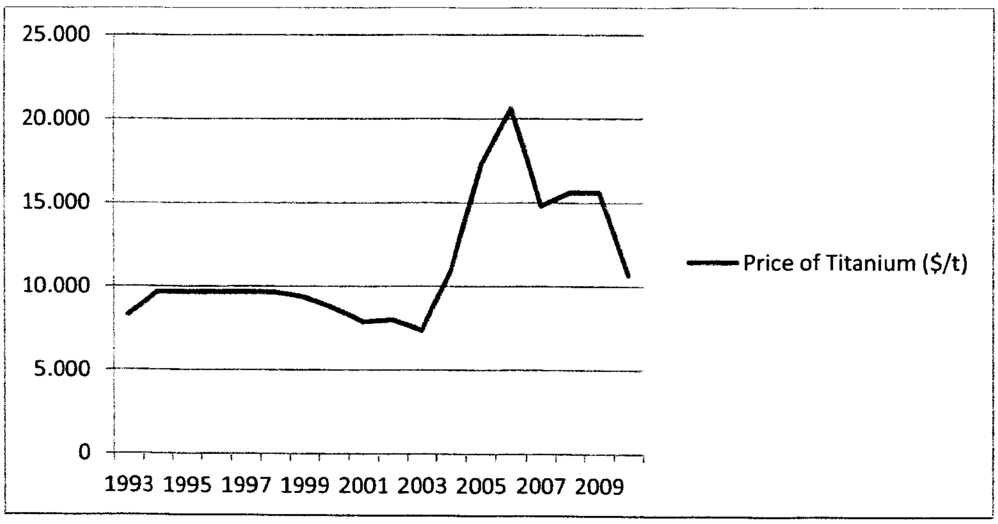


**Figure 10** Price path of Titanium (1993 - 2011) (own chart based on USGS, 2011a)

Since hypothesis H8 could not be confirmed in case of Titanium either, it must be assumed that its validity must be rejected.

It should be noted that it is not possible in principle (and also as part of the short study presented here), to empirically examine the separated effect of recycling on the development of the price path.

### 2.1.4 Simultaneous Integration of Supply-side Drivers

After relating the impact of the previously-analysed supply-side drivers of extraction costs, technical progress, degradation, market power, risk, backstop technology as well as recycling by means of cet. par. observations in relation to the basic Hotelling model, we now attempt to formally show how the *simultaneous* appearance of several drivers that are observable in practice can be described.

Here, extraction costs are assumed to exist in a monopolistic market structure which also includes the risk determinant, backstop technology and recycling. This results in the following variation problem, again in a continuous version:

$$G(y,t) = \int_{t=0}^{T} \frac{p(y,t)y(t)}{e^{\gamma_{ra}t}} dt - \int_{t=0}^{T} \frac{c(t)\,y(t)}{e^{\gamma_{ra}t}} dt + \int_{t=0}^{T} \frac{\Delta c_{tp}(t)\,y(t)}{e^{\gamma_{ra}t}} dt - \int_{t=0}^{T} \frac{\Delta c_{dg}(t)\,y(t)}{e^{\gamma_{ra}t}} dt + \int_{t=0}^{T} \frac{\Delta c_{re}(t)\,y(t)}{e^{\gamma_{ra}t}} dt$$

subject to the isoperimetric constraint

$$\bar{y} = \int_{t=0}^{T} y(t)\,dt$$

or

$$K(y,t) = \bar{y} - \int_{t=0}^{T} y(t)\,dt = 0.$$

This must satisfy the simplified Euler-Lagrange equation with isoperimetric constraint:

$$\frac{\partial L(y,t)}{\partial y(t)} + \lambda \frac{\partial K(y,t)}{\partial y(t)} = 0$$

$$\frac{\frac{\partial p\,(y,t)}{\partial y(t)} y(t)}{e^{\gamma_{ra} t}} + \frac{p\,(y,t)}{e^{\gamma_{ra} t}} - \frac{c(t)}{e^{\gamma_{ra} t}} + \frac{\Delta c_{tp,t}}{e^{\gamma_{ra} t}} - \frac{\Delta c_{dg,t}}{e^{\gamma_{ra} t}} + \frac{\Delta c_{re,t}}{e^{\gamma_{ra} t}} - \lambda = 0$$

It must satisfy the initial value condition on $p_0$ and $c_0$

$$\frac{\partial p_{\,0}(y_0)}{\partial y_{\,0}} y_0 + p_0\left(y_0\right) - c_0 + \Delta c_{tp,0} - \Delta c_{dg,0} + \Delta c_{re,0} - \lambda = 0$$

and, transformed to

$$\frac{\partial p_0(y_0)}{\partial y_0} y_0 + p_0(y_0) - c_0 + \Delta c_{tp,0} - \Delta c_{dg,0} + \Delta c_{re,0} -$$

$$\frac{\frac{\partial p\,(y,t)}{\partial y(t)} y(t)}{e^{\gamma_{ra} t}} - \frac{p\,(y,t)}{e^{\gamma_{ra} t}} + \frac{c(t)}{e^{\gamma_{ra} t}} - \frac{\Delta c_{tp,t}}{e^{\gamma_{ra} t}} + \frac{\Delta c_{dg,t}}{e^{\gamma_{ra} t}} - \frac{\Delta c_{re,t}}{e^{\gamma_{ra} t}} = 0,$$

it leads to the following optimal price path, representing the simultaneous appearance of extraction costs – including adjustments caused both by technical progress and degradation – as well as monopolistic market power, risk, backstop technology and recycling:

$$p\,(y,t) = \min\left(\left(\frac{\partial p_0(y_0)}{\partial (y_0)} y_0 e^{\gamma_{ra} t} - \frac{\partial p\,(y,t)}{\partial y(t)} y(t) + p_0(y_0) e^{\gamma_{ra} t} - c_0 e^{\gamma_{ra} t}\right.\right.$$
$$+ c(t) + \Delta c_{tp,0} e^{\gamma_{ra} t} - \Delta c_{tp,t} - \Delta c_{dg,0} e^{\gamma_{ra} t} + \Delta c_{dg,t}$$
$$\left.\left. + \Delta c_{re,0} e^{\gamma_{ra} t} - \Delta c_{re,t}\right) ; p_{bs,t}\right)$$

In a next step, we set up the second variation again, which reads as follows:

$$\delta^2 G(y,t) = \int_{t=0}^{T} \frac{1}{e^{\gamma_{ra} t}} \cdot \left(\frac{\partial p^2(y,t) \cdot y(t)}{\partial y(t)^2} + 2\frac{\partial p(y)}{\partial y(t)}\right) \cdot h^2 dt$$

Since $\frac{\partial p\,(t)}{\partial y(t)}$ is always negative for normal, linear price-demand functions and, moreover, as $\frac{\partial p^2\,(y,t)\cdot y(t)}{\partial y(t)^2} = 0$ in this case, it holds:

$$\frac{\partial p^2(y,t)\cdot y(t)}{\partial y(t)^2} \leq -2\frac{\partial p(y)}{\partial y(t)}$$

As $h^2 > 0$,

$$\int_{t=0}^{T} \frac{1}{e^{\gamma_{ra}t}} \cdot \left(\frac{\partial p^2(y,t)\cdot y(t)}{\partial y(t)^2} + 2\frac{\partial p(y)}{\partial y(t)}\right) \cdot h^2 dt \leq 0$$

and thus $G(y,t)$ is the *maximum* of the profit (cp. Kielhöfer 2010, p. 23 et seq.).[16]

If we compare the implications resulting from the variation of one *single* driver (discussed in the previous sections) with the case of *simultaneously* integrating them, it becomes clear that the drivers are in each case additively linked with each other. By implication, this opens up – at least theoretically – the possibility of *separating* the various drivers that have an effect on the price path of a finite resource. In turn, this represents a necessary condition for compliance with the call made by Slade und Thille (2009, p. 33): "We must be able to separate the signal from the noise."

[16] The same is true for all normal (i.e. $\frac{\partial p\,(t)}{\partial y(t)} < 0$), *concave* price-demand functions, as $\frac{\partial p^2\,(y,t)\cdot y(t)}{\partial y(t)^2} < 0$.

In case of normal, *convex* shaped price-demand functions, $\frac{\partial p^2\,(y,t)\cdot y(t)}{\partial y(t)^2}$ is positive. Nevertheless, $G(y,t)$ remains maximum up to the limiting case of $\frac{\partial p^2(y,t)\cdot y(t)}{\partial y(t)^2} = -2\frac{\partial p(y)}{\partial y(t)}$. Only if $\frac{\partial p^2(y,t)\cdot y(t)}{\partial y(t)^2} > -2\frac{\partial p(y)}{\partial y(t)}$ (representing an extremely unrealistic scenario from an economic point of view), $G(y,t)$ would not be the maximum of profit any more.

### 2.1.5 Change in Demand

However, changes in demand for finite resources are not acknowledged in the Hotelling approach, even though the recent huge increase in worldwide demand for finite resources has become ever more significant (Stürmer and von Hagen 2012). One reason for the supply side being largely ignored may be due to the fact that the raw materials inventory $\bar{y}$ – and thereby the *quantities* of raw materials that are available on the market and demanded – are not afforded any significance in the Hotelling model when calculating the optimal price path (see above). As a result, the effects of demand are currently only rarely or not at all integrated into a closed model environment.

In order to have an integrated approach, it is therefore necessary to also consider these drivers more closely. Demand for raw materials is now being driven by many new applications and will continue to grow strongly in the future. This is due to global population growth, increasing global prosperity and to the correspondingly higher need for raw materials (Skinner 1989, p. 270; Pollard et al. 2010, p. 9). Technical progress has brought a range of new products onto the market that not only need large amounts of additional raw materials for their manufacture, but also use many additional elements and compounds, due to their specific material properties (Krohns et al. 2011). This trend can be clearly seen in the semi-conductor industry, which in the 1980s used only 12 elements, increased to 16 in the 1990s and which just a decade later had rocketed to over 60 elements (Shadman 2006, p. 9).

In the following we will briefly discuss some papers that emphasize the importance of the demand. Already in 1981, Berck presents an equilibrium model based on seven assumptions and explicitly includes an increase in demand (assumptions 1 and 6). The article, however, refers only to renewable resources and also does not refer the model of Hotelling. With the aim to make predictions about the future price development of finite resources, Radetzki et al. (2008) develop a simple model including the increase in demand. On this basis, they come to the realization that demand-driven price increases may turn into the opposite within a few years.

In an empirically-based study Eggert (1991) examines the reasons for the price volatilities of finite resources and firstly identifies business cycles as a driver affecting the demand for commodities. Secondly, he emphasizes the inflexibility of the commodity consumers to vary their demand depending on the price. By contrast, he identifies that mining quantity of raw material suppliers is fix in short and medium-term perspective and thus affecting prices. Also Rosenau-Tornow et al. (2009) conduct an empirical study on commodity prices and include both the supply and the demand side. With respect to the demand side they stress the importance of the following drivers: new technologies influencing growth in demand, substitution, GDP, industrial production, population or migration into cities, regulatory or other public policy changes (p. 136).

These approaches have in common that they underline the need for the study of supply and demand side. However, they lack connection to a self-contained overall model including a formal relation between the supply and demand side. In contrast, Faucheux and Noël (1995) make a proposal on how the missing relation between the development of the demand and the associated change in the price path can be established. Therefore, the authors use a four-quadrant model (cp. Figure 11). Analogous to Hotelling's basic model it is assumed that the demand for raw materials – as well as the remaining amount –is zero in the end point T. Again, $\bar{y}$ stands for the available amount of raw material, $p$ for price and $t$ for time.

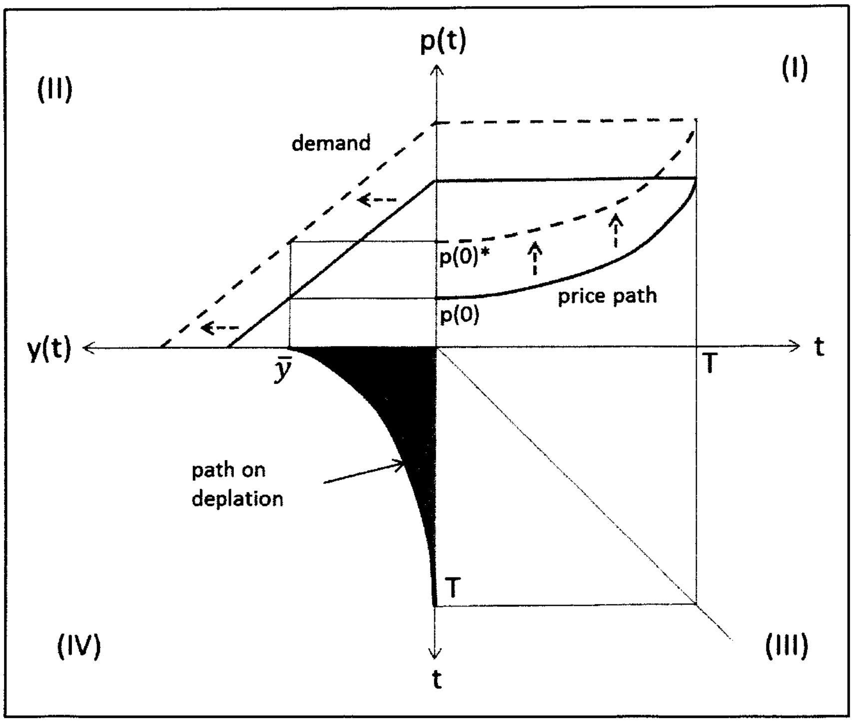


**Figure 11** Variation of the optimal price path of Hotelling''s basic model due to an increase in demand (based on Faucheux und Noël 1995, p. 155)

First, the optimal price path of the Hotelling basic model is shown by the solid line in quadrant (I). In the second quadrant (II), the corresponding demand function is depicted. This is a normal demand function, as quantity demanded decreases with increasing prices of finite resources. Only a bisector is plotted in quadrant (III), which helps to establish a connection to quadrant (IV). The function in this quadrant illustrates the delivered quantity $y$ depending on $t$. If there is a cet. par. increase in demand, the demand curve in quadrant (II) shifts in the direction of arrow to the left (dashed line). This in turn leads to a shift of the price path in arrow direction upwards, which is shown with a dashed line in quadrant (I).

Based on these considerations, the following hypothesis can be formulated:

| |
|---|
| **Hypothesis H9:** The greater the demand, the higher the price path climbs. |

On the basis of empirical literature examining the impact of changes in demand on the price of finite resources, conclusions about the validity of this hypothesis will be derived now. As part of his research on commodity prices since the Second World War Radetzki (2006) analyses three phases (1950-51, 1973-74 and from 2004), in which prices of different resources (metals as well as energy, food and agricultural raw materials) have increased dramatically. He states that "demand shocks predominated as triggers to the commodity price rises" (p. 56). These demand shocks were each preceded by a strong growth in global GDP and a sharp rise in industrial production (p. 62). Similar results can be derived from the examination of copper, as there is a clear correlation between the increase in demand and its price increase: While global copper mining amounted to only 495,000 tons in 1900, the amount has been rising steadily to over 16 million tons in 2010 (i.e. an increase by a factor of 33). During the same period, the price rose – except for small, short-term fluctuations – steadily from \$ 357/t to \$ 7,680/t (i.e. an increase by a factor of 22) (USGS 2011b). Studying copper prices in the years 1994 - 2003, Cerda (2007) derives similar results and proves that increases in demand, particularly from Asia, lead to increases in raw materials prices.

However, using the example of lithium, it can be shown that this statement is not generally valid (cp. Figure 12). While demand and prices move generally the same direction, the fall in prices of \$ 4,470/ton in 2000 to only \$ 1,490/t in 2001 can not only be explained by demand drivers; the same holds for the price increase in 2006.

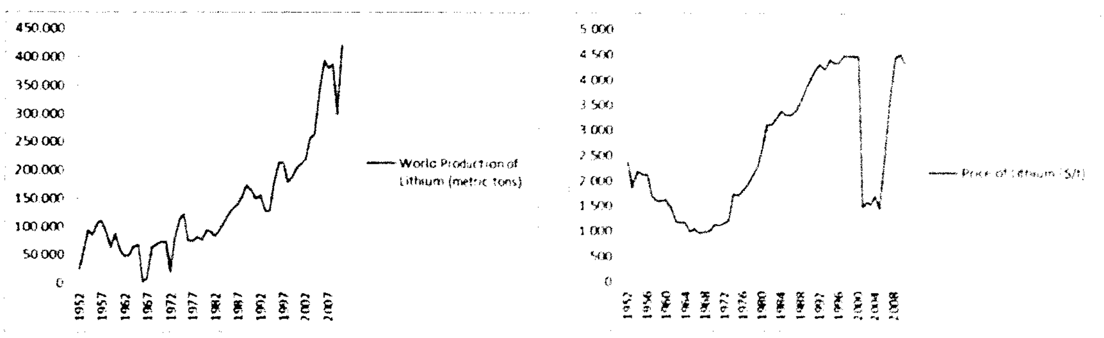


**Figure 12** Word production and price of Lithium (1952 - 2010) (based on USGS, 2011c)

Although the validity of hypothesis H9 thus cannot be confirmed for any finite resource or any time of observation, on the basis of former research it may nevertheless be concluded that an increase in demand tends to price increases.

### 2.1.6 Results on Long Term Drivers

With the objective of allowing a comprehensive analysis of the drivers of raw materials prices, we first of all introduced the most common drivers that have an effect on the price path and suggest how to achieve simultaneous integration of the drivers in the basic Hotelling model. However, an assessment of empirical analyses has proven to be of little use, which may on the one hand be due to the mainly univariate consideration of singular drivers, and on the other hand to the way the analyses tend to concentrate on single, specific, raw materials. Until now there have been no wide-ranging and integrated studies. Although these proposed changes could make the results much more broad-based and hence more meaningful, when we look more closely it seems doubtful whether the drivers that have previously been studied can actually explain the majority of the price movements.

The hypotheses set out in earlier studies and the results based on the empirical findings of the meta-analysis are once again summarised in Table 1.

| No. | Hypothesis | proven | inconsistent | not proven |
|---|---|---|---|---|
| H1 | The later a raw material is extracted and the higher the underlying rate of interest, the higher its price. | 1 | 0 | 3 |
| H2 | The greater the influence of technical progress on the extraction of a finite resource, the lower its price will be in future. | 0 | 0 | 3 |
| H3 | The greater the influence of degradation on the extraction of a finite resource, the higher its price will be in future. | 0 | 0 | 2 |
| H4 | The more recently a raw material is extracted, the lower its extraction costs. | 2 | 2 | 0 |
| H5 | The greater the supplier-side market power, the flatter the price path. | - | - | - |
| H6 | The higher the raw materials risk, the faster the resources are extracted. | 0 | 3 | 0 |
| H7 | If a backstop technology exists, the price of an affected finite resource does not exceed the price of the backstop technology. | 2 | 0 | 1 |
| H8 | The higher the recycling rate of a finite resource, the flatter is its price path. | 0 | 0 | 3 |
| H9 | The greater the demand, the higher the price path climbs. | 3 | 1 | 0 |

**Table 1** Results of general theoretical hypotheses

So far, the basic Hotelling model has been used as a basis for discussion about the influence of the following determinants: extraction costs, technical progress, degradation, the effect of risk, backstop technology, recycling as well as changes in demand on the price path of finite resources. We must conclude that none of the hypotheses, which – as well as the basic model of Hotelling – are only related to the *supply* side, could be confirmed. Instead, only hypothesis H9, as a single referring to the extension of Hotelling's model to the *demand* side – can basically be considered to be proven. For all the other hypotheses, previous empirical studies provide no reliable evidence, or at best give contradictory conclusions.

In this part of the thesis, the question "What drives the prices of finite resources?" was discussed initially from the point of view of a theoretical model. Then individual supply-side drivers like extraction costs, technical progress, degradation, market structure, risk, backstop technology and recycling were examined for their impact on the price of raw materials. In addition, we could identify the need to distinguish between short- and long-term effects and showed their different effects depending on each specific determinant. Corresponding hypotheses were derived and were tested by meta-analysis based on empirical findings. In doing this, none of the hypotheses related to the influence of supply-side determinants could be proven. Expanding the basic Hotelling model to the demand-side, we could show that the hypothesis "price path is positively dependent on demand" can generally be supported. Long-term price increases due to the effects of time and interest rates could not be traced based on existing empirical studies.

There is therefore a need to carry out further studies to analyse the various drivers in an integrated way, and covering a range of finite resources. To carry out further meta-analyses – particularly related to the impact of the determinants backstop technology and recycling – more empirical studies are required. These studies should also take a holistic approach that integrates the current fundamental changes in demand and their increasingly significant drivers, particularly in view of the way they have up to now been ignored by studies based on the Hotelling model. These fundamental changes in demand caused by the range and quantity of different resources involved have created a new phenomenon that requires further study. Further research should focus on developing an integrated, theory-based approach that answers the question of what factors drive the price of finite resources, and bring together supply and demand drivers in one closed, economic model.

It is thus evident that a large number of attempts have been made from a scientific perspective to derive statements about the long-term development of raw materials prices. This is the case both for model-theoretical work and empirical studies. Here, several long-term drivers could be identified, such as mining costs, technical progress, ore quality, market structure, existence of risks, backstop technologies and recycling. However, it is *not* possible on the current state of science to make valid statements about the impact of individual drivers and based thereon, to make valid statements about the long-term development of raw materials prices. Only the long-term driver 'changes in demand' seems to have a distinct effect on the increase in raw materials prices. As part of this research we could show how to handle the occurrence of risk in a model theoretic way. As an adequate quantification of risks is generally difficult, however, and as the risks considered up top now primarily occur in resource-depleting companies, there is still no adequate answer to the question ‚How to include risks arising from the dependence on raw material into the decision calculus of a company *in the producing sector*?'. In summary, it is therefore impossible to make scientifically sound statements about the long-term development of raw materials prices and the level of related risks for companies in the production sector.

## 2.2 What Drives Resource Prices in the Short Term?

Short term fluctuations (also referred to as *volatilities*) of raw materials prices take center stage in the following section (cp. Figure 13). As part of an event study for selected scarce high-tech metals drivers are identified, which are associated with volatilities.

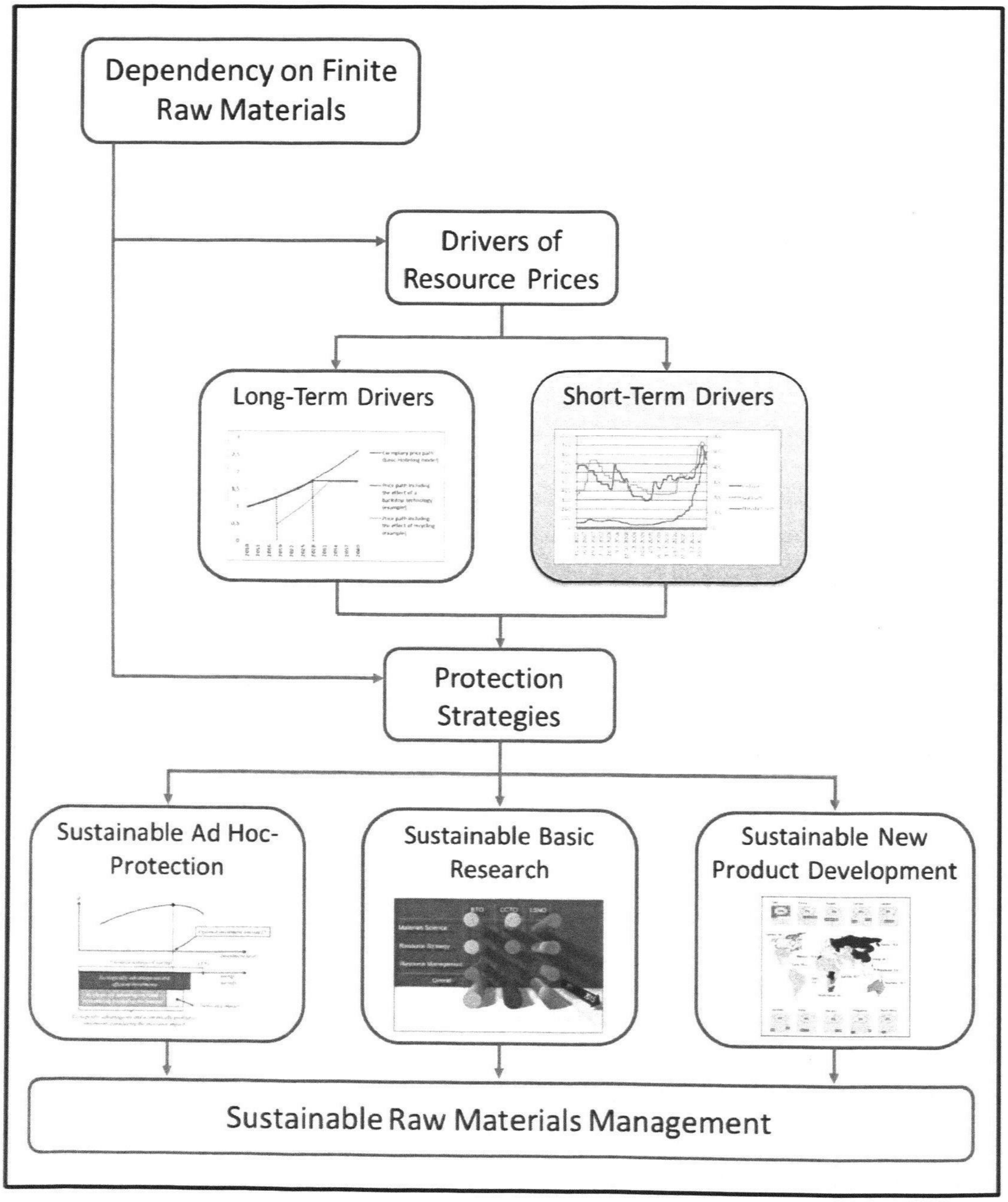


**Figure 13** Structure of the thesis: Short Term Drivers

Depending on the results of our study, we aim to find first answers to the question how a company can usefully secure against short-term price fluctuations.[17]

### 2.2.1 The Need for Research on Short Term Resource Price Volatility

Production, sales, and revenues of modern high-tech goods have increased strongly in recent years, as, for instance, cell phones, notebooks, and photovoltaics have become essential for growing parts of the world's population. This development is not going to end soon, considering recent social and technological developments, like the enormous growth of the Chinese economy and the worldwide debate on an energy turnaround (Moss et al. 2011). All these technologies have one common feature: They depend on a number of very scarce non-renewable resources, especially minor metals like neodymium, gallium, or indium (Angerer et al. 2009; Bublies et al. 2009). With growing demand for these technologies, the demand for these resources, and thus the volatility of their prices, will presumably increase further.

The impact of this already growing demand can be seen by analyzing historical price trends of minor metals, in which we often see high volatility (Chen 2010). For producing companies and whole economies, this development leads to high uncertainty for the future concerning financial and strategic planning, as drops in profits or even production breakdowns are possible consequences (EU 2010; Moss et al. 2011). Therefore, we need to find out which determinants drive these prices.

Furthermore, detailed knowledge of these determinants can be the foundation of future development of efficient policies and forecast methods. As these determinants are reflected within price developments, in this part of the thesis we want to make a contribution to this development by empirically analyzing determinants of minor metals. Since it is not possible to derive consistent results from existing studies (cp. Section 1.3.1), we want to find own answers to the research question of whether fundamental determinants drive the prices or if price developments are

[17] For a detailed analysis of securing strategies, we refer to Section 3.

characteristics of random noise. Furthermore, we want to know if the determinants influence the market's supply or demand.

As the topic of determinants of prices of non-renewable and scarce resources is not new, substantial research exists in this area. An early and, in its setting, fundamental paper was published by Hotelling in 1931 (Hotelling 1931). On the basis of his purely model-theoretic considerations, he emphasizes that the price of a non-renewable resource is determined by the time and the interest rate. These findings later became commonly known as the "Hotelling rule". Different other authors built on this work, like Radetzki, who criticized a number of Hotelling's assumptions. He added, for instance, that technological progress (cp. Section 2.1.3.1.2) achieved by reducing costs might determine the availability of resources and thus their price (Radetzki 2008). Schulze and Heal study extractions costs (cp. Section 2.1.3.1.1) on a purely model-theoretical basis concluding that decreasing extraction costs lead to a decreasing price (Schulze 1974; Heal 1976). In more recent research, Krautkraemer (1998), for instance, summarized that other determinants, like exploration, capital investments, ore quality (cp. Section 2.1.3.1.2), and different market imperfections have to be considered as well when looking at price development. Furthermore, various authors have also analyzed single determinants, like the market structure (cp. Section 2.1.3.1.4), which influences the extraction path of a resource (Stiglitz 1976; Lewis et al. 1979; Gaudet and Lasserre 1988). Krautkraemer and other authors have shown that taxation in general shifts depletion to the future and thus influences price (Slade 1986; Krautkraemer 1990; Karp and Newbery 1991).

Although this list contains only the most common and fundamental papers, it shows that prior research exists in this area and there are indications of several determinants. To date and to our best knowledge, there is no broadly founded empirical analysis of actual determinants for the price of minor metals like neodymium, indium, or gallium, which might be of special interest due to their specific market conditions. For instance, their trading volume is quite small, they are traded over the counter and not within a metals exchange, and there are no futures markets. Thus, their price paths do not contain much random noise, as there is hardly any speculation from brokers. Furthermore, these metals are concentrated very regionally as, for instance, 97% of neodymium is mined in China.

Thus, to identify determinants of the resource price, these minor metals deliver better conditions than other resources, as there are only few mines and hence quite a small market. Furthermore, we assume this market to be suitable as one from to which extract more information than from other markets. Within this part of the thesis, we want to make a contribution to the theory of efficient markets by analyzing whether events lead to a reaction in the market of minor metals and thus drive resource prices. We assume these markets to be at least partially information-efficient and to reflect their information about the determinants, for instance, in the form of events, within the prices. These events will presumably have more implications on the resource prices of these metals. As we want to analyze determinants in the form of events, we will use the methodology of an event study.

All in all, price development, especially of minor metals like neodymium, indium, and gallium, is of strategic relevance for economies and manufacturing industry, but its actual determinants have not yet been empirically examined. Within this part of our thesis, we want to find out which measurable determinants can have an impact on the price of these resources. Therefore, we first present a literature analysis, and then empirically analyze determinants in the form of events occurring in the market. In Section 2.2.2, we begin with an analysis of the relevant literature to identify possible determinants of the resource price. In Section 2.2.3, we define our research hypotheses for the empirical analysis. The methodology we used is explained in detail within Section 2.2.4. Based upon that, we describe the findings in Section 2.2.5 and discuss the results considering our research hypotheses in Section 2.2.6. Finally, we give a conclusion and an outlook for further research in Section 2.2.7.

### 2.2.2 Theoretical Analysis

In Section 2.1, the long-term price development of raw material prices has been studied starting from the basic model of Hotelling. We extended this model to selected drivers and could finally show how different drivers can simultaneously be integrated into a self-contained modeling framework. Once this is possible (at least from a model-theoretic perspective), we will now go the opposite way: Based on existing literature, we will identify a number of (additional) drivers and empirically study their impact on the short-term price of the chosen metals. First of all, the theoretical background required to identify relevant drivers and to answer our research questions will be studied in more detail. To find out what determinants can influence the price of a non-renewable resource, we analyze general and resource-specific literature along the price discovery process with its possible components and their correlations, focusing on short-term effects. With the results of this literature survey, we then generate a list of determinants that may at last influence the price of a non-renewable resource.

According to fundamental economic literature, every price of a commodity paid and received in a perfect market is determined by the intersection between the supply curve and the demand curve (e.g., Stiglitz 1993). Thus, we can assume that every possible change of this equilibrium price is determined by information, leading to a shift of location or shape either in the demand curve, in the supply curve, or in both curves. Hence, these prices reflect the information available in such information-efficient markets (Fama 1970).

The first subject of the following literature analysis is the *supply curve*, and, therefore, we use the fundamental economic work of Stiglitz (1993) and Pindyck and Rubinfeld (1989), supplemented with different non-renewable-resource-specific papers to find out what factors can determine this curve. The supply of a good is the total quantity that firms in an economy are willing to supply at a given price. Hence, we first analyze the "manufacturing process" of a non-renewable resource, which is produced in mines.

Focusing on the mining activities, we first have to consider the area of *exploration* – a driver not examined in Section 2.1. A higher level of exploration activity on the one hand leads to new mines and more supply later on (5 - 10 years), but on the other hand causes higher exploration costs in the present (Hartman and Mutmansky 2002). Regarding these topics, optimal levels of exploration activity have been analyzed by Pindyck (1978) and Deshmukh and Pliska (1980). We also have to consider that there is technological progress in exploration technology, which leads to a shift of the marginal exploration costs and the success rate of an exploration activity over time (Devarajan and Fisher 1982; Swierzbinski and Mendelsohn 1989, Neal 2007; Radetzki 2008). Furthermore, the quality of information (e.g., from USGS) about possible mining districts can also influence the exploration activity and success (Cairns 1990). In our empirical analysis in Section 2.2.3, we will analyze short-run price developments. Therefore, determinants like information about the detection of new deposits will be especially interesting for this analysis.

If exploration activity is successful, mines are built up and resources are extracted (a driver not examined in Section 2.1). Thus, the next area influencing the supply curve is the area of *extraction* (or "exploitation"). First, the initial stock of a resource is one important determinant for supply, which has been analyzed and regarded in fundamental research, for instance by Hotelling (1931) and Gray (1914). As described above, the initial stock in reality does not monotonously decrease, as is often assumed, because exploration activity provides new stocks (Krautkraemer 1998). Optimal levels of extraction quantity are substantial issues and have been analyzed by Hotelling (1931), Stiglitz (1976), Dasgupta and Heal (1974), and other authors (Hotelling 1931; Dasgupta and Heal 1974; Stiglitz 1976). According to Solow and Wan (1976), this quantity depends on extraction costs and extraction technology, which shifts over time (Schulze 1974; Hanson 1980). According to Hartman and Mutmansky every mine has a life cycle and thus its output and costs depend on its period in this life cycle (Hartman and Mutmansky 2002). Furthermore, we have to consider ore quality, as, for instance, ores and metals have different levels of purity, e.g., depending on the mining area and the exhaustion level of the mine (Krautkraemer 1989, 1998). A similar factor, also named by Krautkraemer (1988, 1998), is the so-called cut-off grade, below which it is not economical to mine. As the cut-off grade limits the extraction quantity, it determines the price. The last factor in the area of extraction we can find in the common literature is environmental effects that influence the extracted and hence supplied output of a resource (Stiglitz 1993). All these factors in the area of extraction directly influence the supplied quantity of a resource and thus its price.

One other means of resource production is *recycling* (cp. Section 2.1.3.1.6), as the recycled material can increase the supplied quantity. In 2002, several governments and the European Parliament implemented a project to take back and recycle so-called waste electrical and electronic equipment (The European Parliament and the Council of the European Union 2003). Recycling technology and costs are essential factors for the success of such a project. For instance, Jing reported in 2004 that these projects lead to an increasing supply and are thus influencing the resource price (Jing 2004).

These determinants can all influence the supply of one single mine or country, but in aggregation will influence the global supply curve. In Table 2, we present a list of determinants we identified in the literature analysis.

| Area | Determinants |
|---|---|
| Exploration | • Exploration Activity<br>◦ Information (-)<br>◦ Costs (+)<br>◦ Technology (-)<br>• Exploration Success<br>◦ Information (-)<br>◦ Technology (-) |
| Extraction | • Extraction Quantity<br>◦ Initial stock (-)<br>◦ New stocks by exploration (-)<br>◦ Technology (-)<br>◦ Costs (+)<br>◦ Mine life cycle/cut-off grade (+/-)<br>◦ Environmental effects (+/-)<br>• Ore Quality<br>◦ Mining area (+/-)<br>◦ Mine life cycle (+/-) |
| Recycling | • Recycling Quantity<br>◦ Technology (-)<br>◦ Costs (+) |

**Table 2** Determinants of supply

As we did for the supply curve, we can analyze the demand curve and its determinants, too. The "*demand*" (cp. Section 2.1.5, where the importance of demand factors – which have originally not been considered in Hotelling's model – is emphasized) means the quantity of a good that a household or firm chooses to buy at a given price (e.g., Stiglitz 1993). Regarding non-renewable resources, this demand is mainly concentrated in the manufacturing industry (cp. Section 1.1).

Stiglitz (1993) identified different areas that determine the demand curve. Demand depends on the *population* asking for goods that contain non-renewable resources. Thus, other determinants are population growth and population composition and taste (demographic effect), both now and in the future, as partially analyzed and simulated by Meadows et al. (1972) and Stiglitz (1993). In this area, we can also classify the global *technological progress*. More and more people demand more and more high-tech goods, which obviously leads to increasing demand. We can see this especially in the enormous growth of China (Kaplinskiy 2006).[18]

Next, the demand for a good is determined by the *income* of a household, which depends on the actual economic situation, in case of a manufacturing industry. For instance, the production of high-tech goods increases with a good buying mood based on an adequate economic climate. Here we may regard the present economic situation as well as economic forecasts, which have an influence on the demand (e.g., the American ISM index).

Two more determinants named by different authors are the *prices of substitutes* and *complements* of the resource. A correlation often exists between these prices and the demand for the resource (Hartwick 1978; Hoel 1983; Stiglitz 1993). Here we have to mention that this is presumably less important for non-renewable resources, as in most cases substitutes are uneconomic for the manufacturing industry (EU 2010).

These determinants, derived from literature for the demand curve, are presented in Table 3.

[18] Thus, technical progress has both an impact on the global demand for goods and on the mining technology (cp. Section 2.1.3.1.2).

| Area | Determinants |
|---|---|
| People/Population | • Population<br>◦ Composition (+/-)<br>◦ Taste (+/-) |
| Technology | • Technological Progress (-) |
| Wealth | • Income<br>◦ Economic situation/climate (+) |
| Substitute | • Price of Substitutes (+)<br>• Price of Complements (-) |

**Table 3** Determinants of demand

However, not every determinant influences either the demand *or* the supply curve. A number of determinants can influence both curves, separate and mutually, or influence the price directly.

First, we examine the *financial area*, where interest and exchange rates can influence the price-discovery process. Interest rates determine the value of alternative investments, both for demanding and supplying companies, which influences their economic activity and decisions (Stiglitz 1993). However, the interest rate also influences the optimal extraction/exhaustion path of a non-renewable resource, as Hotelling described in 1931 in his fundamental work (Hotelling 1931, cp. Section 2.1.2). Moreover, the interest rate influences project decisions on supply and demand as it is used as a discount rate for a capital value view (for instance, Bodie et al. 2002). As non-renewable resources are traded in international markets, we have to consider the exchange rates, which can have significant influence on imports and exports and thus on supply and demand. For instance, Bhagwati published articles about these "terms of trade" (Bhagwati and Johnson 1961; Brecher and Bhagwati 1981).

As not all extracted resources are pushed onto the market or are sold by the manufacturing industry immediately, another area we have to consider is *storage*, as did Fama and French (1987). The supply and demand sides may store resources if they expect higher prices in the future. Hence, supply and demand will be influenced by storage strategies and futures prices. Furthermore, we have to consider the costs of capital, as stored commodities can be seen as fixed capital. The marginal storage costs for the resource have an influence on the storage quantity, too (Telser 1958).

These price expectations influencing the storage strategy, and thus the demand and supply curves lead to the next area, *speculation*, which is connected to the storage area. For instance, if consumers expect higher prices, they will buy more resources in the present to build up stocks and will then decrease their buying activity until prices decline or their stocks are consumed. Moreover, suppliers might hold back resources to force up the price through decreasing supply (Brunetti and Gilbert 1995).

Another area that can influence supply and demand is the *economic structure* (cp. Section 2.1.3.1.4). Demand and supply curves have different locations and shapes in monopoly, oligopoly, or perfect competition (Stiglitz 1976; Stiglitz and Dasgupta 1981; Gaudet and Lasserre 1988). Fischer, for instance, presented a paper concerning the monopoly extraction of an exhaustible resource (Fischer and Laxminarayan 2004). Particularly for non-renewable resources like the rare earth elements, about 97% of which are mined in China, we can assume a monopolistic market situation (Bublies et al. 2009, EU 2010).

One important area partly resulting from economic structure is *governmental intervention* (Bhagwati and Feenstra 1982; Makhija 1993). As we can see, for instance, in China, the governmental control over extraction and production and export quotas and drastically increasing taxes are useful tools to sharpen supply and thus increase prices (Bloomberg News 2010). The taxation of non-renewable resources has been analyzed by a number of authors. For instance, Krautkraemer showed that taxation in general shifts depletion and thus supply to the future (Slade 1986; Krautkraemer 1990; Karp and Newbery 1991).

Finally, we have to regard basic economic influencing factors like the *elasticity of demand and supply*, which determines in what magnitude the curve may shift (e.g., Stiglitz 1993).

Determinants of supply/demand are summarized in Table 4.

| Area | Determinants |
|---|---|
| Finance | • Exchange Rate (+)<br>• Interest Rate (+) |
| Storage | • Storage Quantity<br>∘ Storage costs (-) |
| Speculation | • Changed Supply by Speculation (+)<br>• Changed Demand by Speculation (-) |
| Economy | • Market Structure (+/-)<br>• Governmental Intervention<br>∘ Export quotas (+)<br>∘ Extraction quotas (+)<br>∘ Taxes (+)<br>• Elasticity of Demand (+/-)<br>• Elasticity of Supply (+/-) |

**Table 4** Determinants of supply/demand

Within this literature survey, we identified several determinants of the price of a good, especially a non-renewable resource. The results of this analysis will be picked up within the hypotheses for the empirical study in the next section.

### 2.2.3 Hypotheses

With the theoretical derivation of possible determinants in Section 2.2.2, we can frame the research hypotheses for the empirical analysis in Section 2.2.3. As we described, in the rather small and straight markets of minor metals, we assume fundamental determinants to drive the prices. Hence, we expect that a relevant event that influences one or more of these determinants coincides with a resource price development. We define an event as relevant if the related news item lists this event as a rationale for a price chance. This is fulfilled if the news item contains an economically founded notification that, for instance, delivers information about changes in supply, demand, or the price itself.

Thus, we can define our hypotheses, which we want to test, if the determinants from literature lead to price movements within markets for minor metals. With the first hypothesis, we want to find out if the market for minor metals, especially neodymium, indium, and gallium, is at least partially information efficient. This assumption is based on the specific market situation described in Section 2.2.1. Thus, we want to find out whether these events really drive the price, as in information-efficient markets information leads to a reaction of the market.

**Hypothesis H1:** If an event from Table 2 to Table 4 occurs, we can observe a price movement.

As we want to analyze whether the determinants identified in literature are the only ones, we define hypothesis H2 in the opposite direction.

**Hypothesis H2:** If we observe a price movement, there is a coinciding event from Table 2 to Table 4.

For the case of price movements where we cannot identify a coinciding event from Table 2 to Table 4, we extend our hypotheses and define hypotheses H3 and H4:

**Hypothesis H3:** If we observe a price movement, a coinciding event exists (although it cannot be found in Table 2 to Table 4).

**Hypothesis H4:** If an event occurs (although it cannot be found in Table 2 to Table 4), we can observe a price movement.

Furthermore, we will analyze whether the direction of the identified price jumps and coinciding events follows the theoretical assumptions and classification from Section 2.2.2.

**Hypothesis H5a:** If an event results in an increasing (decreasing) demand, the price movement is positive (negative).

**Hypothesis H5b:** If an event results in an increasing (decreasing) supply, the price movement is negative (positive).

### 2.2.4 Methodology

As described in Section 2.1.1, in this part of the thesis we want to analyze empirically the price development of the three minor metals neodymium, indium, and gallium. Therefore, we identify events from news items that would presumably lead to price jumps.

To analyze the impact of events on the market price of a company, a commonly used method is an "event study." Within an event study, fundamentally described in Bodie et al. (2002) and Campbell et al. (1996), the abnormal return induced by an event can be analyzed. This approach can also be used to analyze the price development of resources, as, for instance, Demirer and Kutan (2010) did in 2010. In their paper, they tried to find out at what rate OPEC announcements influence oil spot and future prices.

This typical event study does not exactly fit with our research questions and approach for a number of reasons: First, in contrast to other event studies, we initially do not know all the kinds of events we are looking for, as we first have to find the events themselves, which are responsible for the price movements. Second, we want to analyze more than one kind of event, as we expect to find many events coinciding with price jumps. This assumption is based on the variety of possible determinants, identified in Section 2.2.2. If we analyze common event studies, we can see that single events analyzed in the stock market context often occur more than 100 or even 1,000 times in a few years. With our focus on minor metals with relatively small markets and thus a low quantity of sales, we obviously expect this number to be lower. Regarding this, we have to implement adaptions within the statistical evaluation based on what will probably be a smaller sample size. The last difference from other event studies is the rather low amount of random noise within the price of minor metals. As we can see in Figure 14, price changes of minor metals are less common than changes in, for instance, precious metals. We take this situation into account within the definition of our price jumps.

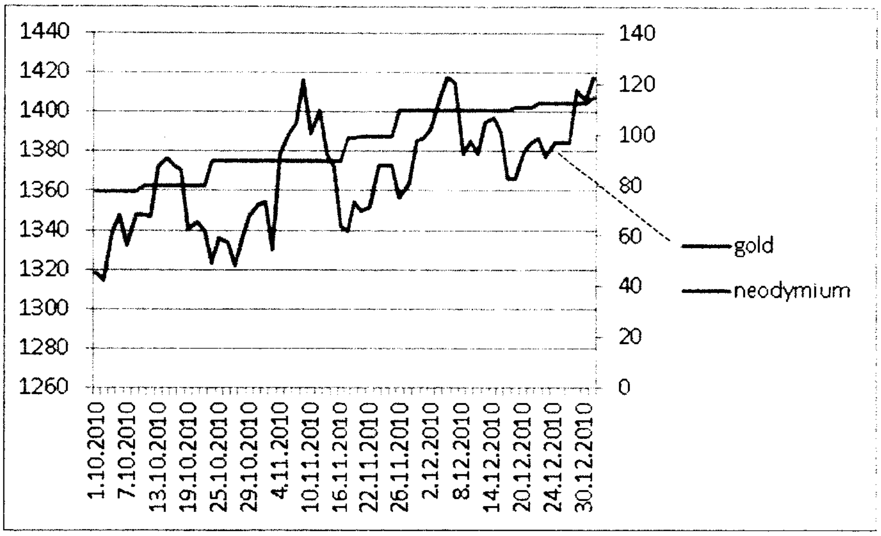


**Figure 14** Price developments of precious metals versus minor metals (2010)

The first step of our empirical analysis and thus our "adjusted event study," is the identification of the resources we want to analyze. As we explained in Section 2.2.1, the market for minor metals seems to be interesting for our analysis of determinants of the resource price. For instance, the regional and small market situation with less random noise within the price paths and the missing speculation by exchange brokers makes these metals particularly suitable for our analysis. Furthermore, supported by the paper of Angerer et al. (2009) and the Critical Raw Material Report (EU 2010), we can identify three important and strategic minor metals for the future.

1. *Neodymium.* It is a rare earth metal, and 97% of its production comes from China. Neodymium is important for the future of global technological progress, as it is an essential component of permanent magnets (e.g., for wind power plants) and laser technology.
2. *Indium.* More than 81% of European indium imports originate in China, and recycling possibilities are quite limited. Indium is used for liquid crystal displays (LCD) and thin-layer photovoltaic cells. The latter is obviously strategic for actual energy turnaround focusing on clean energy.
3. *Gallium.* Gallium is also produced mainly in China, with about 75% of its production there. It currently is not being recycled. Like indium, gallium is used for current and future thin layer photovoltaic cells. Furthermore, it

is an essential component of high-tech goods like Integrated Circles (IC) and White Light Emitting Diodes (WLED).

For a useful and significant analysis, we utilized prices of the three metals on a daily basis from the *Thompson Reuters Datastream*. We chose price values from January 1, 2007 to June 30, 2011. With five trading days a week, we finally got a dataset with 1,173 price values for each of the analyzed metals (Figure 15).

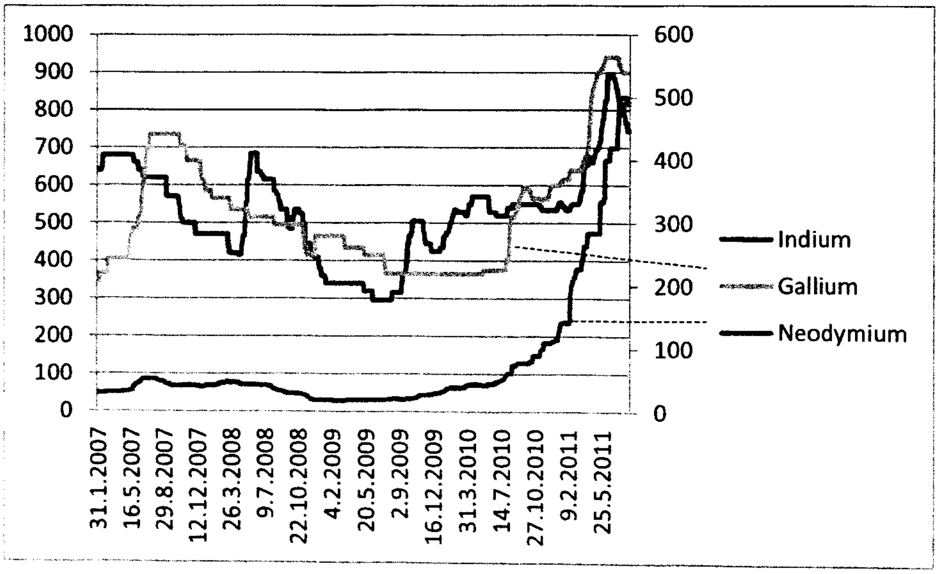


**Figure 15** Price developments of neodymium, indium, and gallium between January 1, 2007 and June 30, 2011

In the second step, we have to identify the price jumps in question. The notion of a "price jump" is not defined clearly in literature, and we found different papers with different definitions (Press 1967; Merton 1976; Aït-Sahalia 2004; Joulin et al. 2008). Regarding one of the most common definitions, we have to compare the values of the examined days with the moving average (Joulin et al. 2008). This identifies a price jump as having occurred if the value r of a specific interval t is higher than the moving average m(t), weighted with a modulating factor s: $|r(t)| > s \cdot m(t)$. This approach is common and useful for underlying values with frequent daily price changes.

We first calculated the relative price changes per day as $\frac{p(t+1)+p(t)}{p(t)}$ and found out that within these three metals, price changes do not occur every day. For neodymium, the price changed only on 180 out of 1,173 days. For indium, there were only 89 price changes, and for gallium, only 88 price changes.

As we can see, the price of these minor metals changes quite rarely. Thus, for our analysis we want to define every price change as a "price jump." Therefore, we define a price jump as having occurred if the following equation is fulfilled:

$\frac{p(t+1)+p(t)}{p(t)} \neq 0$; This equation leads to a number of jumps $i_k$ with $k \in \{1, \dots, n\}$.

If we screen the price values in detail, we recognize that several price changes are followed by price changes in the same direction within a few days. Here, we consider long price movements and assume the following definition:

If the points of time $t_1$ and $t_2$ of two identified jumps i and i+1 do not exceed five days and both are positive or respectively negative, then jump i+1 is assigned to jump i.

The length of the movement is $t_{(i+1)}$-$t_{(i)}$. The height of the movement is $\frac{p(t_{(i+1)})+p(t_i)}{p(t_i)}$.

The five-day interval to assign two single jumps is the result of a screening of all price values where we can spot these long movements. Furthermore, we will see later that the relevant news items are not exactly assignable to one day, but mostly assignable to one week. This assumption will make our analysis more realistic and accurate. Using this definition of a price jump, we finally got 56 jumps for neodymium, 51 jumps for indium, and 32 jumps for gallium. In Section 2.2.5, we present the specific analysis of these findings.

In the next step of our analysis, we want to find out which events can be assigned to the different jumps, if there are any relevant events at all. For this purpose, we use the news archive from Metal-Pages (Metal-Pages 2011). This dataset is suitable for our needs, as it includes news items sorted by metals and date. Furthermore, the news items are specific for the different metals as they contain, for instance, interviews with mine operators to get their estimation of a specific situation. The dataset contains news items for all kinds of metals, including neodymium, indium, and gallium. With these conditions, the specific dataset from MetalPages is well fitted to our requirements for the empirical analysis.

Within this dataset, we get 1,910 news items for neodymium, 2,051 for indium, and 1,340 for gallium. The news items deliver information about developments for a group of different metals or for specific metals. We can find information about global developments like a crisis or increasing demand in Western markets, but we can also find information about specific, domestic activities, like, for instance, the implementation of a new tax system in China or an increasing demand for indium caused by an innovative product. We identified two kinds of relevant news items that contain information about events responsible for the price jumps: The first appears a few days before the price jump and thus delivers information about a current or shortly appearing event. The second is often published a few days after a price jump and analyzes the jump with interviews and opinions from mine operators, suppliers, or buyers. Although these news items appear temporally after the price jumps, they are quite useful for our analysis as they deliver information about relevant events. If we analyze the first announcement of an event within a news item in comparison to the first day of the price jump, we can see in Figure 16 that about 80% of the news items appear temporally before the price jumps and about 20% afterwards.

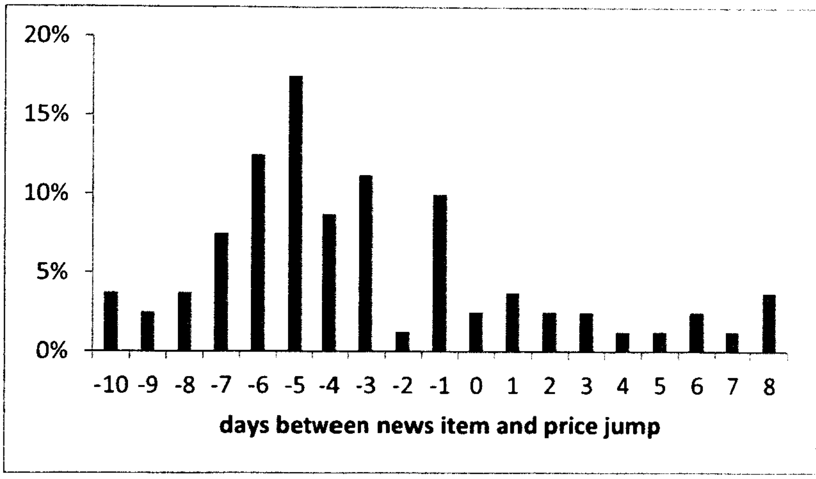


**Figure 16** Price jumps versus news (neodymium)

Furthermore, we identified several news items within a few days that obviously contain information about only one single event. We also have to consider this aspect in our analysis.

As the news items are not structured consistently to look like classical newspaper items, we had to analyze these items manually. We began with a first sample of five price jumps and screened all news items in an interval of 30 days around the price jumps. To identify objectively relevant and significant events from these news items, we set up two assumptions:

1. Based on the news items, the event can be matched clearly to the chosen metal. (Therefore the metal has to be mentioned within the news item.)
2. The news items state that the event is responsible for a development in supply, demand, or even price at the relevant point of time for the examined price jump.

Within this first approach we discovered that only news items from within a range of 10 days at the maximum around the jumps deliver relevant events. Thus, for our analysis we decided to screen the 10-day news interval around a jump for relevant events (Figure 17).

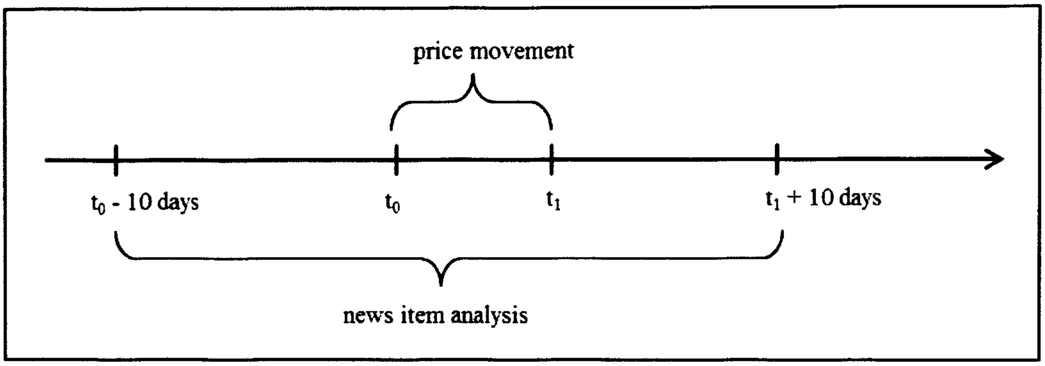


**Figure 17** Timeline event study

With this methodology, we were able to identify relevant events for about 89% of the price jumps for neodymium, 97% for indium, and 91% for gallium. In several cases, we found more than one possible event for a price jump. As the news did not state how much each of the events was responsible for the price development, we assumed all identified events to share the responsibility for this price jump. The result of this step is a list of price jumps with coinciding events.

For a useful result and statistical analysis, in the next step, we clustered the events by their impact and direction on supply, demand, or price. Often the events were quite similar, but with small variations. Therefore, we aggregated events where an obviously similar reason could be found. For instance, we summed up different events involving the Chinese government regulating mines to reduce or stop production. Although they justified this action with several different arguments, for our analysis, we clustered all these events under "Governmental control over production."

Having identified this list of jumps and coinciding events, it is possible to begin our statistical analysis of the results. In the first step, we counted the different and already clustered events to find out which events occurred how frequently. Thus, for each of the events, we were able to calculate the mean height and length of the respective jump. To get a full statistical overview, we added also the standard derivation:

For each event i to n, the mean jump height is $\mu = \frac{1}{m}\sum_j^m h$. Accordingly, the standard deviation of the jump height is $\sigma = \sqrt{E((h-\mu)^2)}$. The values for the jumps' lengths can be calculated in the same way. As the jumps have different lengths, we also calculated the mean jump height and standard deviation per day for each event.

As we mentioned above, we identified different price jumps with one or more relevant coinciding events. In standard event studies, these confounding events are often ignored. As we got confounding events for the majority of jumps, we assumed that every event is responsible for the full price jump. We will discuss this assumption in Section 2.2.7.

As the joining of news items, events, and price jumps appeared to be quite challenging, we want to know whether the results of our analysis have adequate quality. Therefore, we define a precision and recall test. With the recall test, we define at which ratio the jumps lead to a coinciding event. In the first step, we calculated the complete recall, which is defined as

$$\frac{\text{Numberofjumpswithoneormorecoincidingevents}}{\text{Numberofalljumps}}.$$

In a second step, we calculated to which ratio of all jumps an event is responsible for a price jump:

$$\frac{\text{Numberofjumpsforeventi}}{\text{Numberofalljumps}}.$$

The precision test uses the opposite approach:

$$\frac{\text{Numberofeventsiforajump}}{\text{Numberofalleventsi}}$$

Here we want to identify at which ratio our identified events lead to price jumps. For the precision test, we need a more extensive approach. Therefore, we have to analyze all news items, irrespective of price jumps. Thus, we want to identify events of the same kind, although there was potentially no resulting price jump discovered within the empirical analysis. For this approach, we have to define keywords for each event. We detected and extracted these keywords from news items we found in the analysis of the price jumps described above. We implemented this searching algorithm as a Boolean text search within our news items dataset. The results have to be adjusted manually based on objective criteria, as there were different news items in the results that are not relevant. For instance, we eliminated different combined news items clearly concerning the same event. These news items mostly appeared within a few days. In other cases, news items can be found within the results that obviously address no relevant event, but cover other news fitting the keywords. We describe the specific reasons for each event in the appendix to get an objectively identified result set.

As a last step of this scientific study, we want to analyze whether the identified price jumps for each event are significantly different from the mean price development. Therefore, we use three different non-parametric tests, as these are suitable for small samples.

Within the first test, we compare the mean jump height per day (price change per day) of each event with the distribution of all other price changes per day. With the frequency distribution of all price changes per day, we can find out to what impacts each event leads. We are interested in the values for each event as well as in the values for each metal's overall events.

With the second test, we want to compare the distribution of the jumps to the residual values, too. Therefore, we use the common Mann-Whitney-Wilcoxon test (Wilcoxon 1945). We implement this test again for each event. Therefore, we compare two samples: The first sample consists of all price jumps resulting from the event itself, and the second sample contains the remaining values of the price changes from January 2007 to June 2011. As we have both jumps with more than one day of length and more than one jump per type of event, we have to build new samples for each tested event. For instance, we have to compare a 20-day jump with 20-day values. For an event consisting of one 20-day jump and one 10-day jump, we have to build a sample with 50% values of 20 days and 50% values of 10 days.

Finally, we want to prove our results with a third test. Therefore, we use the van der Waerden test (van der Waerden 1952, 1953). This test also converts ranks, like the Mann-Whitney-Wilcoxon test. For the tested samples, we built the same assumptions as for the Mann-Whitney-Wilcoxon test. We implemented both tests also for the precision values, where we added 0% jumps with a median length.

Using this research methodology, we present our findings in the next section.

### 2.2.5 Findings

Based on the empirical analysis described in Section 2.2.3, we have identified price jumps according to our definition for neodymium, indium, and gallium. For almost all of these price jumps, we were able to find one or more coinciding events. In this section, we will explain our findings according to the described research methodology for this empirical analysis.

The first results of our analysis are price jumps, identified within the three metals, sorted by length. These jumps occurred in the period from January 1, 2007 to June 30, 2011. We can see that most price jumps, for all metals, do not exceed a length of five days, and price jumps with a length of more than 20 days are quite rare (Table 5).

| Neodymium | | Indium | | Gallium | |
|---|---|---|---|---|---|
| Length | Number | Length | Number | Length | Number |
| 1 day | 20 | 1 day | 26 | 1 day | 18 |
| 2-5days | 15 | 2-5days | 11 | 2-5days | 4 |
| 6-10 days | 9 | 6-10 days | 6 | 6-10 days | 6 |
| 11-15 days | 4 | 11-15 days | 5 | 11-15 days | 2 |
| 16-20 days | 0 | 16-20 days | 1 | 16-20 days | 1 |
| 21-25 days | 5 | 21-25 days | 2 | 21-25 days | 0 |
| 26-30 days | 2 | 26-30 days | 0 | 26-30 days | 0 |
| > 30 days | 1 | > 30 days | 0 | > 30 days | 1 |
| Σ | 56 | Σ | 51 | Σ | 32 |

**Table 5** Price jumps for neodymium, indium, and gallium

In the next step, we matched the price jumps with the events we identified in the news items. As some price jumps were attributed to more than one coinciding event, the number of events is higher than the number of jumps. In Table 6 - Table 8, we show the resulting events sorted by frequency with the mean value and standard deviation of the jumps' height, length, and height per day.

| Event | Number of price jumps | Mean jump lenght in days | Standard deviation jump lenght in days | Mean jump height in % | Standard deviation jump height in % | Mean jump height per day in % | Standard deviation jump height per day in % |
|---|---|---|---|---|---|---|---|
| **Decreasing supply — speculation for higher prices** | 17 | 8,18 | 8,35 | 15,73% | 15,51% | 1,69% | 3,29% |
| Decreasing supply — lower Export Quotas | 8 | 9,13 | 8,58 | 21,20% | 18,18% | 2,63% | 5,26% |
| **Rainy season** | 7 | 11,43 | 8,63 | 16,85% | 18,94% | 1,27% | 2,62% |
| Decreasing demand — general | 5 | 3,40 | 2,24 | -3,52% | 1,91% | -1,04% | 1,42% |
| **Decreasing demand — speculation for lower prices** | 5 | 15,60 | 14,07 | -14,88% | 14,59% | -1,11% | 1,86% |
| Increasing demand — positive outlook | 5 | 18,40 | 7,31 | 24,57% | 9,83% | 1,20% | 1,84% |
| **Decreasing supply — closure of mines by government"** | 5 | 12,00 | 8,37 | 26,43% | 20,35% | 1,88% | 4,10% |
| Holiday | 4 | 16,50 | 13,16 | -12,19% | 9,90% | -0,81% | 1,41% |
| **Higher export duties** | 4 | 6,75 | 8,32 | 15,84% | 21,91% | 1,60% | 1,74% |
| Increasing supply — suppliers sell stocks | 4 | 11,00 | 14,47 | -8,51% | 10,77% | -0,87% | 1,36% |
| **Holiday before/after** | 3 | 17,00 | 4,32 | 33,97% | 20,58% | 1,73% | 4,05% |
| Decreasing demand — global crisis | 3 | 23,33 | 12,68 | -23,19% | 13,08% | -1,17% | 1,88% |
| **Decreasing supply — governmental control over production** | 3 | 2,00 | 1,41 | 15,01% | 5,32% | 7,45% | 7,65% |
| Increasing supply — new/more production | 2 | 19,50 | 16,50 | -17,03% | 10,13% | -0,98% | 1,55% |
| **Decreasing supply — lower production** | 2 | 4,00 | 2,00 | 5,64% | 1,58% | 1,11% | 1,49% |
| Decreasing supply — state stockpiling | 2 | 13,50 | 7,50 | 17,03% | 9,80% | 1,08% | 1,94% |
| **Fire** | 1 | 21,00 | 0,00 | 53,73% | 0,00% | 2,15% | 4,10% |
| No event found | 10 | | | | | | |
| ***Sum/average over all jumps*** | ***90*** | ***12,51*** | ***8,11*** | ***9,81%*** | ***11,91%*** | ***1,05%*** | ***2.80%*** |
| *Total over all values ("random noise")* | | | | | | *0.24%* | *1.86%* |

**Table 6** Results, neodymium

| Event | Number of price jumps | Mean jump lenght | Standard deviation jump lenght | Mean jump height | Standard deviation jump height | Mean jump height per day | deviation jump height per day |
|---|---|---|---|---|---|---|---|
| **Decreasing demand — general** | **11** | **5.09** | **4,56** | **-7,08%** | **4,33%** | **-1,43%** | **1,98%** |
| Decreasing supply — speculation for higher prices | 9 | 11,00 | 7,41 | 22,10% | 18,44% | 1,90% | 2,88% |
| **Decreasing demand — global crisis** | **6** | **1,83** | **1,86** | **-7,26%** | **3,32%** | **-4,00%** | **3,56%** |
| Increasing demand — general | 6 | 5,83 | 5,84 | 12,37% | 12,95% | 2,29% | 3,14% |
| **Increasing supply — suppliers sell stocks** | **5** | **8,80** | **5,78** | **-7,50%** | **4,85%** | **-0,89%** | **1,30%** |
| Decreasing supply — governmental control | 5 | 11,80 | 7,19 | 17,26% | 14,08% | 1,03% | 1,24% |
| **Decreasing demand — speculation for lower prices** | **5** | **4,00** | **5,51** | **-4,12%** | **3,23%** | **-1,05%** | **1,11%** |
| Decreasing supply — less production | 4 | 9,75 | 8,53 | 27,28% | 26,20% | 2,35% | 3,55% |
| **Decreasing demand — announcement export policy** | **3** | **1,00** | **0,00** | **-3,03%** | **0,08%** | **-3,03%** | **0,08%** |
| Increasing demand — positive outlook | 3 | 7,67 | 3,86 | 10,71% | 1,43% | 1,35% | 1,95% |
| **Holiday** | **2** | **1,00** | **0,00** | **-4,95%** | **3,11%** | **-4,95%** | **3,11%** |
| Increasing demand — fill stocks after disaster | 2 | 14,50 | 8,50 | 17,04% | 11,74% | 1,06% | 1,33% |
| **Higher taxes** | **1** | **1,00** | **0,00** | **6,25%** | **0,00%** | **6,25%** | **0,00%** |
| Increasing supply — recycling | 1 | 1,00 | 0,00 | -6,00% | 0,00% | -6,00% | 0,00% |
| **Increasing demand — innovation** | **1** | **21,00** | **0,00** | **65,06%** | **0,00%** | **2,48%** | **3,77%** |
| Lower taxes | 1 | 6,00 | 0,00 | -12,20% | 0,00% | -2,10% | 3,02% |

**Table 7** Results. indium
(to be continued on the following page)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Unchanged taxes** | **1** | **1,00** | **0,00** | **-5,56%** | **0,00%** | **-5,56%** | **0,00%** |
| Decreasing supply — general | 1 | 6,00 | 0,00 | 9,20% | 0,00% | 1,51% | 2,53% |
| **Holiday before/after** | **1** | **13,00** | **0,00** | **19,09%** | **0,00%** | **1,20%** | **1,64%** |
| Increasing demand — more LCD before FIFA | 1 | 1,00 | 0,00 | 3,64% | 0,00% | 3,64% | 0,00% |
| **Decreasing demand — disaster** | **1** | **4,00** | **0,00** | **-2,22%** | **0,00%** | **-0,56%** | **0,62%** |
| No event found | 2 | | | | | | |
| ***Sum/average over all jumps*** | ***72*** | ***6,49*** | ***2,81*** | ***7,15%*** | ***4,94%*** | ***-0,21%*** | ***1,75%*** |
| ***Total over all values ("random noise")*** | | | | | | ***0,03%*** | ***1,35%*** |

| Event | Number of price jumps | Mean jump lenght | Standard deviation jump lenght | Mean jump height | Standard deviation jump height | Mean jump height per day | deviation jump height per day |
|---|---|---|---|---|---|---|---|
| **Decreasing supply — speculation for higher prices** | 8 | 9,50 | 12,03 | 11,16% | 10,87% | 1,17% | 2,02% |
| Decreasing demand — speculation for lower prices | 8 | 3,38 | 3,60 | -4,60% | 1,81% | -1,36% | 1,76% |
| **Increasing demand — positive outlook** | 4 | 17,00 | 13,55 | 20,75% | 12,85% | 1,22% | 2,00% |
| Increasing demand — LED technology | 4 | 15,50 | 13,35 | 18,41% | 15,43% | 1,19% | 2,18% |
| **Decreasing supply — low stocks** | 3 | 16,33 | 15,76 | 16,64% | 12,98% | 10,96% | 0,00% |
| Decreasing supply — governmental control over production (power) | 3 | 4,33 | 1,25 | 3,91% | 1,80% | 0,90% | 0,71% |
| **Higher export duties** | 2 | 4,50 | 3,50 | 12,20% | 6,40% | 2,71% | 3,13% |
| Decreasing demand — global crisis | 2 | 4,50 | 3,50 | -11,78% | 5,33% | -2,62% | 2,97% |
| **Holiday before/after** | 2 | 21,00 | 17,00 | 19,30% | 15,29% | 0,92% | 1,31% |
| Increasing demand — announcement export duties | 1 | 11,00 | 0,00 | 31,06% | 0,00% | 2,82% | 3,60% |
| **Decreasing supply — general** | 1 | 1,00 | 0,00 | 5,76% | 0,00% | 5,76% | 0,00% |
| Decreasing demand — general | 1 | 1,00 | 0,00 | -4,88% | 0,00% | -4,88% | 0,00% |
| **Decreasing demand — big stocks** | 1 | 9,00 | 0,00 | -5,14% | 0,00% | -0,57% | 0,69% |
| Decreasing supply — state stockpiling | 1 | 6,00 | 0,00 | 6,07% | 0,00% | 1,01% | 0,93% |
| **Holiday** | 1 | 10,00 | 0,00 | -4,32% | 0,00% | -0,43% | 0,53% |
| No event found | 4 | | | | | | |
| ***Sum/average over all jumps*** | *46* | *8,94* | *5,57* | *7,64%* | *5,52%* | *1,25%* | *1,46%* |
| ***Total over all values ("random noise")*** | | | | | | *0,09%* | *1,16%* |

**Table 8** Results, gallium

It is noticeable that the event "Speculation for higher prices" has the highest frequency for neodymium and gallium and the second highest value for indium. Furthermore, we can see that the event "Speculation for lower prices" occurs relatively often for all three metals, but is obviously less frequent than "Speculation for higher prices." Events with a similar frequency are, for instance, the shutdown of mines by the government, export duties, or export policies, whereas events like a fire in a smelter or an innovation can be found less often.

As we can also see in Table 6 - Table 8, we identified coinciding events for almost 90% of the price jumps with our empirical research approach. Therefore, we now explain the substance and the impact of the different events we found within our empirical analysis. The explanations are based on the contents of the relevant news items we identified within our news database. The statistical values of each event can be found in Table 6 - Table 8.

For a better understanding and classification of the events, we have to consider that the People's Republic of China (PRC) mines and produces 97% of the world's neodymium, 58% of indium, and about 75% of gallium. Hence, most of the news and resulting events have their focus on the specific economic aspects in China. As we described in Section 2.2.1, this situation is especially interesting and critical for future development of the prices of minor metals.

We classified these events by their influence on price. Altogether, we identified five categories similar to the areas described within the theoretical analysis: Events can result in *increasing supply, decreasing supply, increasing demand, or decreasing demand.* The fifth category of events *directly* influences the resource price.

The first category of events we have identified influences the supply of the metals, and hence the price. These events belong to the category "*Decreasing supply.*" They result in a significantly increasing price as shown in Table 6 - Table 8.

1. *Speculation for higher prices:* In many cases, we observed that the supply was restrained by the suppliers themselves. In the relevant news items, we found evidence that suppliers were staying on the sidelines and did not sell

their material on the market, as they expected growing demand in the near future, thus increasing prices and profits.

2. *Lower export quotas:* This incident is characteristic of metals mined mainly in China. The Chinese government has set up export quotas for minor metals and adapted them regularly since 2005 (Bradsher 2010). These export quotas were reportedly established to ensure that the domestic companies would not be short in these metals. We identified different news items, where the announcement of lower export quotas leads to price jumps as demanders panicked and bought the material at a high rate.
3. *Rainy season:* Within different news items, we found information about a decreasing supply during the rainy season in China. China is troubled with a rainy and stormy season between spring and summer. This often leads to high masses of water, which can flood the mines and stop production abruptly. Hence, a decrease of supply is inducted immediately.
4. *Government closing mines:* As the news items state, the Chinese government has closed several mines in recent years. The news items show two main reasons for this action: First, the government closed many illegal mines that tried to evade governmental control. Second, they closed several small mines to increase the power of big, state-controlled mines. We found both types of events, but irrespective of the justification for this action, the news items indicate a decreasing supply and, thus, we can observe an increasing price.
5. *Governmental control over production:* We found several situations in which the Chinese government strictly reduced the activity of the mines, and thus their output. They justified this action as environmental protection, as mining of metals causes high air and water pollution values. However, there are opinions that this justification is a pretext for an intended and resulting price increase.
6. *Lower production and stocks:* Several of our identified news items state that suppliers reduce the output of their mines, and thus the supply. In some relevant news items, this is explained as an instrument to counteract falling prices induced by decreasing demand in domestic or global markets, and thus cause rising prices. We also identified news items that stated these low stocks are the result of previous high demand.
7. *State stockpiling:* In many news items, we identified a state stockpiling system as a relevant event. To protect its strategic resources, China introduced

this system for different metals. The announcement of this system has in many cases caused increasing demand from scared industrial demanders, but the implementation has led to a decreasing supply because these demanders, belonging to the state, are preferred and less material will be available on the market.

8. *Disaster:* The news we analyzed often mentioned environmental and external events, which had an obvious influence on the output of the resource. Examples are a fire in a smelter, which reduced production, or an earthquake in a mining area, which destroyed several mines.

Other events we identified had an opposite influence and led to increasing supply of the metals and hence to decreasing prices. These events belong to the category "*Increasing supply.*" It is quite interesting that there are obviously fewer events in this category compared to other categories.

1. *Suppliers sell stocks:* Suppliers regularly clear their stocks and thus increase the supplied quantity of metals. We identified this event mostly at the turn of the year or at the end of a quarter, and found information that the suppliers want to generate cash flow to improve their financial statement to this point of time.
2. *New/more production:* We identified this event as the reason for a positive change in the quantity of the produced metal. According to the relevant news, it is the result of the start of new mines, the restart of formerly closed mines, or increased production activity.
3. *Recycling:* This identified event describes an increasing supply caused by recycled material available on the market.

Some other events we identified explain falling prices, caused by "*Decreasing demand*":

1. *Speculation for lower prices:* With prices falling in a sluggish market, we detected news which state that some buyers expect this trend to go on for some time. Hence, they do not buy the material they need for future production, as they expect falling prices and thus better margins. As the companies in this case have to fall back on their stocks to continue production, this strategy is only feasible if there are enough stocks on hand.
2. *Holidays:* We identified several news items that describe the negative impact of Chinese holidays on domestic demand for metals. China has two

main holidays in which economic life regularly comes to a standstill, which is an explanation for decreasing demand. The first holiday is the Chinese Spring Festival, which slows down the Chinese economy for about one week. This festival is a so-called lunisolar festival, and thus its point in time changes every year, according to the moon and solar cycle. The Chinese National Holiday in the first days of October has the same effect. We also identified news items in summer that explain a decreasing demand because of general holiday-indicated slowdowns in summer all around the world. We identified a second event on this topic, which considers the time before and after holidays. According to its impact, this event can be found in the category "Increasing demand."

3. *Announcement of export policy:* We found several news items that lead to the assumption that export policies impact price changes even before they are adopted. Even at the moment of governmental announcements of upcoming new policies, we identified price jumps as demanders stop buying the material while they wait for the configuration of the new policy.
4. *Global economic development:* We discovered several news items that indicate a decreasing demand based on a sluggish global economy during the global financial crisis. During this global financial crisis since 2007, global economies around the world felt a sensible slowdown, and demand, especially in the manufacturing industry, was drastically reduced. For this event, in particular, we have to repeat that we generally only considered news items that could be matched clearly to a coinciding jump.
5. *Big stocks:* With this event, we identified a situation in which demanders own big stocks for production and thus temporally decrease their buying activities, for instance, waiting for a clearer market situation.
6. *General:* With this event, we cover several news items that indicate a generally decreasing demand in the market but do not specify the reasons for this reaction of the market.

Furthermore, we identified several events of the category "*Increasing demand*" that resulted in increasing prices.

1. *Positive outlook:* In a number of news items, we discovered this event as a kind of speculation for future development. If markets expect good or even outstanding future conditions, their demand for the analyzed metals in-

creases. This reaction is explained with boosted production in many countries, as producers want to be prepared for an expected rise in the demand for produced goods in the near future.

2. *Before/after holidays:* As we described above, during holidays the demand decreases, as there is economic standstill in the market. However, in the days before and after the holidays, the news items we analyzed regularly indicate an increased demand for the metals, which can be seen in increasing prices on these days. This can be explained by the fact that many manufacturing companies have to catch up with their production after the delay during the holidays.
3. *Fill stocks after disaster:* We identified this event especially for indium after the great earthquake in Japan in 2011. The Japanese demanders stopped their production and buying activities suddenly after the earthquake, but restarted these activities with growing demand a few weeks later.
4. *Increasing demand for special products:* We were able to identify a number of events where the demand for a specific product led to growing global demand. For instance, a few months before the soccer World Cup in 2010, buyers increased the production of LCD screens and thus their demand for indium. Furthermore, we found events where innovative goods, like solar and LED products, led to an increasing demand for these materials.
5. *General:* With this event, we cover different news items that indicate a generally increasing demand in the market but do not specify the reasons for this reaction of the market. We may assume that often it is the result of a growing global economic situation, but we did not find evidence within the news items.

Finally, we identified events that did not directly influence demand or supply. Based on the relevant news items, we assume these events directly influenced the resource price.

1. *Higher export duties:* We were able to identify several news items containing information about higher export duties and a resulting price change. Indeed, in the analyzed time frame, China regularly increased export duties for different metals to strengthen the domestic market. Therefore, this event directly leads to higher prices for the global market.

2. *Adaption of taxes:* We also found information about the adaption of taxes and its impact on the resource price. Higher taxes lead to higher prices, but on the other hand, unchanged taxes or even a suddenly announced rebate on taxes lead to an easing of the market and thus falling prices. Hence, these events have the same basis as export duties but are also relevant for the domestic market, as they are not restricted to exported metals.

In Section 2.2.5, we will discuss to what degree these events are similar to events found in our theoretical analysis in Section 2.2.2, and where possible differences lie.

We identified all the events mentioned and explained above with our empirical analysis, illustrated within our research methodology in Section 2.2.3. We can see the statistical effects of each event and metal in Table 6 - Table 8. These results of our analysis are already quite revealing in terms of our research questions. Nevertheless, their statistical validity has to be analyzed. Therefore, we used different testing methods.

As a first approach, the results of the precision and recall tests can be found in Table 9 - Table 11. Thus, with our methodology, on the recall side we can explain about 89% of the jumps with the identified events from the news items for neodymium, 97% for indium, and 91% for gallium.

| Event | Number of price jumps | Recall | Number of events precision | Precision |
|---|---|---|---|---|
| **Decreasing supply — speculation for higher prices** | **17** | **18,89%** | **21** | **80,95%** |
| Decreasing supply — lower Export Quotas | 8 | 8,89% | 12 | 75,00% |
| **Rainy season** | **7** | **7,78%** | **9** | **77,78%** |
| Decreasing demand — general | 5 | 5,56% | 16 | 31,25% |
| **Decreasing demand — speculation for lower prices** | **5** | **5,56%** | **15** | **33,33%** |
| Increasing demand — positive outlook | 5 | 5,56% | 10 | 50,00% |
| **Decreasing supply — closure of mines by government"** | **5** | **5,56%** | **6** | **83,33%** |
| Holiday | 4 | 4,44% | 7 | 57,14% |
| **Higher export duties** | **4** | **4,44%** | **11** | **36,36%** |
| Increasing supply — suppliers sell stocks | 4 | 4,44% | 6 | 66,67% |
| **Holiday before/after** | **3** | **3,33%** | **6** | **50,00%** |
| Decreasing demand — global crisis | 3 | 3,33% | 5 | 60,00% |
| **Decreasing supply — governmental control over production** | **3** | **3,33%** | **5** | **60,00%** |
| Increasing supply — new/more production | 2 | 2,22% | 4 | 50,00% |
| **Decreasing supply — lower production** | **2** | **2,22%** | **10** | **20,00%** |
| Decreasing supply — state stockpiling | 2 | 2,22% | 4 | 50,00% |
| **Fire** | **1** | **1,11%** | **1** | **100,00%** |
| No event found | 10 | 11,11% | | |
| ***Sum/average over all jumps*** | ***90*** | ***100,00%*** | | ***57,75%*** |

**Table 9** Results precision recall test, neodymium

| Event | Number of price jumps | Recall | Number of events precision | Precision |
|---|---|---|---|---|
| **Decreasing demand — general** | **11** | **15,28%** | **13** | **84,62%** |
| Decreasing supply — speculation for higher prices | 9 | 12,50% | 11 | 81,82% |
| **Decreasing demand — global crisis** | **6** | **8,33%** | **9** | **66,67%** |
| Increasing demand — general | 6 | 8,33% | 9 | 66,67% |
| **Increasing supply — suppliers sell stocks** | **5** | **6,94%** | **11** | **45,45%** |
| Decreasing supply — governmental control | 5 | 6,94% | 9 | 55,56% |
| **Decreasing demand — speculation for lower prices** | **5** | **6,94%** | **9** | **55,56%** |
| Decreasing supply — less production | 4 | 5,56% | 7 | 57,14% |
| **Decreasing demand — announcement export policy** | **3** | **4,17%** | **4** | **75,00%** |
| Increasing demand — positive outlook | 3 | 4,17% | 9 | 33,33% |
| **Holiday** | **2** | **2,78%** | **5** | **40,00%** |
| Increasing demand — fill stocks after disaster | 2 | 2,78% | 3 | 66,67% |
| **Higher taxes** | **1** | **1,39%** | **4** | **25,00%** |
| Increasing supply — recycling | 1 | 1,39% | 6 | 16,67% |
| **Increasing demand — innovation** | **1** | **1,39%** | **6** | **16,67%** |
| Lower taxes | 1 | 1,39% | 2 | 50,00% |
| **Unchanged taxes** | **1** | **1,39%** | **4** | **25,00%** |
| Decreasing supply — general | 1 | 1,39% | 2 | 50,00% |
| **Holiday before/after** | **1** | **1,39%** | **8** | **12,50%** |
| Increasing demand — more LCD before FIFA | 1 | 1,39% | 2 | 50,00% |
| **Decreasing demand — disaster** | **1** | **1,39%** | **1** | **100,00%** |
| No Event found | 2 | 2,78% | | |
| ***Sum/average over all jumps*** | ***72*** | ***100,00%*** | | ***51,16%*** |

**Table 10** Results precision recall test, indium

| Event | Number of price jumps | Recall | Number of events precision | Precision |
|---|---|---|---|---|
| Decreasing supply — speculation for higher prices | 8 | 17,39% | 11 | 72,73% |
| Decreasing demand — speculation for lower prices | 8 | 17,39% | 10 | 80,00% |
| Increasing demand — positive outlook | 4 | 8,70% | 8 | 50,00% |
| Increasing demand — LED technology | 4 | 8,70% | 5 | 80,00% |
| Decreasing supply — low stocks | 3 | 6,52% | 4 | 75,00% |
| Decreasing supply — governmental control over production (power) | 3 | 6,52% | 4 | 75,00% |
| Higher export duties | 2 | 4,35% | 2 | 100,00% |
| Decreasing demand — global crisis | 2 | 4,35% | 3 | 66,67% |
| Holiday before/after | 2 | 4,35% | 4 | 50,00% |
| Increasing demand — announcement export duties | 1 | 2,17% | 3 | 33,33% |
| Decreasing supply — general | 1 | 2,17% | 3 | 33,33% |
| Decreasing demand — general | 1 | 2,17% | 4 | 25,00% |
| Decreasing demand — big stocks | 1 | 2,17% | 2 | 50,00% |
| Decreasing supply — state stockpiling | 1 | 2,17% | 4 | 25,00% |
| Holiday | 1 | 2,17% | 5 | 20,00% |
| No event found | 4 | 8,70% | | |
| *Sum/average over all jumps* | *46* | *100,00%* | | *55,74%* |

**Table 11** Results precision recall test, gallium

On the precision side, we analyzed, as described in Section 2.2.3, which ratio of events result in a price jump. As we can see in Table 9 - Table 11, we found a number of additional news items for each event. With this keyword search and the following analysis and adjustment of the resulting news items, we identified the number of events in Table 9 - Table 11. The keywords and adjustment reasons can be taken from appendices A - C. Finally, we got a precision value often higher than 70% for frequently appearing events and very specific events and mean values above 50%.

As we described in Section 2.2.3, as a next step we tested whether the jumps resulting from the identified events could be just characteristics of the random noise or whether they indeed represent a significant correlation. Hence, in the second test we compared the mean price change per day ("jump per day") for each event with the distribution of the mean height of all 1,173 price changes per day for each of the three metals. The results can be seen in Table 12 - Table 14. As we can see, all events lead to price changes per day in the 10% level under the distribution of all price changes. Furthermore, the average value for neodymium is 4.9%. For indium, this value is 3.1%, and for gallium 2.0%.

To confirm the result of this basic test, we used two additional tests to compare the distribution of the jumps to the distribution of the remaining values, as described in Section 2.2.3. The results of the Mann-Whitney-Wilcoxon test can be also found in Table 12 - Table 14. As nearly all events are significant at a 5% level or higher, the Mann-Whitney-Wilcoxon test proves our assumption of significant jumps, too.

As an additional validation, we implemented the Van der Waerden test, described in Section 2.2.3. The results of this test can also be found in Table 12 - Table 14. The compared distributions – event and random noise of the residual values – are significantly unequal for most of the events. We can see that for both the Mann-Whitney-Wilcoxon test and the Van der Waerden test, nearly all events are significant with at least a 5% level of significance. Furthermore, we can outline that the majority of events is significant to a 0.1% level. We can see this especially for events with a higher frequency.

Finally, we implemented the two tests for each event with the precision values of jumps. Therefore, we added 0% jumps for all additionally occurring events not resulting in a price jump. Consequently, we can see that the test values are less significant than for the original recall values.

| Event | Quantile | P-value recall (Wilcoxon) | P-value recall (van der Waerden) | P-value precision (Wilcoxon) | P-value precision (van der Waerden) |
|---|---|---|---|---|---|
| Decreasing supply — speculation for higher prices | 5,70% | 0,00000 *** | 0,00000 *** | 0,00000 *** | 0,00000 *** |
| Decreasing supply — lower Export Quotas | 4,90% | 0,00000 *** | 0,00000 *** | 0,00213 ** | 0,00006 *** |
| Rainy season | 5,80% | 0,01462 * | 0,00509 ** | 0,03971 * | 0,01226 * |
| Decreasing demand — general | 3,30% | 0,00002 *** | 0,00001 *** | 0,00053 *** | 0,00042 *** |
| Decreasing demand — speculation for lower prices | 6,10% | 0,00007 *** | 0,00004 *** | 0,00178 ** | 0,00059 *** |
| Increasing demand — positive outlook | 9,10% | 0,00229 ** | 0,00206 ** | 0,06090 | 0,01995 * |
| Decreasing supply — closure of mines by government" | 4,90% | 0,00206 ** | 0,00016 *** | 0,00591 ** | 0,00066 *** |
| Holiday | 3,80% | 0,00017 *** | 0,00112 ** | 0,00080 *** | 0,00151 ** |
| Higher export duties | 5,40% | 0,01029 * | 0,01102 * | 0,22893 | 0,09847 |
| Increasing supply — suppliers sell stocks | 4,30% | 0,00017 *** | 0,00086 *** | 0,00080 *** | 0,00182 ** |
| Holiday before/after | 4,20% | 0,01286 * | 0,00109 ** | 0,13545 | 0,02002 * |
| Decreasing demand — global crisis | 3,20% | 0,00023 *** | 0,00032 *** | 0,10491 | 0,00070 *** |
| Decreasing supply — governmental control over production | 1,40% | 0,00428 ** | 0,00000 *** | 0,03532 * | 0,00077 *** |
| Increasing supply — new/more production | 7,40% | 0,00062 *** | 0,00918 ** | 0,00486 ** | 0,01346 * |
| Decreasing supply — lower production | 1,00% | 0,04655 * | 0,03829 * | 0,68894 | 0,46623 |
| Decreasing supply — state stockpiling | 8,40% | 0,07097 | 0,06893 | 0,24916 | 0,15744 |
| Fire | 7,10% | 0,08874 | 0,01648 * | 0,08874 | 0,01648 * |
| *Average* | 4,9% | | | | |

**Table 12** Results of non-parametric tests, neodymium (*** = 0.1%, ** = 1%, * = 5%)

| Event | Quantile | P-value recall (Wilcoxon) | | P-value recall (van der Waerden) | | P-value precision (Wilcoxon) | | P-value precision (van der Waerden) | |
|---|---|---|---|---|---|---|---|---|---|
| **Decreasing demand — general** | **3,9%** | **0,00000** | *** | **0,00000** | *** | **0,00000** | *** | **0,00000** | *** |
| Decreasing supply — speculation for higher prices | 3,4% | 0,00000 | *** | 0,00000 | *** | 0,00001 | *** | 0,00000 | *** |
| **Decreasing demand — global crisis** | **1,7%** | **0,00000** | *** | **0,00000** | *** | **0,00008** | *** | **0,00000** | *** |
| Increasing demand — general | 2,6% | 0,00020 | *** | 0,00000 | *** | 0,00147 | ** | 0,00000 | *** |
| **Increasing supply — suppliers sell stocks** | **4,9%** | **0,00009** | *** | **0,00010** | *** | **0,00476** | ** | **0,00051** | *** |
| Decreasing supply — governmental control | 2,6% | 0,00311 | ** | 0,00004 | *** | 0,01589 | * | 0,00031 | *** |
| **Decreasing demand — speculation for lower prices** | **4,8%** | **0,00129** | ** | **0,00018** | *** | **0,00766** | ** | **0,00040** | *** |
| Decreasing supply — less production | 4,7% | 0,00004 | *** | 0,00002 | *** | 0,00150 | ** | 0,00012 | *** |
| **Decreasing demand — announcement export policy** | **2,2%** | **0,00012** | *** | **0,00000** | *** | **0,00082** | *** | **0,00000** | *** |
| Increasing demand — positive outlook | 4,5% | 0,00583 | ** | 0,00117 | ** | 0,08630 | | 0,00649 | ** |
| **Holiday** | **1,2%** | **0,00034** | *** | **0,00000** | *** | **0,02227** | * | **0,00100** | *** |
| Increasing demand — fill stocks after disaster | 4,8% | 0,04496 | * | 0,02628 | * | 0,07357 | | 0,03069 | * |
| **Higher taxes** | **0,8%** | **0,08920** | | **0,00035** | *** | **0,40329** | | **0,07714** | |
| Increasing supply — recycling | 0,6% | 0,00060 | *** | 0,00012 | *** | 0,15317 | | 0,10694 | |

**Table 13** Results of non-parametric tests, indium (*** = 0,1%, ** = 1%, * = 5%)
(to be continued on the following page)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Increasing demand — innovation** | **2,5%** | **0,08380** | | **0,00149** | ** | **0,45824** | | **0,14093** | |
| Lower taxes | 2,6% | 0,00057 | *** | 0,00161 | ** | 0,01513 | * | 0,00901 | ** |
| **Unchanged taxes** | **0,9%** | **0,00062** | *** | **0,00033** | *** | **0,08340** | | **0,06775** | |
| Decreasing supply — general | 4,1% | 0,10598 | | 0,04745 | * | 0,23238 | | 0,10925 | |
| **Holiday before/after** | **4,6%** | **0,10295** | | **0,05194** | | **0,53022** | | **0,21045** | |
| Increasing demand — more LCD before FIFA | 1,8% | 0,09607 | | 0,00169 | ** | 0,24187 | | 0,02722 | * |
| **Decreasing demand — disaster** | **5,0%** | **0,00188** | ** | **0,14825** | | **0,00188** | ** | **0,14825** | |
| ***Average*** | **3,1%** | | | | | | | | |

| Event | Quantile | P-value recall (Wilcoxon) | | P-value recall (van der Waerden) | | P-value precision (Wilcoxon) | | P-value precision (van der Waerden) | |
|---|---|---|---|---|---|---|---|---|---|
| **Decreasing supply — speculation for higher prices** | 3,2% | 0,00003 | *** | 0,00000 | *** | 0,00028 | *** | 0,00000 | *** |
| Decreasing demand — speculation for lower prices | 1,6% | 0,00000 | *** | 0,00000 | *** | 0,00000 | *** | 0,00000 | *** |
| **Increasing demand — positive outlook** | 3,2% | 0,00293 | ** | 0,00037 | *** | 0,02875 | * | 0,00120 | ** |
| Increasing demand — LED technology | 3,2% | 0,00498 | ** | 0,00082 | *** | 0,00982 | ** | 0,00108 | ** |
| **Decreasing supply — low stocks** | 0,3% | 0,01150 | * | 0,00382 | ** | 0,02386 | * | 0,00472 | ** |
| Decreasing supply — governmental control over production (power) | 3,8% | 0,00979 | ** | 0,00107 | ** | 0,02402 | * | 0,00161 | ** |
| **Higher export duties** | 1,9% | 0,02003 | * | 0,00014 | *** | 0,02003 | * | 0,00014 | *** |
| Decreasing demand — global crisis | 1,4% | 0,00028 | *** | 0,00000 | *** | 0,00252 | ** | 0,00001 | *** |
| **Holiday before/after** | 3,8% | 0,05154 | | 0,03362 | * | 0,13598 | | 0,04599 | * |
| Increasing demand — announcement export duties | 1,8% | 0,08433 | | 0,00138 | ** | 0,36337 | | 0,03608 | * |
| **Decreasing supply — general** | 0,9% | 0,08976 | | 0,00005 | *** | 0,35876 | | 0,01487 | * |
| Decreasing demand — general | 0,7% | 0,00060 | *** | 0,00001 | *** | 0,07153 | | 0,01047 | * |
| **Decreasing demand — big stocks** | 2,1% | 0,00103 | ** | 0,05984 | | 0,01445 | * | 0,05772 | |
| Decreasing supply — state stockpiling | 3,8% | 0,12008 | | 0,04777 | * | 0,46862 | | 0,10415 | |
| Holiday | 2,1% | 0,00147 | ** | 0,10913 | | 0,10059 | | 0,08939 | |
| *Average* | 2,0% | | | | | | | | |

**Table 14** Results of non-parametric tests, gallium (*** = 0,1%, ** = 1%, * = 5%)

## 2.2.6 Discussion

As we presented the findings of our literature analysis in Section 2.2.3 and the findings of our empirical analysis in Section 2.2.5, we now discuss the results considering the hypotheses from Section 2.2.2.

We formulated hypothesis H1 to analyze whether events identified from the literature survey (see Table 2 - Table 4) result in price movements. Based on our empirical analysis, we were able to identify a number of events already mentioned in the literature that led to significant price movements. For instance, both previous studies and the present analysis lead to environmental effects as possible influencing factors for the supplied quantity (Stiglitz 1993). Regarding the area of demand, we found factors like the economic situation (for instance, a global crisis) and technological progress within both analyses (e.g., Schulze 1974; Stiglitz 1993). We identified this technological progress especially for new and growing technologies like LED or solar technology on the demand side. Furthermore, events like governmental intervention (e.g., Makhija 1993) and speculation in close contact to storage activities can be found within both analyses. We identified many governmental interventions and regulations in China that were implemented to increase the price. Moreover, speculation for higher prices by suppliers, and thus decreasing supply, could be found in this area. Within the statistical test, we calculated precision values mostly greater than 60% and thus were able to confirm the influence of these determinants.

However, we did not discover events like exploration activities as mentioned in Deshmukh and Pliska (1980), extraction costs, ore quality (Krautkraemer 1998), and mine output depending on its period in the life cycle in our empirical study. Moreover, events related to the price of substitutes and complements (Stiglitz 1993) could not be found in our empirical data, probably because there are no economically suitable substitutes for minor metals.

With hypothesis H2 we tested whether all price movements were caused by the determinants identified in the literature. In sum, we were able to find relevant events for about 90% of the price jumps. However, not all events can be found in the literature. Indeed, we identified different regional, political, environmental, and geographical events that lead to a market reaction, visible as a price movement. For instance, we identified determinants like the growing demand before and after the Chinese holidays, the sluggish market during these holidays and the summer slowdown, the shutdown of mines by governmental force, the decreasing output based on governmental pollution regulations, and finally the regularly appearing rainy season in China. All these events are also important determinants that have not yet been analyzed, although they have a measurable impact on the price of minor metals, and thus need to be investigated in future research and practice.

As we detected a number of events that have not been considered in the literature, we can examine hypotheses H3 and H4. With these hypotheses, we wanted to find out to what extent all identified events determine the resource price. With hypothesis H3, we wanted to analyze whether price jumps lead to coinciding events. We can accept this hypothesis with a precision test within our empirical study, as we were able to find relevant events for about 90% of the price jumps.

We only selected events from news items that could doubtless be connected contextually and temporarily to a specific price jump. In a number of cases, we even identified more than one event from our news items. With this analysis we can clearly see that the majority of price jumps are the result of an identified and relevant event, and thus not the result of random noise. With the results, we can assume that nearly every price jump for minor metals is determined by one or more specific events.

For this analysis, we used a number of assumptions that we have to mention here again. For instance, the definition of a price jump had an impact on the number of jumps and on their length and height. Here, we accepted each daily price change with a value other than 0 as a price jump. Furthermore, we connected two jumps within five days to one coherent price movement. Although these two assumptions for the definition of a price jump used in this scientific study seem to be adequate for the analyzed metals, we could of course modify the parameters and get, for instance, more and thus smaller jumps. However, as we saw within the analysis of the news items, it is quite difficult to match events and news to an exact point of time. As we did with our assumption of coherent jumps within five days, we got this high value of coinciding events that could be matched clearly to a price jump. The third assumption is that our news item dataset contains news from one single source. However, as our data source is one of the biggest news, price, and information databases for worldwide metals and delivers reliable news items, we can consider this limitation justifiable. The fourth assumption we have to mention is the treatment of confounding events: We treated each event as responsible for the price jump, as it was not possible to discriminate between these events suitably. Furthermore, we did not exclude these confounding events from the analysis, which is a common practice in empirical literature, especially event studies, as this would have diminished our sample radically. Considering our research questions, we can justify these assumptions, as we wanted to find out what kinds of determinants drive resource prices.

In the next step, we wanted to analyze to what extent all events lead to price movements following hypothesis H4. As we described, this hypothesis is based on the theory of information-efficient markets, in which information leads to a reaction in the market. We have described the findings within the recall test in Sections 2.2.5 and Section 2.2.6. Here we can see that for some events we got recall values over 70%. Hence, given an event, for example, from news items or other sources, we can assume a price change in the near future. This information can help to enable better decision making for industry and politics. With our analysis, we identified about 20% of events from news items that temporally followed price jumps. This result is not contradictory to our findings, as these news items contained information about events that were chronological before the relevant price jump. Furthermore, the time frame between information and market reaction is quite small, and thus information has to be provided in time and has to be screened effectively. Only under these circumstances can the benefits mentioned above be realized profitably. Finally, we can accept this hypothesis, as we identified weak information-efficient markets, especially for events occurring often within our analyzed time frame.

Furthermore, we wanted to analyze whether our identified price movements are significantly different from the average price development. Using the Wilcoxon-

Mann-Whitney test we showed that about 90% of our price jumps for neodymium, indium, and gallium are significant at a level of 5% or higher. The van der Waerden test proved these results with a value of about 80% significant price jumps at a level of significance of 5% or higher. Furthermore, we identified that many events, like the speculation for higher prices, even showed a significance of 0.1%. Even the results for the tests with recall values show a majority of significant events. Finally, we can confirm our results, as our price jumps are significantly different from average price development for most of the events. Regarding the assumption about our definition of price jumps above, we can note that these statistical results also confirm this assumption.

With hypotheses H5a and H5b, we wanted to analyze whether the impacts of equal determinants show the same direction. As we can see in Section 2.2.5, Table 6 - Table 8, we can prove the assumption from the literature analysis, as increasing (decreasing) demand leads to higher (lower) prices and increasing (decreasing) supply leads to lower (higher) prices (Stiglitz 1993). Thus, we can accept these hypotheses for our analysis.

Overall, we were able to identify a number of determinants that drive the price of a minor metal. Not all of these determinants have been analyzed in the literature reviewed. Hence, with the results of our analysis, we can assume that most of the price jumps are the result of fundamental determinants and not characteristics of random noise.

### 2.2.7 Results on Short Term Drivers

Regarding our research question, with this part of the thesis we wanted to analyze whether price developments of minor metals are the result of fundamental determinants. Through our literature analysis, we discovered several determinants from general as well as resource-specific studies. As these determinants were quite general or had been analyzed only for resources like crude oil or copper, we presented an empirical analysis for determinants of minor metals. With this empirical analysis, we identified price jumps for neodymium, indium, and gallium and coinciding events that in most cases could explain these price jumps. We discovered much overlap between the results of our literature survey and our empirical analysis, but many differences, too. The regional events in China, in particular, like the rainy season or holidays, quite often had a significant influence on the resource price, although these factors were not mentioned or even analyzed in the existing literature. With the different statistical tests, we showed that the identified events often lead to significant price jumps.

With the results of this scientific study, we can contribute to the comprehension of the short term determinants of resource prices. We showed that markets for minor metals are partially weak as regards information efficiency (Fama 1970), as price jumps can mostly be related to coinciding events. Finally, with this analysis we hope to improve the comprehension of prices of non-renewable resources for better and more suitable long-term planning for companies and governments. We can see that especially for developing efficient policies, information of events in the market environment has to be analyzed. Therefore it is necessary that this information gets published by reliable institutions. These institutions like for instance USGS in the United States or BGR in Germany have to be supported in delivering specific market environment observations of these strategic resources for companies and governments.

Therefore, we hope that these findings can make a small contribution on the way to a well-informed and long-term-oriented utilization of our natural resources.

As the number of de facto available events is quite small for each of the analyzed metals, it would be beneficial to analyze other metals or non-renewable resources in a similar way in further research to test and compare our findings. Especially the comparison with less rare metals with different market conditions like copper would be beneficial. Furthermore, we could extend the time period back to the past, where other events could possibly have occurred, and choose more and other data sources for the news items. For further analysis and forecasts, we could use other sources like local newspapers to indicate these events in time, which of course would be possible, for instance, for events like holidays or a rainy season.

As part of our empirical analysis, which was carried out on the basis of a raw material-specific event study, we could exemplarily show for the three metals neodymium, indium, and gallium that short-term price fluctuations can be explained mostly by specific events. So, these events (like the rainy season or holiday in China, which significantly influence these raw materials prices) can be seen as valid short-term drivers of raw materials prices. This result represents a novelty in literature and can help a company relying on these metals to reduce its raw materials risks e.g. by buying neodymium, indium, and gallium at the appropriate time (i.e. at a decreased price level during Chinese holiday time).

In the course of our scientific investigations, both long-term and short-term drivers were identified that have an impact on the development of commodity prices. Even though we could *identify* specific drivers in the case of a long-term view (Section 2.1), it is – based on the latest research – not possible to *quantify* their influence on the price of finite raw materials. Consequently, valid statements about the long-term development of raw materials prices that allow a company to precisely protect against long-term risks *on the basis of scientific price forecasts* are *not* possible. In contrast, we could *identify* individual drivers and their *effect* on the price development in the case of short-term price fluctuations (Section 2.2). This – so far gained – knowledge allows companies to better protect against risks arising from the short-term demand for non-renewable raw materials.

Nevertheless, a sustainable company also needs to protect against long-term risks arising from its consumption of raw materials. For this purpose, securing strategies are presented in the second part of the thesis. These strategies, however, do not aim at a better explanation or prediction of prices and their development, but show ways to secure against price increases and fluctuations. Thus, these strategies and measures enable a company to secure against raw materials risk even in the long term.

# 3 Strategies and Measures to Protect against Raw Materials Risks

After the discussion of long- and short-term price drivers in the previous section, strategies to secure a company against raw materials risks are the focus of Section 3. Especially because of the fact that it is very difficult to precisely predict long-term future price developments, it is useful for a company to concentrate on possible protection strategies and to implement them in a reasonable extent.

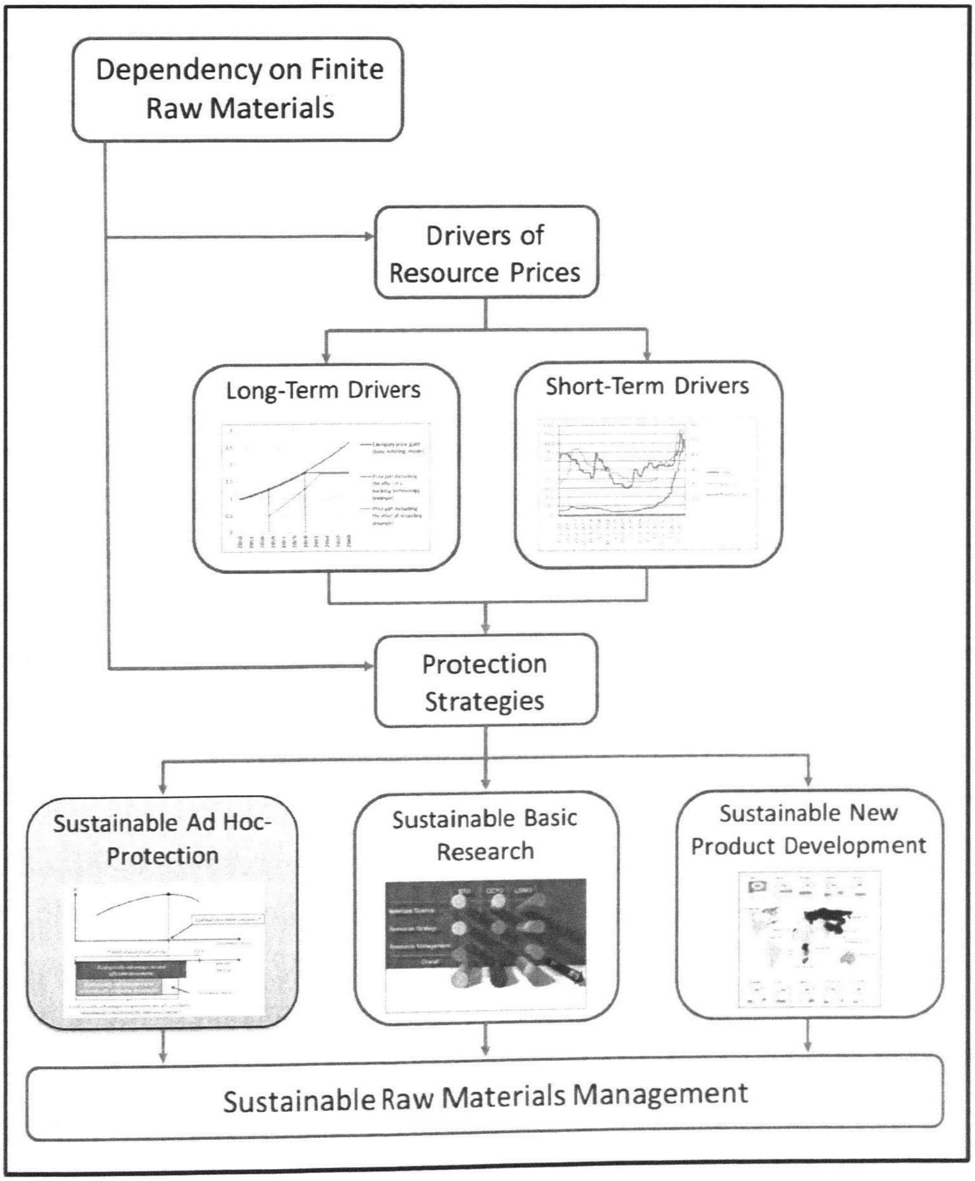


**Figure 18** Structure of the thesis: Sustainable Ad Hoc-Protection

## 3.1 Sustainable Ad Hoc-Protection

In the following section, an ad hoc-protection strategy for the sustainable use of energy resources in the area of ‚building energy efficiency‘ is examined (Figure 18). Since very high energy savings are possible in this area, the following scientific investigation may be useful for a company in the manufacturing industry, as it has production facilities whose energy efficiency can be increased. In our model, we particularly focus on IS-investments, which can contribute to increase energy efficiency to a large extent. We use a mathematical optimization approach to examine the extent to which risks resulting from changes and the increase of energy prices can be reduced by investments in energy saving measures. In this context, we examine the optimal investment amount in an intelligent building and try to find out whether it is possible to reduce negative economic and environmental impacts at the same time. In addition, we will discuss the appropriate timing to undertake investments in the area of ‚building energy efficiency‘.

### 3.1.1 The Need for Research on Building Energy Efficiency

‘Even with modest UN projections for population growth, consumption and climate change, by 2030 humanity will need the capacity of two Earths to absorb $CO_2$ waste and keep up with natural resource consumption‘ (Pollard et al. 2010, p. 9). To counteract this trend and the concomitant pollution of our planet, technical innovations in various disciplines have been developed. Likewise, information systems develop such innovations. IS can be used to enhance the efficiency of business processes comprehensively over various economic sectors (Buhl and Laartz 2008). In this way almost 7.8 $GtCO_2e$ (billion tonnes (Gt) carbon dioxide equivalent) can be saved until 2020 based on the level of 2002. This reduction of carbon emissions would be five times as large as the whole carbon footprint caused by IS itself (The Climate Group 2008, p. 6). One measure to reduce energy consumption and carbon emissions outstandingly strong is the application of IS in properties in so-called Intelligent Houses (also: ‘Smart Homes’ or ‘Green Buildings’). IS can be used as a tool for monitoring, feedback and optimization at every stage of a property‘s life cycle to raise energy efficiency. Global carbon emissions can be lowered simply by using IS in properties (based on the level of 2002 until 2020) about 1.68 $GtCO_2e$ and the global energy consumption of buildings about 15 % (The Climate Group 2008, p.6). Further IS innovations, which will be available for the first time in the future, could even raise the denoted savings. In this manner Intelligent Houses are a key enabler for energy efficiency. Although the ecological advantages of Intelligent Houses are evident, the investment rate to higher energy efficiency is currently only 1-1.5 % in non-residential buildings and actually only 0.07 % in residential buildings (Rottke 2009). The use of IS in commercial or private properties should thereby be far lower. But which factors are opposed to the ecological contribution of IS at this point? Considering Intelligent Houses from an economic point of view, the following specifications appear, which influence the result of investment valuations:

*Specification 1:* The landlord-tenant-dilemma. Often, IS energy efficiency investments are not made because of the landlord-tenant-dilemma (The Climate Group 2008). The landlord decides on the investment amount, but only the tenant benefits from the resulting energy cost savings. In contrast, tenants do not have the right to claim an IS investment from the landlord (Bengtsson 1998). The profitability of IS investments thus depends on the perspective.

*Specification 2:* Dependence on future energy price. The advantageousness of investments in Intelligent Houses depends on the future energy price (Atkinson et al. 2009).

*Specification 3:* Dependence on energy price volatility. IS investments reduce energy costs and (at the same time) its volatility, which originates from the volatile energy price (e.g. calculated standard deviation of oil was 0.33 (Schwartz 1997, p. 937). Thus, the advantageousness of Intelligent House investments depends on the volatility of the energy price (Thompson 1997).

To the best of our knowledge, there are no established investment valuation methods that (adequately) consider these three specifications. However, the special economic potential of Intelligent House investments is founded on these characteristics. Furthermore, established valuation methods capture the specifications only qualitatively and / or are only applicable for a particular technology. A universally applicable, quantitative valuation method is not available. Many ecologically advantageous and economically profitable investments are thus not identified. To counteract, this scientific study will answer the following research question: How can Intelligent House investments be correctly evaluated economically and consequently contribute to use the ecological and economical potentials of IS?

To answer this research question we describe the conflict between ecology and economy of Intelligent Houses in chapter 3.1. In chapter 3.2 general assumptions and definitions that are necessary for a formal analysis are introduced. In chapter 3.3 we illustrate in an integrated risk and return consideration how to identify investments, which are ecologically advantageous and economically profitable at the same time. In chapter 3.4 the economically optimal investment out of all identified investments is determined. Subsequently we illustrate the practical applicability of the model with a practical example. We close with a summary of all results and a critical acclaim in chapter 5.

### 3.1.2 Literature review

IS in properties can contribute to energy efficiency already during the property's design and construction phase. Virtual construction methods improve property lot's logistics and thus lower energy consumption. But IS can also be used during the use of the property to increase energy efficiency. IS can increase energy efficiency through teleworking and collaborative technologies to reduce need for office space (achievable carbon savings until 2020: 0.11 $GtCO_2e$), improved building design (0.45 $GtCO_2e$ savings), building management systems (automatically controlled and adjusted heating, cooling, lighting and energy use; 0.39 $GtCO_2e$ savings), voltage optimization (0.24 $GtCO_2e$ savings), automated heating, ventilation and air conditioning (0.13 $GtCO_2e$ savings) and much more (The Climate Group 2008, p. 40). The Climate Group (2008, p. 9) estimates the achievable savings and states a globally IS-enabled saving potential of € 644 billion (between 2002 and 2020), of which € 216 billion can be saved by using IS in real estate. Kuckshinrichs et al. (2010) find even higher $CO_2$ abatement costs, which would raise the contemplated amount considerably.

To integrate IS in properties the investment alternatives which are best to achieve the elected objectives have to be identified out of all existing alternatives. For this purpose, both the necessary investment payout and the value added need to be considered in order to reach an economical valuation. As mentioned above, an appropriate IS investment valuation method has to take into account the landlord-tenant-dilemma, the future energy price and its volatility and valuate investments quantitatively and as universally applicable as possible.

For this reason, research papers valuate investments that increase energy efficiency by measuring the hence emerging benefits solely on the basis of non-monetary utility values for environmental, social or economic benefits, e.g. Power (2008). These methods account for many different important factors and do not concentrate only on economic aspects. However, they are not quantitative and do not consider the importance of the future energy price (see *specification 2*) and its volatility (see *specification 3*).

Furthermore, decision-makers use so-called discounted-cashflow methods, which discount the investment's expected future cash flows with a discount rate to a present value (Gallinelli 2008). In this way, the time-value of money is considered (which is very important for long-term investments). However, these discounted-cashflow methods do not measure or quantify an investment's risks, like the volatility of the energy price (see *specification 3*).

Keown et al. (1994) recognise the special importance of risk for energy efficiency investments and suggest a basic approach to integrate risk into a discounted-cash-flow valuation. They suggest the adaption of the discount rate depending on the height of the risk. Therefore a higher discount rate should be used for investments that have higher risk than a typical investment and a lower discount rate should be used for investments that have lower risk than a typical investment. However, this method is very inexact in measuring risk correctly. Johnson (1994) realises that the use of the adapted discount rate is broadly discussed in literature, but is not a satisfying way to adequately take risk into consideration. Johnson (1994) furthermore reviews the relevance of classic economic models like the capital as-set pricing model or the arbitrage pricing theory for energy technology investments. Despite some good propositions being made to incorporate risk, the author does not refer to the landlord-tenant-dilemma (see *specification 1*) nor to the actual application of the economic models taking into account the future energy price (see *specification* 2).

For this reason, a glance into other disciplines like architecture or material science is necessary. Bollatürk (2006) examines the optimum isolation thickness for building walls in the Journal of Applied Thermal Engineering and Al-Sallal (2003) compares polystyrene and fiberglass roof isolation in warm and cold climates in the Journal of Renewable Energy. These approaches consider the future energy price and are also quantitative. However, they do not consider risk either (see *specification 3*) and are only applicable for particular (non-IS) technologies. Atkinson et al. (2009, p. 2583) find that 'the majority of existing research focuses on either the technical attributes of different low carbon solutions on small or large scales, or the macro-economic effects of carbon-reducing energy strategies'. These methods again are hence not adequate for our needs.

For this reason, current valuation methods are not appropriate to valuate Intelligent House investments subject to their specifications named above or to determine the actual value of a sustainable building adequately (Rottke 2009). Lützkendorf and Mrics (2008) criticize a lack of methodologies to connect the ecological component of an investment with its economic value. That is why a valuation method to identify ecologically advantageous and simultaneously economically profitable Intelligent House investments is developed in this scientific study followed by the determination of the economically optimal investment amount.

### 3.1.3 Planning of Intelligent House Investments

Implementing each technically possible measure in line with an Intelligent House investment is not necessarily reasonable. First of all, we will identify all investments that are advantageous from an ecological perspective and profitable from an economical perspective. Building on that, we will determine the economically optimal investment amount.

#### 3.1.3.1.1 Intelligent Houses in the Conflict Between Ecology and Economy

As shown in chapter 2, IS provide various measures to raise energy efficiency of properties. Each implemented measure creates ecological value, but also requires an investment payment. The potential of IS to lower carbon emissions and energy consumption is estimated at 15 % (The Climate Group 2008, p. 6). To achieve this amount, all possible IS measures have to be implemented. However, it is possible that certain IS measures consume more energy during their construction phase than they economize in the end. The application of these measures is in fact advantageous from the ecological perspective of the property, but not for the whole (global) carbon footprint. Therefore the amount of all possible investments has to be reduced by all these ecologically inefficient investment alternatives. Nevertheless, it is unclear which of all residual measures shall be implemented. Each ecologically advantageous and efficient investment alternative is thus not necessarily profitable from an economic perspective. For this reason we will develop a tool to identify those investments out of all ecologically advantageous and efficient investments, which are also economically profitable, in the next chapters.

#### 3.1.3.1.2 Assumptions and Definitions

A property is rented and used by a tenant from time $T_0$ until $T_1$. The tenant pays a constant periodic basic rental charge (excluding energy costs) at the specific amount $RC$ to the landlord. Furthermore, the tenant has to pay energy costs $EC$ to a gas and electricity supply company, which is necessary for the property's operation. These energy costs are the product of the property's energy demand $d$ and the effective energy price at time $t$, $P(t)$. Additional expenses like e.g. expenses for water supply are irrelevant for this analysis and are not considered.

The landlord receives the periodic basic rental charge $RC$ from the tenant. At the end of the letting in $T_1$, the landlord sells the building and receives the resale return

*RR*. The amount of *RR* can be seen as the net present value of all future achievable rental charges (the value of the land shall be disregarded at this point). Hence, it is irrelevant for our consideration whether the property is actually sold or not. In the following, we assume the resale of the property in $T_I$ for the sake of simplicity. The property's energy demand can be reduced with the help of an IS investment, which is determined by the amount of its necessary payout *P*, with $P \in [1;\infty[$. However, many energy saving measures of Intelligent Houses need energy for themselves. The net present value of these costs as well as further costs (e.g. for possible breakdown) shall be integrated in *P*.

At this point a special characteristic of IS becomes evident: Other than e.g. architectural measures like roof insulation plates which wear out and lose their effect due to atmospheric exposure, IS measures are not likely to lose quality over time. Doubtlessly the hardware components of IS energy-efficiency investments also wear out. However, due to the ability of IS to receive software updates they can also raise, or at least maintain their effect over time. For reasons of simplicity, we consider this IS characteristic in our model by modeling energy costs which can be lowered permanently to a level of $EC_{new} < EC$ by reducing the energy demand from $d$ to a permanent $d_{new}$. Other (non-IS) investments would demand another approach with time-dependent energy demands.

Moreover, the resale return *RR* can be raised to $RR_{new} > RR$. This coherence is verified by an empirical survey, assuming the demand for energy-efficient properties is on the rise because of the expected long-term increase of the energy price. Consequently, increased resale returns can be realized (Bienert 2009). Furthermore, Rottke (2009) affirms that already today energy-efficient properties are rewarded by the market with higher prices. This coherence originates from expected strict future energy obligations, which cannot be complied with conventional buildings (Lützkendorf and Mrics 2008). Moreover, the lifetime of energy-efficient properties is higher than the lifetime of conventional properties, so rental charges can be realized during a longer period of time (Kuckshinrichs et al. 2010). The necessary investment payout occurs in $T_0$ and has to be paid completely by the landlord at first. Though the landlord has the possibility to turn over a certain portion of the investment payout to the tenant (see next section). On account of this the basic rental charge rises to $RC_{new} > RC$.

Thus Intelligent Houses generate benefits for both tenant and landlord. However, both sides do not necessarily benefit from the investment to the same degree. That is why we want to dissolve the landlord-tenant-dilemma (see *specification 1*) by dividing the investment payout proportionally to the individual value added. In this way we can make sure that the value generated by the Intelligent House investment (respectively the realized savings) is divided evenly. Furthermore, both landlord and tenant have an incentive to participate in the investment, because they obtain their individual share of value / savings either way. In doing so we make sure a reasonable IS investment is made and are able to overcome a big IS investment barrier. We conclude the following assumptions:

***A.1*:** Landlord and tenant pay the necessary investment payout according to the proportion of their marginal willingnesses to pay. The portion of the tenant is divided over all periods of the letting and increases the basic rental charge in the form of a rent increase. At this, possible legal restrictions to the cost being turned over to the tenant shall be neglected.

***A.2*:** Landlord and tenant calculate with the identical risk-free discount rate $i$. For risk we account for in *A.4*.

***A.3*:** The energy price increases in the long run.

However, the consideration at hand not only accounts for the increase of the energy price, but for its short term volatility (see *specification 3*). For this purpose we assume normally distributed energy prices. As mentioned above, the energy costs are composed of the product of the energy prices at time $t$ with the demand $d$ and are thus normally distributed, too. The time-dependent, volatile energy costs can then be discounted to an expected present value of the cash flow $\mu$, which is also normally distributed. Because of the energy price's volatility the calculated present value of the IS investment is volatile, too. Here we interpret the volatility of the present value as the possible positive or negative deviation of the present value from the expected present value of the cash flow. We measure this deviation with the variance $\sigma^2$ ($\sigma^2>0$). $\sigma_E^2$ shall be the variance of the energy price. To integrate measures for risk ($\sigma^2$) and return ($\mu$), we use a preference function:

**A.4:** *The risk-adjusted value of the IS investment is determined by both parties with Bernoulli's theory of expected-utility (Bernoulli 1954) and the following preference function:* $\Phi(\mu,\sigma) = \mu - \frac{\alpha}{2} \cdot \sigma^2$. *We assume risk-averse decision makers, i.e. the present value of the IS investment's cash flow is valued less, if its variance is higher (assuming a fixed expected value* $\mu$*).*

The risk adjusted value corresponds to a preference function which is developed according to established methods of decision theory and integrates an expected value, its deviation, and the decision maker's risk aversion. This preference function is based upon the utility function $U(x) = -e^{2\alpha x}$ and is compatible to the Bernoulli principle (Bernoulli 1954). Its Arrow-Pratt characterisation of absolute risk aversion (Arrow 1971) is $-2\alpha$ with $\alpha > 0$ modeling a risk-averse decision maker. The presented preference function was introduced by Freund (1956) and applied in many other papers on IS, e.g. by Fridgen and Müller (2009), Hanink (1985) and Katzmarzik et al. (2008).

#### 3.1.3.1.3 Identification of Ecologically Advantageous and Economically Profitable Investments

Out of all investments remaining after the ecological analysis, we want to identify those IS investments which are also economically profitable. For this, we have to analyze their economical characteristics. For this purpose we use a quantification with financial measurements in general, as well as with cash flows in particular. To ensure that we do not identify investments which generate only one-sided benefits and which will not be made because of the landlord-tenant-dilemma, we take on the perspective of the landlord as well as the tenant. The economic consideration of the tenant is influenced by the rent increase on the one hand and by the achievable energy cost savings during the time of the letting on the other hand. For this, the future energy price is important (see *specification* 2). Considering the energy prices during the last decades, we observe strong increase. The price for light fuel oil increased from ~ 8 € ct/l in 1970 to 80 € ct/l in 2008 (i.e. ~ 6.2 % p.a.). Furthermore, the world population will continue to rise exponentially in the forthcoming decades (Tucker and Patrick 2007) and the consumption level of many nations will more and more reach western standards. Hence we can forecast a rising energy demand. On the other hand we recognize non-renewable energy sources to be finite. Because of the excess demand resulting sooner or later we can assume exponentially rising energy costs in the future. This forecast is supported by Buhl and Jetter (2009), who state that the price of each non-renewable resource – depending on the specific availability and demand – rises exponentially. One possibility to formalize the exponential rise of the energy price P(t) is: $P(t) = P_0 \cdot (1+r)^t$. In this connection, P0 is the energy price in its initial state in T0. The parameter r is the periodical growth rate of the energy price compared to the previous period. The time dependence of the energy price is implied by the exponent t.

Moreover, we consider the energy price's short-term volatility (see *specification 3*). Resources and commodities are more and more subject to speculative transactions. Investments in commodity indexes increased by a factor of 20 from US $ 13 billion in 2003 to US $ 260 billion in 2008 (Masters, 2008). As shown by Shiller (1981), increased speculation and trading of commodities and energy sources cause an increase of price volatility (Duffie et al. 1999). Considering this energy price volatility in our valuation, we discover a particular effect: Taking into account the rules of linear transformation of random variables (in our consideration the present value of the energy costs), the reduced energy demand results in reduced volatility of the energy costs (Greene 2008). Thus Intelligent Houses operate like an insurance: By paying a premium (rent increase) the insurance holder (tenant) can insure himself against the impact of a possibly occurring damage event (energy price volatility). The tenant's willingness to negotiate such an insurance and the amount of premium he is willing to pay depends upon his individual risk-attitude: Tenants who negotiate an insurance want to avoid (or lower) risk. They prefer to pay a certain amount of money (here the rent increase) rather than accepting an uncertain, more volatile payout. In this way, we can mentally divide the rental charge $RC_{new}$ into three parts: The first part is the basic rental charge $RC$. The second part is the countervalue for the achievable energy cost savings. The third part is the insurance premium, which is the achievable risk reduction's value. This (over all periods of the letting) accumulated value $IP$ equates to the difference of the second part of Bernoulli's preference function before and after the investment: $IP = \frac{\alpha}{2} \cdot (d^2 - d_{new}^2) \cdot \sigma_E^2$. As mentioned in assumption *A.4*, we assume risk-averse (and consequently insurance affine) decision makers (Bamberg and Spremann 1981). For them, the risk-reducing effect of Intelligent Houses creates a value added and on that account their willingness to pay rises. Considering an exponentially rising energy price and its volatility, the tenant is willing to pay a maximum amount of money, which he is willing to pay in form of a rent increase. This amount is $I_{T,max}$:

$$(1) \qquad I_{T,\max} = \sum_{t=1}^{T_1} \frac{EC_t - EC_{new}}{(1+i)^t} + IP = \underbrace{(d - d_{new})}_{\text{Energy demand reduction}} \cdot \underbrace{\sum_{t=1}^{T_1} \frac{P_0 \cdot (1+r)^t}{(1+i)^t}}_{\text{Energy price at time } t} + \underbrace{\frac{\alpha}{2} \cdot (d^2 - d_{new}^2) \cdot \sigma_E^2}_{\text{Present value of insurance premium}}$$

This willingness to pay is compounded of the present value of the energy cost reduction over all periods of the letting plus the countervalue of the energy costs' volatility reduction subject to the individual risk-aversion. Taking on the perspective of the landlord, we have to consider the property's increased resale return and the necessary investment payout. The outcome of this is the landlord's maximal willingness to pay $I_{L,max}$:

$$(2) \qquad I_{L,\max} = \frac{RR_{new} - RR}{(1+i)^{T_1}}$$

$I_{L,max}$ equates to the difference of the new and the old resale return, which is discounted to a present value. By summing up the two willingnesses to pay, we can claim the following condition (3) for the maximum overall investment amount, which has to be fulfilled by our favored investment alternatives (in this connection we assume, that the property's resale return does not depend on the energy price and its volatility):

(3)
$$I_{\max} \leq I_{L,\max} + I_{T,\max}$$
$$I_{\max} \leq \frac{RR_{new} - RR}{(1+i)^{T_1}} + (d - d_{new}) \cdot \sum_{t=1}^{T_1} \frac{P_0 \cdot (1+r)^t}{(1+i)^t} + \frac{\alpha}{2} \cdot (d^2 - d_{new}^2) \cdot \sigma_E^2$$

By testing each investment to the condition (3) the amount of all considered IS investments will be reduced again. If the decision makers disregard the energy costs' volatility reduction (i.e. the insurance), the amount of ecologically advantageous and economically profitable investments would be much lower (i.e. the third addend of condition (3) would cease to apply). Figure 19 shows the impact of the insurance:

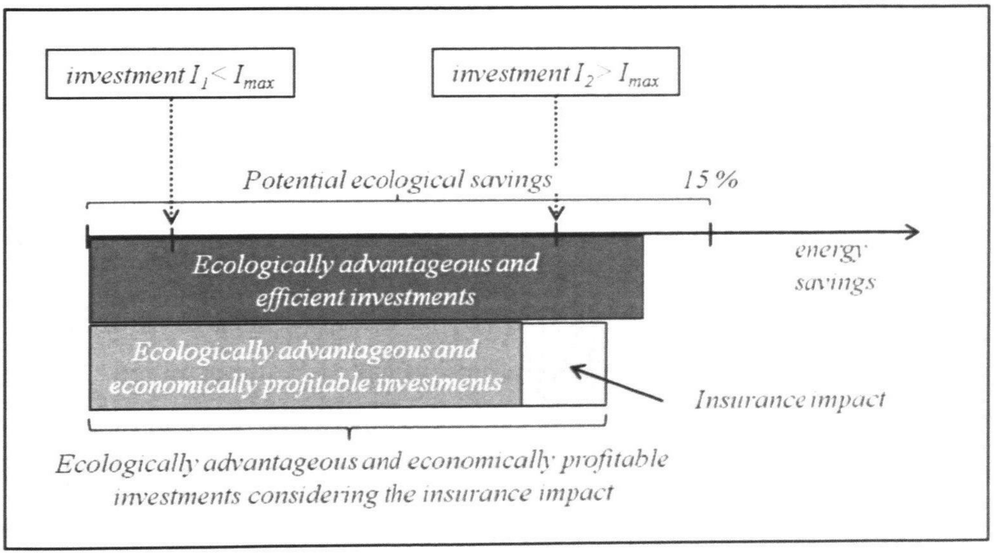


**Figure 19** Ecological and economical classification of IS investments

In this example investment alternative $I_1$ is classified as ecologically advantageous and economically profitable. On the contrary, investment alternative $I_2$ will only be valued as economically profitable, if the Intelligent Houses' ability to reduce risk like an insurance is considered. According to this, more IS investments generate benefits if the energy price is volatile, because IS can then be used to reduce this volatility like an insurance. Yet, it is still indistinct how we can decide between different investments which all fulfill the ecological and economical requirements. For the ultimate decision we need to develop a quantitative optimization model to identify the optimal investment amount in an economically substantiated way. An optimization model of this kind shall be introduced and solved in the following chapter.

#### 3.1.3.1.4 Determining the Economically Optimal Investment Amount

As stated in assumption *A.1*, landlord and tenant share the necessary investment payout according to the proportion of their marginal willingnesses to pay. Hence landlord and tenant can be considered as a unity and the rental charge can be disregarded. Evaluating all cashflows and risks of the landlord-tenant unity with Bernoulli's preference function we come to the following objective function to be optimized:

$$(4)\quad \Phi(\mu,\sigma) = \Phi(\mu(I),\sigma(I)) = \Phi(I) = -I + \Delta d(I) \cdot \sum_{t=1}^{T_1} \frac{P_0 \cdot (1+r)^t}{(1+i)^t} + \frac{\Delta RR(I)}{(1+i)^{T_1}} + \frac{\alpha}{2} \cdot \Delta\sigma^2(I)$$

The first addend of the objective function is the necessary investment payout, which incurs in $T_0$ and whose optimal amount has to be determined. The second addend corresponds to the achievable energy cost savings that can be increased in subject to the investment amount. The third addend equates to the additional achievable resale return, which rises in dependence on the investment amount. The last addend corresponds to the volatility reduction of the energy costs weighted with the risk aversion parameter $\alpha$ and which can also be increased with the investment amount. To solve the optimization problem at hand, we have to analyze the course of the functions for *RR(I)* and *d(I)*.

At this point another special characteristic of IS becomes evident: Investments in IS can – again compared to e.g. architectural investments – be sized more precisely within certain ranges. Imagine a decision maker with limited financial resources who wants to spend a certain amount of money on his property's energy efficiency. He only has enough money to either a) thermally insulate half of the roof using architectural measures or b) invest in IS to integrate chips and controllers for BMS (building management systems) in half of the property's area. Needless to say, insulating half of a property's roof would not induce an appreciable contribution to energy efficiency since the property would still lose heat energy through the non-insulated part of the roof, i.e. making only half the investment does not lead to 50 % savings. The IS measure however can also be integrated partly, e.g. only in certain (separate) parts of the property. This way these parts of the property contribute fully to energy efficiency, so that this investment can actually facilitate 50 % of the achievable savings. The scalability of the IS measure can even be increased by selecting not only certain parts of the building for the integration of chips and controllers, but also selecting certain functional ranges like management of only heating, heating and ventilation or heating, ventilation and air conditioning. The interrelations between the investment amount in IS and its positive effects are hence, at least in certain prevailing ranges, approximately continuous. We account for this IS characteristic and therefore model the interrelations between investment amount and energy demand and resale return in a continuous time model with scalable-at-will IS investment amounts.

As mentioned above, the resale return rises with the investment amount. Due to many properties' value drivers like location, age or condition, one cannot assume that an IS investment can raise the resale return of a property infinitely. Hence we can conclude that the investment's effect declines. Thus we can conclude a strictly monotone increasing ( $\frac{\vartheta RR}{\vartheta I} > 0$ ), concave ( $\frac{\vartheta^2 RR}{\vartheta^2 I} < 0$ ) course of the function for $RR$ (starting from the resale return without any IS investment $RR_0$). This coherence can be formalized exemplarily for $I \geq 1$ (as assumed in the following) as: $RR(I) = RR_0 + s \cdot \ln I$. The parameter $s$ determines the inclination of the resale return curve. The higher $s$ we choose, the more an IS investment raises the building's resale return. Hence the achievable raise of the resale return with an IS investment is $\Delta VE(I) = VE_{neu} - VE = VE_0 + s \cdot \ln I - VE_0 = s \cdot \ln I$. The second element of the objective function describes the development of the property's energy demand $d(I)$ depending on the investment amount. As mentioned above, the energy demand decreases permanently when the IS investment amount rises ($\frac{\vartheta d}{\vartheta I} < 0$). At this point, we use a linear relation between the energy demand and the investment amount in the relevant region. One possible function for this is $d(I) = d_0 - v \cdot I$. $d_0$ is the property's energy demand in the initial state, i.e. without any IS investment. $v$ determines the curve's inclination and equates to the marginal energy demand of the property: If the investment amount is raised about one monetary unit, the energy demand of a property drops permanently about exactly $v$ units. The achievable permanent energy demand reduction is: $\Delta d(I) = d - d_{new} = d_0 - (d_0 - v \cdot I) = v \cdot I$. It is important that these coherences are technology-dependent. It is self-evident that an IS investment for the integration of an intelligent energy management system has a different impact on a property's energy demand and its resale return than an investment of the same amount to integrate an intelligent commissioning system. Furthermore, properties have individual cost functions, which are determined by specific prevailing conditions (Atkinson et al. 2009). We approach this problem by using only generic functions that will cover a general case to illustrate the basic interdependencies. Our model can be tailored arbitrarily to specific IS measures by simply adapting the course of the functions. We hence claim our model to be universally applicable for IS measures. To sum up, we can formalize the induced effects of an IS investment in properties to raise energy-efficiency depending on the investment amount as follows:

*(5)*
$$\Phi(I) = -I + v \cdot I \cdot \sum_{t=1}^{T_1} \frac{P_0 \cdot (1+r)^t}{(1+i)^t} + \frac{s \cdot \ln I}{(1+i)^{T_1}} + \frac{\alpha}{2} \cdot (d_0^2 - (d_0 - v \cdot I)^2) \cdot \sigma_E^2$$

A mathematical analysis shows that the objective function is strictly concave in the domain (e.g. $I > 1$) and reaches its maximum at the investment amount

*(6)*
$$I^* = \frac{-1 + v \cdot \sum_{t=1}^{T_1} \frac{P_0 \cdot (1+r)^t}{(1+i)^t} + \alpha \cdot v \cdot d_0 \cdot \sigma_E^2 + \sqrt{\left(1 - v \cdot \sum_{t=1}^{T_1} \frac{P_0 \cdot (1+r)^t}{(1+i)^t} + \alpha \cdot v \cdot d_0 \cdot \sigma_E^2\right)^2 + 4 \cdot \frac{s}{(1+i)^{T_1}} \cdot \alpha \cdot v^2 \cdot \sigma_E^2}}{2 \cdot \alpha \cdot v^2 \cdot \sigma_E^2}.$$

Consequently, (if $I^* \geq 1$, which we assume) it is reasonable to raise the investment amount up to *I**. Below this investment amount, an elevation of the investment sum leads to a higher resale return increase, energy cost reduction and reduction of the energy cost's volatility than the necessary payout. In contrast, the positive effects above the investment amount *I** in fact exceed the incidental payouts, but disproportionally high capital expenditure is necessary. Figure 20 shows these coherences:

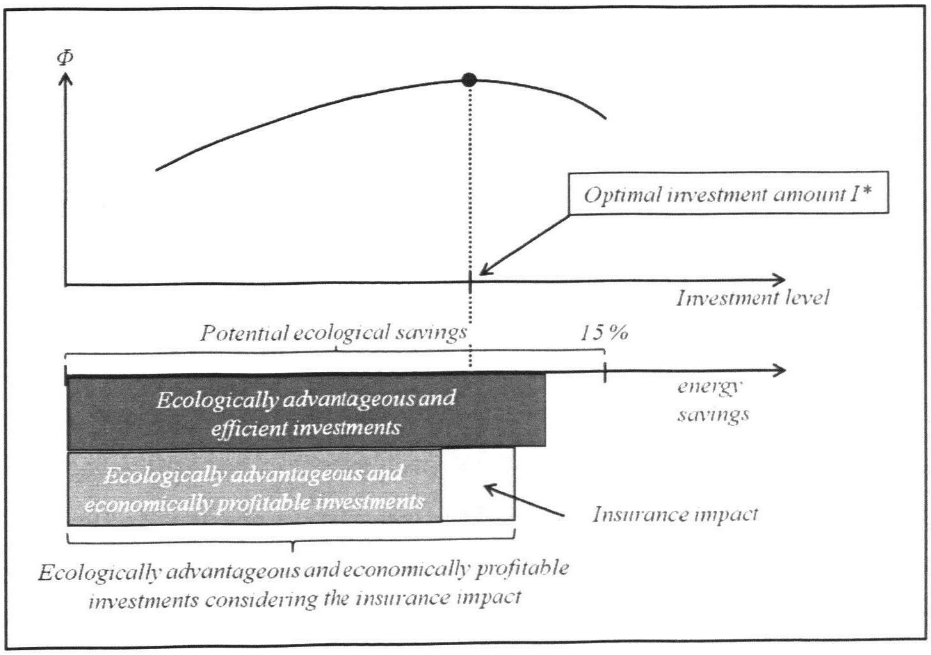


**Figure 20** Course of the preference function (exemplary)

By comparing the computed optimal investment amount to the optimal investment amount of a risk-neutral decision maker we can show that the optimal investment amount considering energy price increase and volatility (see *specifications 2 and 3*) is always higher than assuming a non-volatile energy price. Considering the energy price accurately will not only lead to a higher amount of ecologically advantageous and economically profitable investments, but also to an increase of the actual optimal investment amount. By using the presented model, IS' initially mentioned high potentials to reduce the energy demand and the carbon footprint of properties can be utilized far better. The model's application and benefits shall now be illustrated in the following example.

### 3.1.4 Example of Use

A building society wants to design a block of offices under construction in an energy-efficient way. Since the company knows about the advantages of sustainable investments and wants to save the planet's resources, the company wants to use the high potentials of IS. For this example we assume the following facts to be given: The duration of the letting after the completion of the property is 30 years ($T_l=30$). The company receives a one-time resale return for the property after 30 years and calculates (like their tenants) with a discount rate of $i$=3 %. The resale return can be raised by an IS investment starting from an amount of 1,000,000 monetary units (MU) in a form that can be described by the following function: $RR(I) = 1000000 + 10000 \cdot \ln I$. The property's demand for domestic fuel oil can be lowered about 0.06 l p.a. with each invested MU starting from a basic demand of 3000 l p.a.. Hence we can conclude the following coherence for the energy demand: $d(I) = 3000 - 0{,}06 \cdot I$. We assume an energy price increase of 7 % p.a with an initial price of $P_0$=0,85 MU/l. The volatility is assumed to be $\sigma_E^2$=0,006. For the parameter of risk-aversion we assume $\alpha$=1. Considering the insurance impact of Intelligent Houses, we recognize that all investment alternatives with an investment amount of at most *74,554.4 MU* fulfill the condition (3) and are thus ecologically advantageous and economically profitable. If the company disregards the insurance impact of Intelligent Houses, only those investments with a necessary payout of at most *49,799.4 MU* are ecologically advantageous and economically profitable. Alternatives with a higher necessary payout are hence ignored by risk-neutral decision makers in the further decision process. We can determine the position of the optimal investment amount through mathematical optimization (setting the objective function's first derivative to 0 and verifying the second order condition). Considering the insurance impact of Intelligent Houses we thereby determine an optimal investment amount of $I^*=18{,}748$ *MU*. If the company disregards the energy price's volatility, the optimal investment amount is only *4,604 MU*. Considering the insurance impact of IS clearly raises the optimal investment amount and energy demand and carbon footprint can be reduced remarkably. The company in this example will save *37.5 %* of its periodic energy demand if it chooses the optimal IS investment alternative, whereas the company would only save *9.2 %* of energy if it disregarded the insurance impact. Taking into account energy volatility as illustrated, the economic and ecological potential of IS can be utilized far better than with existing financial valuation methods used today. The application of our model will hence countervail the prevailing structural underinvestment degree.

### 3.1.5 Results for Sustainable Ad Hoc-Protection

IS innovations can generate a valuable ecological and economical contribution. Intelligent House investments lower a property's energy costs permanently and raise its resale return at the same time. Moreover, the energy cost's volatility can be reduced and the tenant is thus insured against energy price volatility. This scientific study shows how these effects can be evaluated correctly by identifying all ecologically advantageous and economically profitable investments. To choose the economically optimal investment alternative, we developed a formal model. We showed that the amount of all ecologically advantageous and economically profitable investments as well as the optimal investment amount can be increased by considering the insurance effect of Intelligent Houses. Nevertheless several assumptions and resulting conditions of this scientific study have to be examined critically, which opens up possibilities for further research. First of all, the resolution of the landlord-tenant-dilemma may not be possible in each case in practice due to possibly existing legislative reasons (e.g. German landlords can only pass on 11 % p.a. of the costs of energy efficient refurbishment measures to the tenant). In that case, the identified amount of ecologically advantageous and economically profitable investments is likely to sink. Second, the model at hand considers tenant and landlord as a collaboratively optimizing unity. The outcome of individually optimizing parties could be subject to further research (e.g. by using game theory). Third we developed a continuous time model, which is only applicable for IS investment due to their high scalability and their permanent effect on the energy costs. The model is so limited to the range of high scalable IS investments yet.

The model is thus not transferable to other (non-IS) measures and is, just like the modeling of dependencies between IS and non-IS measures, subject to further research (possibly with a discrete time model). Anyhow, developing our model and concentrating on IS makes sense for us, since the relevance of other disciplines like architecture or material science for saving energy and reducing the carbon footprint is self-evident, whereas the ability of IS as enabler is yet unknown to many decision makers (as mentioned above, IS could lower global carbon emissions based on the level of 2002 until 2020 about 1.68 $GtCO_2e$ and can help to save a value of € 644 billion globally (The Climate Group 2008, p. 6, p. 9)). Even in the current political debate and in the media, the focus is mostly limited to improved insulation materials or double glazed windows. Furthermore, the collecting and consolidation of data as well as the valuation of investments and the generation of incentive systems are IS key issues. For this reason, the discipline of IS should continue to extend the evaluation of its own methods thus revealing its high potentials.

Upon completion of this research, which was conducted on the basis of valid assumptions, the following key findings can be derived: The ecological *and* economic optimum level of investments in "Intelligent Houses" (and equally, in production facilities of a company in the production sector) can be determined quantitatively. In addition, it is formally demonstrated that this type of investment additionally comprises an insurance aspect against energy price increases and therefore reduces a company's energy price risk related to its production facilities. Moreover, it becomes evident that investment in energy efficiency measures, such as those presented in the context of this research, should be made as early as possible to minimize the negative effects of the assumed energy price increases.

## 3.2 Sustainable Basic Research

After the discussion of an ad hoc-strategy to reduce energy price risks in the previous section, we will now show how sustainable raw materials management can be used in basic research to develop novel materials for the semiconductor industry (Figure 21).

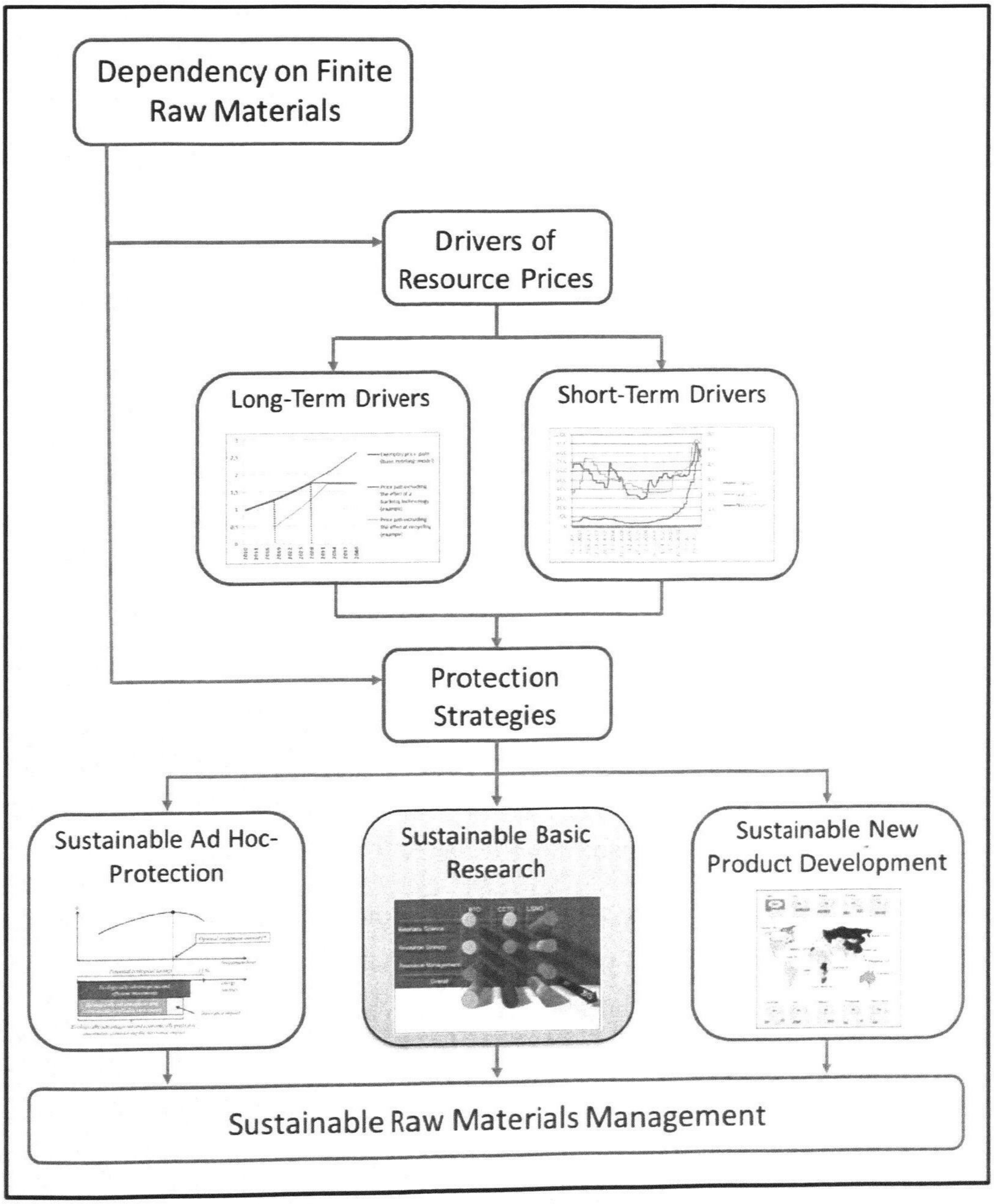


**Figure 21** Structure of the thesis: Sustainable Basic Research

Within this research project the following partial questions in the fields of economy, ecology and technology are studied in more detail: It is examines whether raw materials-related risks can be included into the decision calculus of a company already in the phase of basic research and how a company can thereby reduce price risks related to raw materials. In addition, resource-strategic considerations concerning the criticality of required raw materials are discussed. We also study the possibilities arising from technical selection decisions in the phase of basic research and show to what extent it is possible to replace materials identified as critical by less critical ones. Also the time dimension is discussed in the following analysis.

### 3.2.1 The Need for Interdisciplinarity in Basic Research

Scarcity and possible future shortages of key elements used in modern technology has come into the focus of public interest and was the topic of a recent special issue of Nature Materials (Nature Materials 2011). It is one of the most imminent challenges of modern materials science to develop new materials that enable replacement of rare elements by more abundant ones that have comparable or better functionalities than those currently used (Nakamura and Sato 2011; Service 2010). So far most scientists developing new functional materials are accustomed to use material parameters as sole guidance in their research. It is equally important, however, to judge the economic merits and resource availability, too. Incorporation of these interdisciplinary aspects at an early stage of the research has to be a key priority in future materials Research & Development.

To illustrate this approach, we apply it to the prototypical example of materials with extremely high dielectric constant ($> 10^3$), which could pave the way for a new generation of electronic components, e.g., capacitors with outstanding energy-storage capabilities intended to replace batteries (Homes et al. 2001; Sinclair et al. 2002; Lunkenheimer et al. 2010). Here we demonstrate the prospects of several materials from a perspective of materials science, resource strategy and resource management providing three filters that have to be passed by a material to be suitable for application. Criteria for the material science filter are based only on technically relevant properties whereas criticality of materials is considered in the resource strategy filter. The final filter deals with economic aspects of the resources and of the processing techniques. Combining these filters and estimating the time-dependent criticality of the resources and economic aspects, leads to a selection of a specific material for the defined application. Cross-linking research fields of materials science, resource management and resource strategy, realized in the present work, can serve as a valuable methodology in future development and applications of advanced functional materials.

Recently, the discovery of new materials showing a very high, so called "colossal" dielectric constant (CDC) has triggered significant research activity (Lunkenheimer et al. 2010). The dielectric constant is the primary materials parameter determining the performance of capacitors. Such electronic devices are ubiquitous in electronic circuits and can also be considered for energy storage, e.g., recuperation of braking energy in hybrid cars. So far, capacitors using CDC materials are mostly based on ferroelectrics, i.e. materials with ordered electric dipoles. These ferroelectrics have been used for decades (Haertling 1999) and more than one trillion units of ferroelectric-based multilayer ceramic capacitors (MLCC) (Pan and Randall 2010) were fabricated in 2010. Dozens are included, e.g., in every smartphone. $BaTiO_3$ (BTO), doped with rare earths (REs), at present is the most suited material for such devices (Kishi et al. 2003). The recent shortage of REs is expected to have a dramatic influence on the MLCC market in the near future, which can be verified through an economic risk analysis. Here we describe a case study for developing alternative materials for MLCCs. Starting with state-of-the-art materials we compare those to newly developed ceramics, applying the three-fold-filter approach discussed above.

In Figure 22 several compounds are compared including CDCs regarding their suitability as capacitors: CDC materials $La_{15/8}Sr_{1/8}NiO_4$ (Krohns et al. 2007) and $CaCu_3Ti_4O_{12}$ (Homes et al. 2001; Lunkenheimer et al. 2010), ferroelectrics BaTiO3 (Hirose and West 1996) and barium-doped lead zirconate titanate (PBZT) (Kanai et al. 1994), ferroelectric $SrTiO_3$:$DyScO_3$ multilayers16, and the so-called relaxor ferroelectric $Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ (PMN:PT) (Choi et al. 1989).

Four material parameters are compared: dielectric constant (ordinate) and loss tangent (abscissa) at 1 kHz, capacitance variation between 30°C at 65°C (outer ring, color coded) and upper frequency limit of the applied ac voltage (inner circle, color coded).

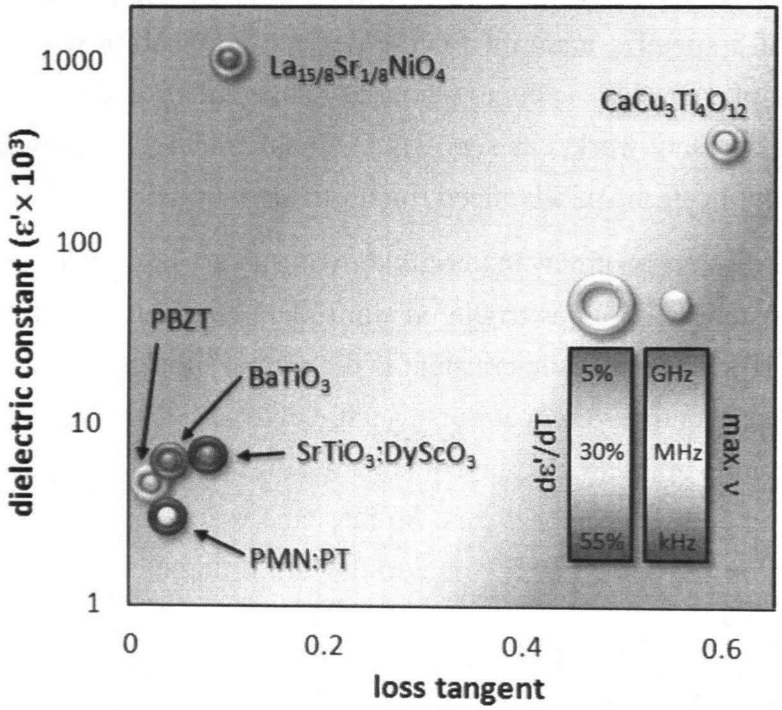


**Figure 22** Comparison of several compounds regarding their suitability as capacitors

## 3.2.2 Aspects of Materials Science

The most relevant materials parameters of capacitors are: dielectric constant, $\varepsilon'$; loss tangent, tan $\delta$; temperature stability of $\varepsilon'$; and the maximum frequency of ac voltage, up to which the material can be applied. $\varepsilon'$ should be large to enhance the capacitance (i.e., the charge storage ability) of the MLCC and to enable increased volumetric efficiency (e.g., capacitance per volume), a prerequisite for further device miniaturization. tan $\delta$ must be minimized to reduce dissipation of field energy into heat and avoid draining of stored charge.

The most relevant materials parameters of capacitors are: dielectric constant, ε'; loss tangent, tan $\delta$; temperature stability of ε'; and the maximum frequency of ac voltage, up to which the material can be applied. ε' should be large to enhance the capacitance (i.e., the charge storage ability) of the MLCC and to enable increased volumetric efficiency (e.g., capacitance per volume), a prerequisite for further device miniaturization. tan $\delta$ must be minimized to reduce dissipation of field energy into heat and avoid draining of stored charge.

The high ε' of the state-of-the-art material BTO ($\varepsilon' \approx 10^3$ - $10^4$) arises from ferroelectric ordering of Ti-ions. Unfortunately, this effect is strongly temperature dependent and thus ferroelectric MLCCs are hampered by poor temperature-stability of their capacitance. Recently, a number of new materials with nearly temperature independent CDC's have been discovered and they have been considered as potentially useful capacitor materials (Adams et al. 2002). A prominent example is $CaCu_3Ti_4O_{12}$ (CCTO) (Homes et al. 2001) with a temperature independent ε' of 104 near room temperature. Other transition-metal oxides with CDCs (Lunkenheimer et al. 2010) near room temperature including, e.g., $La_{2-x}Sr_xNiO_4$ ($x$ = 1/3 or 1/8) (Park et al. 2005; Krohns et al. 2007) are also viable. The physical mechanism leading to the CDCs in these materials is not fully resolved but there is general consensus that they are related to the development of heterogeneities (surface layers, domain boundaries, etc.) within the samples Sinclair et al. 2002; Lunkenheimer et al. 2010.

The afore mentioned material properties of several conventional and new CDC materials (Krohns et al. 2007; Kanai et al. 1994; Hirose and West 1996; Choi et al. 1989; Haeni et al. 2004) are compared in Figure 22, with traffic light colors illustrating their figures of merit. The properties of CCTO generally surpass those of the more conventional materials but it is severely hampered by its high loss. In contrast, from a materials-science perspective alone, $La_{15/8}Sr_{1/8}NiO_4$ (LSNO) is superior in all respects. In the following, we focus on LSNO, CCTO and BTO as a test study to illustrate the approach and discuss them from the viewpoints of resource strategy and management.

### 3.2.3 Aspects Resource Strategy

Resource strategy assesses raw materials based on various economical, ecological, socio-cultural and political indicators accounting for the whole life period of a specific technology (EU 2010; Bublies et al. 2009). First, data are collected on deposits, reserves and annual production. Industrial manufacturing of BTO, CCTO or LSNO requires specific raw materials containing barium, titanium, lanthanum etc., in the form of oxides or a salt such as a carbonate, nitrate or sulphate. For example, barium is commonly extracted from barite, $BaSO_4$. Lanthanum is mainly extracted from monazite and bastnäsite. In Figure 23, world-wide allocations of the most important barium and titanium mineral deposits are shown (USGS 2011d). In separate frames the proportions of global reserves and annual productions are compared for the most prominent nations holding many of the other raw materials (USGS 2010). For various elements, the supply depends critically on only a few countries.

Second, the supply risk is estimated by considering the current reserves-to-production ratio (RPR; expressed in years), the market concentration of deposits, of reserves and of production sites, the political stability of the supplying nations and the ecological impact of extracting ores (Haertling 1999). Furthermore, factors like emerging technologies requiring the same raw materials and the potential for recycling are considered. In most cases, these criteria can be quantified by indices (USGS 2010), e.g., the Herfindahl-Hirschmann index (Herfindahl 1950; Hirschmann 1945) defining market concentration by the sum of the squared fractional shares of the largest producers.

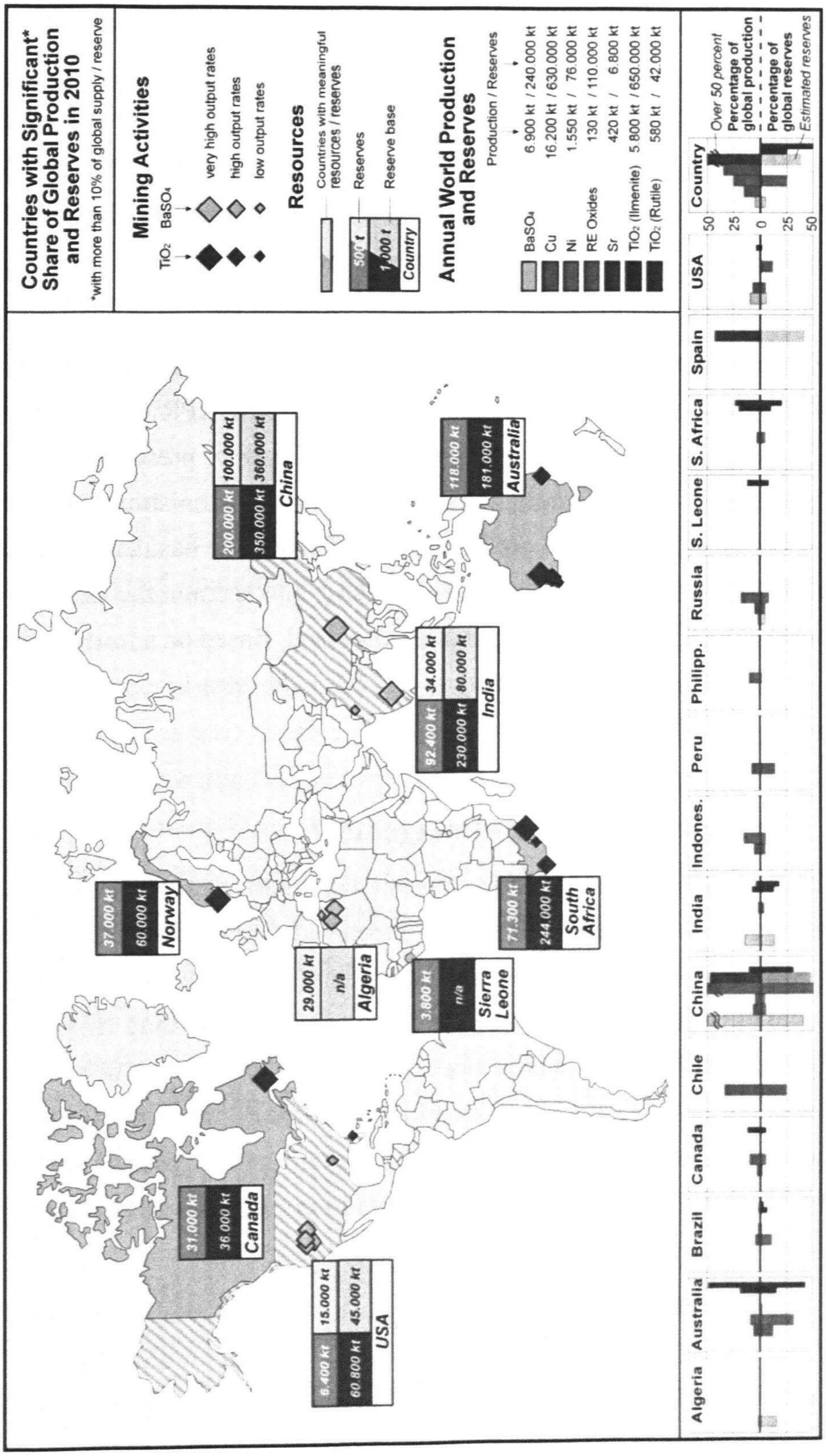
Countries with Significant* Share of Global Production and Reserves in 2010
*with more than 10% of global supply / reserve
Mining Activities
TiO2 BaSO4
very high output rates
high output rates
low output rates
Resources
Countries with meaningful resources / reserves
Reserves
Reserve base
500 t
1.000 t
Country
Annual World Production and Reserves
Production / Reserves
BaSO4 6.900 kt / 240.000 kt
Cu 16.200 kt / 630.000 kt
Ni 1.550 kt / 76.000 kt
RE Oxides 130 kt / 110.000 kt
Sr 420 kt / 6.800 kt
TiO2 (Ilmenite) 5.800 kt / 650.000 kt
TiO2 (Rutile) 580 kt / 42.000 kt
6.400 kt 15.000 kt 60.800 kt 45.000 kt USA
31.000 kt 36.000 kt Canada
37.000 kt 60.000 kt Norway
29.000 kt n/a Algeria
3.800 kt n/a Sierra Leone
71.300 kt 244.000 kt South Africa
92.400 kt 34.000 kt 230.000 kt 80.000 kt India
200.000 kt 100.000 kt 350.000 kt 360.000 kt China
118.000 kt 181.000 kt Australia
Algeria Australia Brazil Canada Chile China India Indones. Peru Philipp. Russia S. Leone S. Africa Spain USA Country
50 25 0 25 50
Over 50 percent
Percentage of global production
Percentage of global reserves
Estimated reserves

**Figure 23** World map of mineral deposits and reserves of $TiO_2$ and $BaSO_4$

Mineral deposits and reserves of $TiO_2$ and $BaSO_4$ are illustrated in Figure 23. In this connection, upper numbers in the boxes denote the currently and economically available reserves. The lower numbers include reserves that have reasonable potential for becoming economically available in the future. For various other raw materials, the lower charts provide information on the proportions of global reserves and annual productions for the most prominent nations (USGS 2011d).

For the elements considered here and for a short time scale of several years, strontium is the most critical element due to its rather low RPR of ~ 16 years (see Figure 23 for reserves and annual production). In light of present discussions regarding shortages of REs, lanthanum currently has an astonishingly high RPR of ~ 850 years. However, due to growing demand this value has decreased dramatically over the last 15 years. If, in addition, taking into account the market-concentration criterion, REs can also be considered critical. Based on a resource-strategy, using all the criteria mentioned above, CCTO is the best among the considered materials for our test case.

### 3.2.4 Aspects of Resource Management

The third filter assesses the implementation of alternative capacitor materials from a producer's point of view. It uses the Discounted-Cash-Flow (DCF) method involving the calculation of the net present value (NPV) (Huang and Litzenberger 1988), which is the sum of cash flows for a company resulting from the implementation of a new technique/product, in this example, for a 10 year period. It includes initial investments (e.g., machinery), future cash inflows (revenues) and outflows (expenses; e.g., operational costs). Future cash is of less value than present cash. Thus, the present value Rp of any future cash flow Rt (t: year) has to be adjusted with a discount rate i, leading to Rp = Rt / (1+i)t.

As an approximate discount rate, the typical weighted average cost of capital (WACC) of a company within the electronic semiconductor industry (11.5%) can be used (Copeland et al. 2005). WACC is the rate of return expected by different investors, weighted by their proportion of the total capital. In this case study, for practical reasons we assume the production procedure is cost-equal for the considered materials. Then the relevant parameters are the prices and quantities of the respective materials. When comparing economic merits of alternative materials, the difference of the investment alternatives' NPVs can be taken as decision criterion. For the examples of BTO and LSNO this is expressed by:

$$\Delta E_{NPV} = \sum_{t=t_0}^{t_n} \frac{price_{BTO}(t_0) \times amount_{BTO}(t_0)}{(1 + wacc)^t} - \sum_{t=t_0}^{t_n} \frac{price_{LSNO}(t_0) \times amount_{LSNO}(t_0)}{(1 + wacc)^t}$$

In the case of equal amounts per MLCC, the less expensive material would be preferred.

Next, a risk analysis of the investment alternatives is performed. This includes, e.g., a statistical time series analysis of the past price developments of raw materials, including a determination of expected value and standard deviation, which enables an extrapolation to estimate future cash outflows (Hamilton 1994).These are used as input parameters for the DCF method. Finally, some additional value can be assigned to the ability of a company to react to future developments, e.g., by switching to an alternative material if the price of a presently inexpensive material increases (Copeland et al. 2005).

For the present example, assuming a replacement of one quarter of the current annual production of MLCCs, we arrive at $\Delta E_{NPV}$ = -1.1 billion \$ for CCTO and +0.6 billion \$ for LSNO (both compared to BTO). From an economic viewpoint, LSNO is clearly preferable, even if we neglect its better material properties, which should lead to even higher NPVs. Keeping the option to reconvert production to the less risky, but more expensive BTO is worth 29 million \$. A further interesting outcome of our analysis is that the risk of fluctuations in raw material costs (e.g., barite) is negligible because they only marginally influence the overall price.

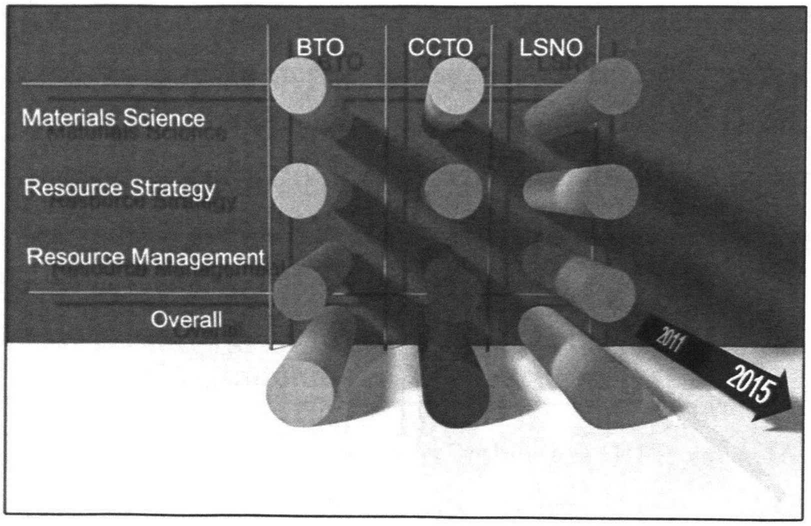


**Figure 24** Time development prospects of three CDC materials from the perspectives of materials science, resource strategy and resource management, including an extrapolation up to the year 2015. In addition, in the lowest row the overall suitability's are indicated. Traffic-light colors denote the merits of the respective material, green and red signifying high and poor suitability, respectively.

### 3.2.5 Results for Sustainable Basic Research

The suitability of the considered materials for capacitor production is presented from the viewpoint of the three disciplines, including an extrapolation to 2015, in Figure 24. The time development of the materials-science criteria mirrors the fact that sticking to BTO will make it difficult to follow Moore's law of continuous device miniaturization. This will lead to a slight degradation of the overall suitability for this material in the future (last row in Figure 24). CCTO is critically hampered by its high loss, however future developments may reduce this value. Irrespective of this, the overall performance of CCTO is poor, mainly due to its negative $\Delta E_{NPV}$. For LSNO the rather low RPR of Sr represents no major problem on the time scale of Figure 24. For the RE lanthanum the current RPR is not yet critical. Only a complete delivery failure would represent a major problem and thus, due to the high market concentration, LSNO has to be judged potentially critical in the future. However, if the current RE situation can be resolved, e.g., by opening of new mines (Kato et al. 2011), LSNO will clearly be competitive among the materials considered in this case study.

Here we have provided a worked example for an interdisciplinary approach to assess the suitability of new materials for a given application. Its importance is exemplified by the final result that the highly rated CCTO, whose investigation was mostly motivated by its application prospects, is far less suited as new capacitor material than commonly thought, if applying the three filters introduced in this commentary. We are convinced that this approach can serve as a useful guide for future research aiming at the development of novel functional materials for commercially viable applications.

Based on our interdisciplinary research approach, the following key finding can be derived: Examining different source materials for the production of capacitors we show that CCTO, which is the advantageous compound from a purely technical viewpoint, becomes less attractive in comparison to LSNO as soon as resource strategic and economic aspects are additionally taken into account. Moreover, it was shown that individual risks related to materials science, resource strategy and resource management have different levels of weight in the course of time.

## 3.3 Sustainable New Product Development

While primarily techno-economic and resource-strategic aspects of sustainable raw materials management were discussed in the previous section, this approach is extended to environmental and social dimensions in the following part (Figure 25).

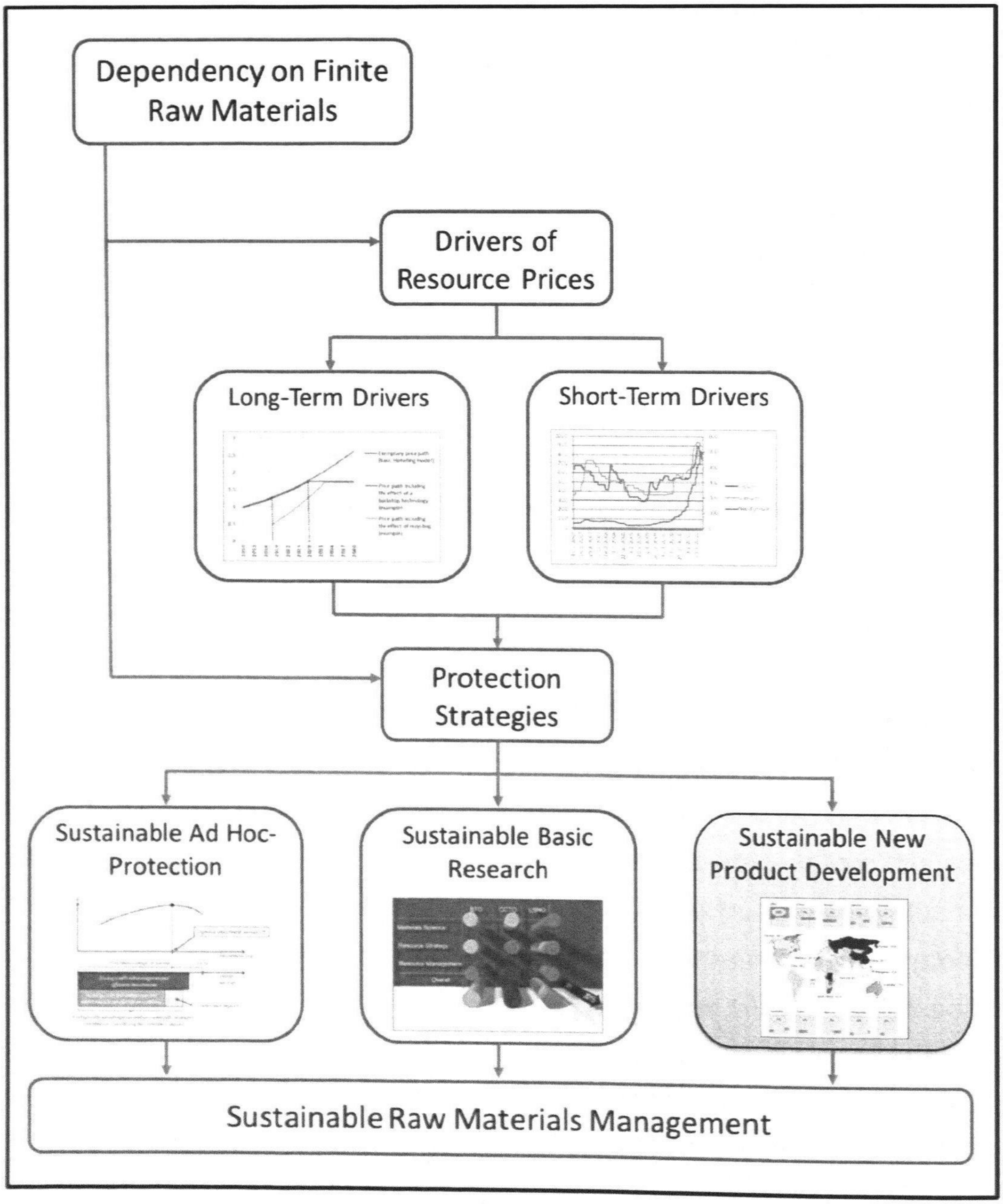


**Figure 25** Structure of the thesis: Sustainable New Product Development

The implementation of the resulting 'roadmap' is exemplarily explained for the case of cobalt. As part of this research, we focus the company-specific level of dependency on raw materials as well as the increase of demand, which was identified relevant for raw materials prices development in Section 2.1. Environmental and social issues arising from the mining of cobalt are also discussed. In addition, possibilities of material substitution are elaborated and scope for decisions regarding the timing and extent of securing strategies are outlined. Also specific protection measures of sustainable raw materials management are presented, which can help a company to reduce its commodity risk.

### 3.3.1 The Need for Research on Sustainable New Product Development

To strengthen the European Union economically in the short and medium term, the real economy (i.e. the manufacturing and processing industry) plays a major role. This is reflected e.g. in the plans of the European Commission to increase the share of industry in GDP to 20% in 2020. This 40% increase (compared to today's level) would be achieved through a partnership between the EU, its Member States and the industry, and is considered to be the starting point of a "new industrial revolution" (EU 2012, p. 4). With a gross value of over 600 billion Euros (Destatis 2012a), manufacturing and processing industry can be seen as an anchor for economic prosperity. Manufacturing and processing industry is both the largest and currently most stable economic area (Destatis 2012b, p. 9) in Germany – especially in times of global economic turmoil. However, manufacturing and processing industry is heavily dependent on secure access to raw materials: Material costs represent app. 40% – and thus the largest share – of this industry's total costs (Fraunhofer 2012). In 2010, raw materials imported to Germany had a value of 109.3 billion Euros (BGR 2011a, p. 19). From a long term perspective raw prices for material heavily increase (Destatis 2007). In the opinion of a vast majority of corporate decision-makers this trend will continue in the future (Handelsblatt 2012). As a result rises in commodity prices as well as price volatilities are currently are seen as the two most serious threats for business results of both SMEs and large industrial companies (Deutsche Bank 2012). In order to maintain and expand their international competitiveness, companies rely on earning their customers' loyalty with high quality and technologically advanced (new) products – particularly in innovative, high-growth industries such as engineering, public health engineering, automotive, chemistry, sustainable mobility, environmental technology and resource efficiency (Gönner 2010, p. 183).

Angerer et al. (2009) point out that an increase of demand for raw materials is particularly expected due to the development and production of innovative new products. First, this increase is quantitative. Second, the number of the requested elements (whose specific material properties are essential for a variety of future technologies) increased from about 25 in the 1970s to over 70 (Achzet et al. 2011, p. 11; Krohns et al. 2011, p. 899). Therefore, industrial companies particularly dependent on the supply of raw materials face a double challenge in developing new products: On the one hand, criticality of raw materials intended for use is to be checked out already in the phase of product development and product design. It should be the aim to reduce the use of critical raw materials or to substitute these materials by less critical ones (Buhl et al. 2010). On the other hand, a company has to ensure availability of each material required for production over the entire life cycle of the product (or its complete product line) – both in terms of quantity and in terms of its calculated purchase price. In addition, a company should be mindful of its social and environmental responsibility, which refers increasingly to the purchase of raw materials (BMU 2012).

## Case Study: The role of Cobalt for Efficient Energy Storage

To clarify the 'sustainability roadmap' presented in the following section, we will refer to an exemplary company that is engaged in the development and production of rechargeable, electric energy storage. Especially because of the German 'energy transition' electrical energy storage is of increasing importance (DLR 2012). Depending on the requirements on power or energy density of such a battery, several storage technologies are available, such as electrolytic capacitors, double layer capacitors and batteries based on lead, nickel-cadmium, nickel metal hydride, zinc-air or lithium-ion (Braess and Seiffert 2005, p. 116). From a technical perspective, lithium-ion batteries are characterized by the currently highest energy density and therefore are considered "the electricity storage technology of the future" (Angerer et al. 2009, p. 171, p. 260). Since it can be assumed that the long-term supply of lithium is guaranteed (Yaksic and Tilton 2009), cobalt is the bottleneck resource of this technology (Angerer et al. 2009, p. 173). Against this background, this metal is used as an example for the application of sustainable resource management.

### 3.3.2 Resource Related Basic Information

Before we will refer to economic, environmental and social impacts of raw material demand, a manufacturing company is confronted with if it plans to develop a new product, a quantity structure of the required raw materials has to be established first. In this step the following questions should be answered:

- Which raw materials are needed for the production of the new product?
- How many end products are planned to be sold per year? What is quantity of each of these raw materials needed for the production of a final product?
- Which product life cycle is expected?
- Are there any consequences for further products or product lines, if the company commits to the use of certain raw materials?

An exemplary establishment of the quantity structure for cobalt for a company that strives for a world market share of 4% in lithium-ion-based energy storages results in an estimated demand of 650t of cobalt in 2012. Due to increasing demand it can be assumed that the company's demand for cobalt will increase to app. 9.000t in 2020 and to app. 1.200t in the year 2030, the assumed end of the product line (cp. average scenario by Angerer et al. 2009, p. 173). For the whole period, this corresponds to a total demand of about 17.000t of cobalt. In order to assess risks for a sustainable new product development, which arise from the demand for individual raw materials, an overview of the mining countries is necessary, too. If this investigation is conducted using the example of cobalt, it becomes clear that raw material depletion primarily takes place in countries, which are considered to be critical in terms of their economic and political status: 53% of global mine production derives from the Democratic Republic of Congo (DRC), 7% each from China and Russia, 6% from Zambia (USGS 2010). Further information on global cobalt mining (top 10 mining countries) as well as the political stability of these mining countries is shown in Figure 26.

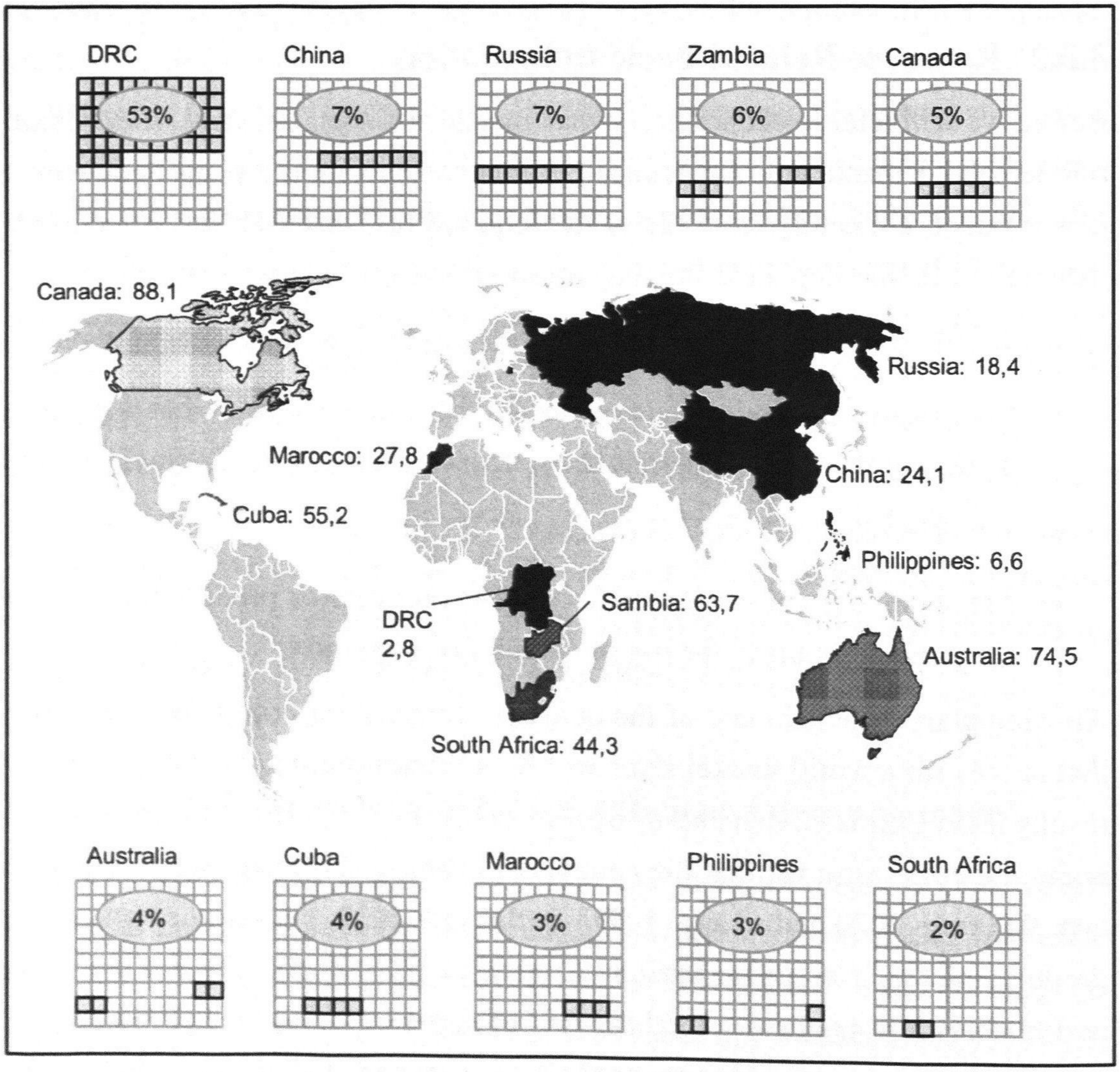


**Figure 26** Worldwide cobalt mining by country (in %) as well as their political stability (scale: 0 - 100 points) (own illustration with data from USGS 2010 and World Bank 2010)

### 3.3.3 Economic Aspects

In the following section we will discuss the economic implications arising from a company's demand for raw materials. At first and based on specific questions again, potential risks and their implications are illustrated. Referring on this, specific actions a company can take to reduce these risks will be discussed in the second part of this section.

In most cases economic risks are directly related to the current and future raw material price available for the company. Therefore it is necessary to answer the following raw material-specific questions:

- What is the current price of the raw material?
- What are the raw material-specific costs arising for the company?
- What economic criticality is attributed to the resource in the future?
- What is the direction of future price development of the specific raw material?
- What is the expected price volatility?
- Is there any (short-term) availability risk?

At a current price level of about \$ 37,000/t (Metal Prices 2012) the subject cobalt-processing company can anticipate cobalt specific material costs of approximately \$ 24 million in 2012. (Unrealistically) assuming unchanged raw materials prices and including the aforementioned increase of demand, accumulated cost for the purchase of cobalt is approximately \$ 629 million until 2030. In order to predict future price development, commodity specific indicators for criticality can be used. These indicators combine (static or dynamic) geological availability, relevance in terms of the required quantity, concentration of mining country and companies, political conditions and other risks to a single indicator (see Graedel et al. 2012). In the case of cobalt Erdmann et al. (2011, p. 44) state medium criticality. In contrast, cobalt is regarded as one of the 14 "critical raw materials at EU level" (EU 2010, p. 6). Although forecasts of changes in commodity prices should generally be handled with care and scientific findings are contradictory in terms of price development of raw materials (Slade 1982; Svedberg and Tilton 2006; Radetzki 2008), it can be assumed that – on the basis of the above mentioned studies – the medium or high criticality as well as the increasing demand for cobalt (BGR 2011a, p. 137) will result in a rising price trend. If an annual price increase of e.g. 3% is assumed, the additional cost for the purchase of cobalt in our example (2012 - 2030) amounts to approximately $ 200 million. In addition, it can be expected that volatility of commodity prices will increase in the future (Goldman Sachs 2011, p. 5). In the same time, the consideration of cobalt's historical price curve (see Figure 27) suggests that high price volatility must also be expected in the future.

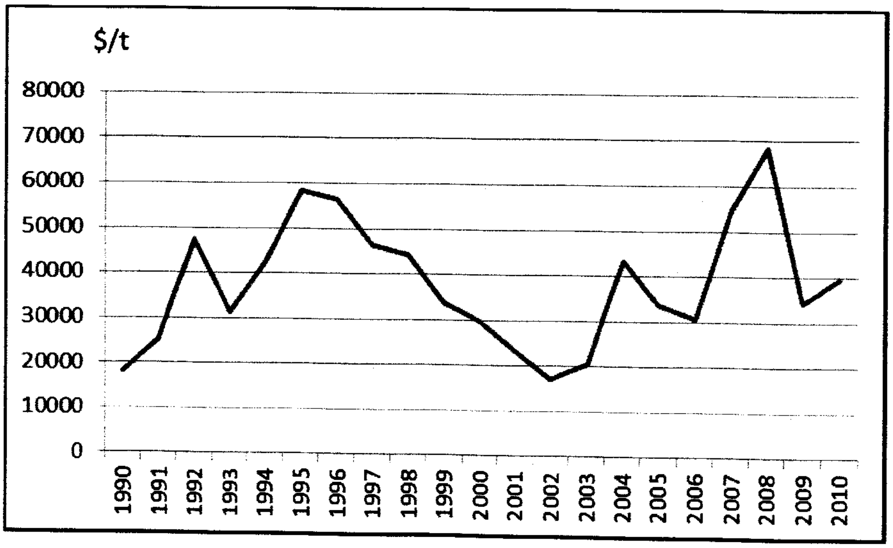


**Figure 27** Historic cobalt price 1990 - 2010 (own illustration with data from USGS 2012)

As it can be assumed that cobalt deliveries from DRC, a country depending on the exportation of raw materials (Knoke and Binnewies 2010, p. 7), will continue in the future, as additional cobalt mines in politically stable countries will start their production within the next few years (USGS 2010) and as the (static) geographical availability is currently about 110 years (Frondel et al. 2007, p. 13), a continuous availability of cobalt can be expected. I.e. (short term) availability risks for cobalt seem to be highly unlikely.

Based on the economic risk assessment, which must be done separately for each raw material, there are several ways to reduce these risks. These include (sorted by increasing effort)

- securing the current price level of raw materials by storing them in own stocks,
- securing the current price level by purchasing appropriate financial products like futures (hedging) (Deutsche Bank 2007, p. 5); even though this strategy is generally restricted to short or medium-term maturities and only possible for a few commodities,
- passing of the commodity price risk to the customer, for example by price adjustments or the prior agreement of cost escalation clauses,
- conclusion of long-term supply contracts with producers of raw materials and long-term price agreements,
- search for new suppliers who source their raw materials from different producing countries and thus contribute to the diversification of country risks,
- the increase of own R&D activities with the aim to gain resource efficiency and thus to reduce the cost of raw materials,
- the substitution of raw materials of high criticality by alternative raw materials, which are less critical in the medium and long range – provided that technical characteristics and constraints do allow this,
- establishing or strengthening of an internal resource management system to connect data on current and future consumption of raw material to the aforementioned price and availability risks (IHK 2010, p. 4) and to enable specific resource planning already in the phase of new product development,
- purchase of recycled materials and the establishment of an own recycling system, e.g. connected with the introduction of a deposit or a return premium on old products and

- exploration for own sources of raw material (vertical backward integration) or cooperation with organizations (such as the German Mineral Resources Agency), which accelerate the exploration of medium and long term reliable sources of raw materials (Buhl et al. 2010; Achzet et al. 2011; DERA 2012).

The specific applicability of these economic measures to the case of cobalt is apparent from Table 15 and – in detail – from the also cited references.

| Possible individual measures | Cobalt case | Reference |
|---|---|---|
| storage | possible both in own stocks or e.g. in LME's stocks (current price: $ 0.53/ton/day) | LME (2012b) |
| financial products | hedging with futures on the LME (possible since 2010) | LME (2010), LME (2012c) |
| passing of the commodity price risk | possible depending on price sensitivity of customers and competition | Berger (2012, p. 5 et seq.) |
| supplier selection and conclusion of long-term supply contracts | possible depending on the amount of demand | Cobalt Development Institute (2012, p. 3) |
| increasing resource efficiency | possible, but depending on own R&D intensity | Ellis et al. (2007) |
| substitution | only to a limited extent | BGR (2007, p. 8), Angerer et al. (2009, p. 173) |
| development of a resource management system | possible, but depending on the dependence of critical raw materials | Buhl et al. (2010), Clausmark (2012) |
| use of recycled materials | technically feasible, but economically dependent on the price of primary raw material | Faulstich et al. (2010, p. 31), Treffer et al. (2011, p. 67), USGS (2012, p. 14) |
| vertical backward integration | possible, but depending on the amount of raw materials required | RA (2012) |

**Table 15** Individual measures to reduce economic commodity risks

## 3.3.4 Ecological Aspects

After the discussion of economic risks as well as possible measures to reduce them, we will now discuss ecological drivers, which are to be considered to ensure sustainable new product development and production. Reasons to consider ecological risks as well, derive – on the one hand – from a corporate responsibility towards the environment, as this is required, for example, by the EU (EU 2011, paragraph 65) – even if this may conflicts with purely economic interests. On the other hand, companies can economically value achievement or conscious over-achievement of environmental objectives, if this may help to establish a positive corporate image. In addition, risk of negative media reporting e.g. on a lack of environmental standards (or an environmental disaster caused by a lack of environmental standards) can be reduced due to sustainable management

Environmental impacts arising from the demand for raw materials arise during the mining of ore, its enrichment and during the smelting process (Oertel 2003, p. 2), as well as in subsequent stages. These impacts lead to the following questions:

- Are there any expected morphological effects such as lowering trends or the emergence of tailings, which are caused by the mining of raw materials?
- Does resource extraction cause disorders of water balance (hydrological impacts)?
- What is the extent to which flora and fauna are negatively affected?
- Which atmospheric side effects are expected (Reller and Meißner 2012, cap. 2, p. 15)?
- What is the environmental impact of the raw material's transportation?
- Are there any dangers arising from the disposal of the raw material at the end of the utilization phase?

If these questions are applied to the case of cobalt, it is clear that morphological effects are currently of little relevance. This stems from the fact that the majority of cobalt is mined artisanally and therefore large-scale devices are usually not in use (Tsurukawa et al. 2011, p. 19). In contrast, waste water resulting from the mining of cobalt as well as tailings are a major environmental hazard since they contain toxic substances such as arsenic, cadmium and lead, which are normally not treated in sewage plants in developing countries (Heydenreich and Schelhove 2012). To produce 1 kg of cobalt, approximately 125 MJoul energy equivalents and approximately 36,000 liters of water are needed (EcoInvent 2010a). Moreover, to produce 1 kg of cobalt, air is polluted with 8.3 kg of $CO_2$ equivalents (EcoInvent 2010b). For the future is to be feared that environmental pollution from cobalt mining will continue to increase. On the one hand, prevailing economic conditions in most cobalt mining countries force miners to ignore (at least partially existing) environmental regulations. Secondly, it should be noted that state-owned Chinese resource companies, having invested nearly $ 10 billion in resource depletion and the necessary infrastructure since 2008 in the DRC, as well as Indian mining companies and international commodities trading houses pay very little attention on an environmentally friendly cobalt mining (Tsurukawa et al. 2011, p. 17 et seq.). In contrast, environmental impact of transportation of the annually approximately 100.000 t of copper (USGS 2012, p. 47) only plays a minor role. If it is properly disposed at the end of the use phase, cobalt is not dangerous for the environment (Treffer et al. 2011, p. 66).

After the discussion of the environmental risks resulting from the extraction of raw materials, we will now introduce measures that can contribute to a more sustainable use of raw materials from an environmental perspective. As already mentioned, also ecological risks have to be evaluated individually for each raw material. Based on these results measures have to be accelerated especially with respect to the mining of those raw materials, which – depending on the amount of raw materials needed by the company – cause the biggest environmental harm. The following measures can be distinguished:

- Selection of suppliers of raw materials, who can prove that their mining activities meets ecological (minimum) standards; e.g. by certificates from reputable institutions and the (enhanced or exclusive) purchase of raw materials from companies and from countries that have both an environmental regulation with high standards and enforce its compliance,
- reduction of the need for environmentally critical resources through measures (which have already been discussed in the Section 3.3.3) like the increase of resource efficiency, substitution by more environmentally friendly raw materials as well as purchase of secondary raw materials from recycling systems,

- promotion of research on technologies which enable to prove the geographical origin of raw materials, for example, based on chemical-mineralogical fingerprints and, by that, to trace back trade flows and patterns,
- an ideological or financial support for initiatives and organizations, which promote and work for environmentally friendly raw material mining, purification of polluted water, tailings, etc., and
- an active communication of the company's environmental engagement to inform current and potential customers as well as the public about this unique selling proposition.

The applicability of these measures depends on the company specific dependence on raw materials and will be exemplarily illustrated for the case of copper again (Table 16).

| Possible individual measures | Cobalt case | Reference |
|---|---|---|
| selection of environmentally responsible raw material suppliers | possible, but depending on the amount of raw materials required | BGR (2011b), Cobalt Development Institute (2012, p. 3), EPI (2012) |
| reduction of the need for ecologically critical raw materials | possible in principle, provided that it is also possible from a techno-economical perspective | Ellis et al. (2007), BGR (2007, p. 8), Angerer et al. (2009, p. 173) |
| promotion of technologies for determining the geographical origin of raw materials | possible in analogy to the so-called "coltan fingerprint" | BGR (2010) |
| support of initiatives and organizations that promote environmentally friendly raw material mining | possible, for example, by signing the "Code for Sustainability" initiated by German Council for Sustainable Development | Nachhaltigkeitsrat (2012) |
| active communication of environmental engagement | possible | - |
| selection of environmentally responsible raw material suppliers | possible, but depending on the amount of raw materials required | BGR (2011b), Cobalt Development Institute (2012, p. 3), EPI (2012) |

**Table 16** Individual measures to reduce environmental commodity risk

## 3.3.5 Social Aspects

To also establish a fair and cooperative interaction with people who work on the extraction and processing of raw materials, social impacts of resource depletion are focused in the next section. These impacts are related directly to the employees in mining, but also indirectly the communities in the mining areas as well as the countries' society as a whole (Benoît et al. 2009, p. 26). The implementation of these measures may be economically motivated to avoid, for example, strikes and related supply disruptions or reputational risks. The overachievement of social standards can be also explained by a sense of responsibility towards the local workforce. Here, the main focus is on the following questions:

- Are there any serious health problems of the inhabitants of mining areas, which are caused by the previously discussed environmental damage? Are there qualitative or quantitative crop losses, which are attributed to the pollution of soils caused by the extraction of resources? To what extent does mining of raw materials affect air and water?
- What working conditions are prevailing in the mining regions? Are the employees paid appropriately? Are there reasonable working hours and safety regulations? Do employees have the opportunity to unionize and to enforce workers' rights? Can it be ensured that there is no child labor?
- What role does the government play for a fair distribution of wealth resulting from the mining of raw materials? Do social security systems exist? What is the impact of corruption in the country where the raw materials are mined?
- Are there social tensions or armed conflicts, which are stimulated by money from the smuggling of raw materials? Did struggles over resource-rich areas lead to violent clashes, civil wars and refugee flows?

With respect to the mining of cobalt the social component of sustainability is of high importance, since the vast majority is produced in artisanal mining. In the last 10 years, for example, in the Katanga region (DRC), in which half of the global cobalt mining takes place, 60 to 90% of cobalt was mined in manual small-scale mining. There are about 75,000 full-time workers mining cobalt in this region; in times of high demand, their number rises to more than 100,000 miners (Tsurukawa et al. 2011, p. 5 et seq.). The biggest health problem is radioactivity of the ore cobalt gets extracted from (US Embassy, 2010). As a result, populations living in a radius of 10 km around an area with mining activity show extremely higher urinary concentrations of uranium, cobalt, lead and cadmium (Tsurukawa et al. 2011, p. 39). Moreover radioactive contamination of soil destroys the source of income for farmers in the regions in which cobalt is mined (Heydenreich and Schelhove 2012). Direct consequences of the radiation are even greater for the miners, who are directly in contact with cobalt ores. In some mines workers are exposed to radiation doses of up to 24 mSv/year (while e.g. in the EU a limit of 20 mSv/year is applied for radiation exposed adults). The earnings of miners in Katanga amounts to about 3 - 5 $ per day and thus are relatively high (compared with an income of 2.5 $ an average family of five persons earns). In this respect, the high number of overtime is compensated. As safety rules are often ignored in artisanal mining, the rate of miners dying in an accident ranges – depending on the mine – between 0.1 and 0.5% per year. As there usually are only temporary employment contracts and as only 0.5% of the mine workers are unionized, it is difficult to enforce workers' rights. In addition, child labor is widespread: 28% of employees in cobalt mining are under 15 years old, another 14% are 15- to 17-year-old. 73% of the Congolese are considered poor (Tsurukawa et al. 2011, p. 28 et seq.) and social security systems are only rudimentarily developed. One of the reasons for this is that – lack of transparent trade chains – DRC's government loses up to 90% of the potential tax revenue from the export of raw materials (Nachhaltigkeitsrat 2010). With respect to corruption, DRC is the world's number 168 out of 182 (Transparency International 2011). Last time it was in 1992 when 3,000 people were killed and 500,000 were displaced because of conflicts among different ethnic groups (Tuseko 2001). Depending on which raw materials are needed in what quantity and depending on the intensity of the raw material-specific risk, it is recommended for a sustainability-oriented company to take appropriate action. For this it is suitable in particular,

- to commit the entire supplier network to meet social (minimum) standards (combined with an agreement of penalties in case of non-compliance and local monitoring of the implementation) and, in return, to sign long-term supply agreements with cooperating suppliers helping them to increase their planning and investment security,

- to engage for transparency with respect to the raw material trade flows. This engagement towards suppliers, trade associations and government agencies should refer to both goods as well as financial flows.
- to support initiatives and organizations that support training programs in resource extraction areas, where mine workers are educated in terms of health risks and possible protective measures,
- to reduce the demand for raw materials that are produced under inhumane working conditions or for which resource wars are led (for example, by increasing resource efficiency, substitution, purchase of recycled materials),
- to utilize measures implemented by the suppliers to fairly treat its own employees (as well as employees in upstream production steps) for establishing a positive corporate image.

  So it would be a desirable result – especially from the perspective of the affected workers – that a similar social rethinking takes place in the raw material sector like it was the case for coffee or cocoa in food industry a few decades ago (Hütz-Adams 2012, p. 4).

The improvement of living conditions in raw material exporting countries, which are experiencing poverty and war at present, is a long and complex challenge for a variety of stakeholders. Against this background, it makes sense for a sustainable company to cooperate with its suppliers and NGOs to develop a long-term roadmap for the development and improvement of social standards in mining countries. Doing so, the abovementioned individual measures could be gradually implemented and in addition, their standards could then be increased step by step. Also for the social aspect of sustainable new product development – again using the example of cobalt and relating to other references – the feasibility of the proposed measures will be outlines in Table 17.

| Possible individual measures | Cobalt case | Reference |
|---|---|---|
| Definition of social (minimum) requirements/ certification and its enforcement against all suppliers | possible subject to economic constraints; certification e.g. in analogy to tin mining in the DRC (2011b BGR) | BMZ (2010, p. 16), ILO (2012) |
| Promotion of transparency in relation to raw material and their financial flows | possible, e.g. by supporting Electronic Industry Citizens Coalition (EICC) and Global e-Sustainability Initiative (GeSI) | Heydenreich and Schelhove (2010) |
| support of initiatives and organizations that promote employee-friendly raw material mining | possible, for example, by signing the "Code for Sustainability" initiated by German Council for Sustainable Development | Nachhaltigkeitsrat (2012) |
| reduction of the need for socially critical raw materials | possible in principle, provided that it is also possible from a techno-economical perspective | Ellis et al. (2007), BGR (2007, p. 8), Angerer et al. (2009, p. 173) |
| active communication of social engagement | possible | - |

**Table 17** Individual measures to reduce social commodity risks

### 3.3.6 Results for Sustainable New Product Development

Against the background of the strong dependence on raw materials in the manufacturing sector, we illustrated in the previous chapters that a company should deal with raw material risks already in the development phase of a new product. As part of this interdisciplinary approach economic, environmental as well as social issues a company must deal with as a result of its dependency on materials have initially been discussed. Subsequently possible measures have been discussed which can contribute to a more sustainable use of scarce resources. This was exemplarily discussed in detail for the case of cobalt, which plays an important and critical role in the production of high-power lithium-ion batteries.

Within these considerations it was deliberately decided neither to prioritize the three aspects of sustainability nor to rate or rank the measures described before. This is partly due to the fact that weighting has to be taken subjectively by each decision-maker. On the other hand such decisions are to be made on a company-specific basis as they are dependent on the particular demand for raw material. With this approach we would create awareness for critical and active engagement with the facets of sustainable new product development.

As part of further research it would be appropriate to evaluate the presented single measures in terms of their positive and negative mutual interactions. Moreover and in addition to the aforementioned results focused on the design of new products, it would make sense to develop scientific approaches to integrate and co-evaluate the role of both policy makers and consumers for a sustainable use of raw materials.

In this scientific contribution a sustainability roadmap was presented. The potential implementation of this roadmap was illustrated using the example of a company that plans the large-volume production of high-performance Lithium-ion batteries. It was shown that cobalt – especially because a substitution is hardly possible from a technical perspective – is the bottleneck resource of this company. As it is assumed that the demand for this metal will strongly rise in the future, a price increase can be expected. As we could show, a company can protect itself against economic risks with a series of measures. Moreover, it was shown which environmental and particularly social risks (keyword 'radioactivity') arise from the mining of cobalt. We have pointed out the implications of these risks even for a cobalt-depending company and could propose possible measures to protect economic, ecological as well as social 'stakeholders'. It was also shown, that some securing measures can be implemented immediately, that some measures require a longer lead time to plan and implement them and that some measures have a higher, some a lower temporal priority.

# 4 Summary and Outlook

The present thesis aims to identify strategies and actions that a company in the manufacturing industry can use to sustainably manage raw materials risks. In this context we contribute to answer the meta-question "How can a company in the manufacturing sector manage its demand for non-renewable raw materials – and the associated risks – considering technological and economic, as well as environmental and social objectives?" (Section 1). Mindful of the fact that it is not possible to entirely answer this meta-question in this work, we further examined it from two different perspectives (Footnote 2): On the one hand, application-oriented *partial questions* were derived (Section 1.2 and Section 4.2). Interdisciplinary answers to these partial questions may primarily address companies in the production sector, which are depending on raw materials in the short, medium and long term. On the other hand, theoretical *research questions* were derived and answered in each part of the thesis. Key results of both perspectives are briefly summarized in the two following sections.

## 4.1 Scientific findings

Once the relevance of the topic was shown in Section 1.1, it became clear that manufacturing companies are heavily concerned by raw material price increases and fluctuations. Subsequently these long- and short-term prices changes and their drivers were extensively studied in Section 2.

In Section 2.1 we focused on the question of which factors have an impact on *the long-term* price of finite resources (i.e. mining costs, technical progress, ore quality, market structure, existence of risks, backstop technologies, recycling and changes in demand). Firstly, the theoretical and empirical approaches used to study the development of resource prices were considered. Then these drivers were studied, first of all individually and then together, starting from the model of Hotelling. The implications for the future price of finite resources were then looked at in more detail and theoretical hypotheses could be derived. These were then tested by means of a meta-analysis based on empirical findings. We could show that the approaches used to date have only limited applicability in terms of drawing conclusions about which drivers impact the price of finite resources. One of the main reasons for this is identified as the growth in demand for finite resources has so far not been incorporated into Hotelling's model.

In Section 2.2 we focused on *short term* drivers of finite resources. Therefore, we analyzed empirically what really drives the price of non-renewable resources in the short term and performed an event study on three important minor metals: neodymium, indium, and gallium. Our study showed that for almost 90% of all price jumps corresponding events can be found (recall). We show that if any of these events occurs, with a probability of over 50% there is also a price jump within 10 days (precision). In addition, our analysis demonstrates that these metal prices are in fact influenced by fundamental events. But the classical set of price determinants has to be extended, as unorthodox factors like holidays or weather account for a considerable part of price changes. These findings represent a novelty in literature.

In summary, we could work out that it is not possible to explain current prices of raw materials from the analysis of various drivers. Valid explanatory approaches of *long-term* price developments of raw materials can neither be made on the basis of existing model-theoretic approaches nor based on empirical findings. Also the combination of both approaches does not help to validly explain the impact of various drivers on the (historic or future) price of raw materials. Moreover, a deeper understanding of *short-term* price volatility is of scientific (and practical) interest. Results, which have been found in our scientific research in this field, show that it is possible to - (at least partly) explain the driver-dependent composition of short-term raw materials prices – provided that they are made on a raw material-specific basis. These first results do not provide a sufficient basis for a company in the production industry to make elaborated decisions in the context of a sustainable management of raw materials. Therefore, different securing strategies and measures were presented in Section 3, enabling a sustainable management of raw materials.

In the first of the three examples, which was presented in Section 3.1, the improvement of building energy efficiency – especially through investments in information systems (IS) – took center stage. The measures described in this part are also useful for a production company to secure its production facilities against increases and volatilities of energy prices.

Innovations in the field of information systems (IS) open up new possibilities to increase energy efficiency – reducing energy costs of a company – and carbon reduction. For this, real estate is an area with remarkably high potential. Here IS can be integrated into 'Intelligent Houses'. But many of these ecologically advantageous investments are not made yet, because they do not seem to be economically profitable. We therefore developed an IS-specific model to identify investment alternatives out of all ecologically advantageous investment alternatives which are also economically profitable. For this, we compared the investment amount with the achievable energy cost reduction and – in addition – the raise of the buildings' resale returns. Out of all identified investments we determined the economically optimal investment amount. In this connection we put special emphasis on the valuation of risk and – for the first time – pointed out the applicability of Intelligent Houses as insurance against energy price volatility. Thus the quantity of all ecologically advantageous and economically profitable investments was enhanced as well as the economically optimal investment amount. IS' potentials to combine economy and ecology could thus be detected and made useable.

While this example is suitable for immediate implementation and is therefore described as 'ad hoc'-securing strategy, Section 3.2 deals with the sustainable management of raw materials in basic research: Combining the efforts of physicists, materials scientists, economists and resource strategy researchers opens up an interdisciplinary route enabling the substitution of rare elements by more abundant ones and serving as a guideline in the development of novel materials. Undoubtedly, the presented methods are only a first attempt to combine the three dimensions already set out in Section 1.4 (World of *volume* units, World of *physical* units, and World of *monetary* units).

Nevertheless, it seems to be useful to consider interdisciplinary issues relate to the demand for scare raw materials already in basic research as tradeoffs in the exploration of various technologies or materials are associated with lower costs in this early stage than it would be the case at a later time. Under the given assumptions and initially from a purely technical perspective, we could show that CCTO is the most favorable source material for further basic research in the field of semiconductors. However, CCTO loses its top ranking to LSNO as soon as resource strategic and economic aspects are additionally taken into account.

In contrast to this approach, which is suitable for basic research, an application-oriented example is presented in Section 3.3. Since in the current scientific literature, which is concerned with the implications of finite raw materials, is primarily focused on (techno-)economic aspects, it is in the scope of this part of the thesis to combine them with ecological and social implications. After the discussion of possible raw material risks occurring in each of these areas, possible countermeasures are summarized to a 'sustainability roadmap'. Using the example of cobalt, the applicability of our approach is illustrated. We could show that expected price increases of this increasingly required, strategic metal constitute the primary economic risk in the areas of R&D and production of Lithium-ion based high-power batteries. It also became evident that a lack of health and safety standards in the mining countries leads to serious health problems of employees and inhabitants in the mining areas (keyword 'radioactivity'). Thus, this research contribution aims to raise awareness of the need for sustainable new product development. It also can serve as the basis of sound business decisions in the field of sustainable raw materials management.

## 4.2 Application-oriented Implications

Having answered these theoretical *research questions*, it is also possible to focus on their practical implications. To implement a sustainable management of raw materials in company in the manufacturing industry, knowledge about current and especially appreciations of future raw materials prices is required. Therefore, the scientific approaches and results presented in Section 2 can serve as a basis. The resulting assessments of raw materials prices and their long- and short-term drivers may be seen as the first building block of a sustainable raw materials management. Strategies and measures, which can help a company to better protect against raw materials risks constitute its second block and are presented in Section 3. To complete this thesis, the results are summarized by addressing the application-oriented partial questions raised in Section 1.2 in a row now. The question to what extent a company is dependent on the purchase of raw materials can only be answered company- and resource-specific (cp. esp. Section 3.2). In addition to the quantity of raw materials, which the company has to buy to meet its current and future needs, prices of the required raw materials play an important role (Section 2). As part of the work we could show that – from a scientific point of view – it is indeed possible to identify long-term drivers that influence the development of raw materials prices. However, since the strength of the individual drivers as well as their causal connections have not yet been studied extensively enough, it is not possible to explain current prices of raw materials only from the analysis of various drivers at the present state of scientific knowledge (cp. Section 2.1). It is only an increase in demand, which seems to be a driver of rising raw materials prices. More valid statements can be made only with respect to short-term price fluctuations, provided that they are made for a specific raw material (cp. Section 2.2). Against this background, a company in the manufacturing sector should focus on this driver. To adequately assess raw materials risks arising for a company in the short-, medium- and long-term, an interdisciplinary approach is required. Investment in measures to increase sustainability in the energy sector (Section 3.1) can also lead to a risk reduction as is the case when decisions in basic research are made by simultaneous consideration of technical, resource-strategic and economic aspects (Section 3.2). In addition, the application-oriented 'roadmap' presented in Section 3.3 shows how to identify and reduce raw materials risk.

Also in terms of environmental and social issues a case-specific approach is required in order to provide answers to the partial questions arising in this context: this is particularly illustrated for the case of cobalt in Section 3.2. How to determine the resource-strategic criticality of raw materials was mainly discussed in Section 3.1. Individual measures to reduce environmental and social risks were presented in Section 3.2. However, it is the decision of each company, whether it also takes responsibility for these 'soft' aspects, or whether it complies with them only on a small scale (e.g. to avoid reputational risks). The present work also made contributions to answer technology-related issues in the context of sustainable raw materials management. A methodology was presented, how sustainable material selection decisions can already be made in the stage of basic research, if already at that time also resource-strategic and economic aspects are integrated into the decision-making process (Section 3.2). Possibilities and limitations of material substitution were also discussed in Section 3.3. Moreover, it was shown that due to technological progress an increasing number of raw materials are required for the manufacturing of innovative products (Sections 1.5.2 and Section 3.3). The question to what extent technical progress leads to a reduction of raw materials prices has to remain unanswered (Section 2.1). In contrast, it is obvious that technical progress causes an increase in (energy) efficiency (Section 3.1).

Based on these findings, a company can better assess how prices of raw materials are formed. We could additionally show that a company should be very careful in dealing with or relying on (long-term) predictions about the changes in commodity prices. In summary this means that it is not sufficient for a company to analyze the pricing of raw materials. Likewise, a variety of interdisciplinary protection strategies and specific measures presented in the second part of this thesis can be examined and applied by a company dependent on raw materials.

In this context, our study shows that corporate responsibility does not only refer to economic areas, but is to be expanded towards environmental as well as ethical responsibility. It was additionally shown from a scientific as well as an application-oriented perspective that – besides economic, ecological and social aspects – the technical dimension plays a major role for the sustainable management of raw materials.

## 4.3 Targets for Further Research

Within its capabilities, the present thesis would thus contribute to answering the already initially asked meta-question: "How can a company in the manufacturing sector intertemporally manage its demand for non-renewable raw materials – and the associated risks – considering technological and economic, as well as environmental and social objectives?" As also described in Section 1.2, , we did not aim to fully answer the meta-question in this study. Instead, we approached the question from two perspectives: On the one hand side, scientific *research questions* were derived and answered. On this basis, we focused and responded to application-oriented *partial questions*. As we could only give partial answers to the meta-question, there is a need for further, interdisciplinary research efforts in the field of the sustainable management of non-renewable raw materials.

Further research with respect to the question "What is driving resource prices?" could target the following areas: Already in this study the basic model of Hotelling could be formally expanded to different relevant supply-side drivers as well as their simultaneous occurrence. In a further step it would be reasonable to formally integrate the demand side and its impact on raw materials prices into Hotelling's model. As soon as it is possible to formally integrate supply- as well as demand-side related drivers into a self-contained model, a further scientific step can be tackled: It would be of scientific interest to separate these 'fundamental' drivers from another diver: speculation. This driver does most likely have an important influence on the price of raw materials. Nevertheless, we could not study its influence in the context of our model-theoretic consideration. This is because a better understanding of all other drivers (which is missing at the present state of science) is the basis profound research on speculation. So, the currently unknown impact of speculation also motivates and requires for further research. Further research could also focus on undertaking a comprehensive, empirical study on short- and long-term drivers of raw materials prices. As we could derive in the first part of this thesis, it is a precondition for valid results that a study like this is conducted only on a *raw material-specific* basis.

Further research with respect to securing strategies and measures against raw material risks, which were discussed in the second part of the thesis, should focus the following aspects: Is it possible to transfer the risk-reducing approach arising from investments in sustainable raw materials management (which was illustrated by the example of „Intelligent Houses") to other energy-intensive economic sectors, such as transportation? In addition, a further development of interdisciplinary research methods is required. It should be the goal of interdisciplinary research, to support further exchange and scientific cooperation between the "world of volume units", the "world of physical units" and the "world of monetary units". In this context, cost-benefit analysis seems to be a promising methodological approach to enable a simultaneous assessment of economic, technological, environmental and social dimensions. As part of future scientific activity, the sustainability roadmap developed in the last part of this thesis could be applied and expanded to other materials.

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# Appendix

Appendix A - C: With the keywords in row 2, we built a Boolean text search for each event. As the results covered several news items, concerning the same event or concerning other non-relevant events, we had to adjust them manually. The reasons for the adjustments for each event can be found in row 5.

# Appendix A

| Event | Keywords | Number of news items | Number of events | Reasons for adjustment |
|---|---|---|---|---|
| Decreasing supply - speculation for higher prices | +(Nd neodymium) +(sidelines sideline) (wait waiting) +(higher high) +(price prices) -holiday -roundup -insider | 31 | 21 | similar news within a few days, news about demanders on sideline |
| Decreasing supply - lower export quotas | +(quota quotas) +(low lower decrease decreasing allocates allocate) -roundup -insider | 44 | 12 | similar news within a few days (one adjustment of quotas), company-specific news, critic and international discussion and reports about quotas |
| Rainy season | +(rain rainy storm stormy hurricane) +china season -insider | 26 | 9 | similar news within a few days, news about water power, company-specific news, analyses about rainy seasons a year ago |
| Decreasing demand – general | +(Nd neodymium) +(price prices) +("sluggish demand" "decreasing demand" "less demand" "low demand") -roundup -insider -crackdown -mines -crisis -slowdown -(sideline sidelines) -(wait waiting) -(holiday holidays festival) | 29 | 16 | similiar news within a few days, other events |
| Decreasing demand - speculation for lower prices | +(buyer buyers demand demanders) +(wait waiting postpone postponed) (sidelines sideline "unable to obtain") +("slow down" "slowed down" lower low "due to high prices" "due to the high prices" "due to softening prices") +(price prices) -"waiting for higher prices" -holiday -roundup -insider' | 24 | 15 | similar news within a few days, news about suppliers waiting for higher prices |

**Table 18** Specific reasons for each event in the case of neodymium (to be continues on the following pages)

| | | | | |
|---|---|---|---|---|
| Increasing demand - positive outlook | +(Nd neodymium) +(positive good strong) +future +(demand demanders buyer buyers "strong market") +(price prices) -"waiting for higher prices" -sideline* -cautious -roundup -insider' | 35 | 10 | similar news within a few days, monthly reports, news focusing gadolinium, careium etc., company-specific news, Canada-specific news |
| Decreasing supply – closure of mines by government | +(Nd neodymium rare) +(Chinese China) +(supervision crackdown "crack down" "shut down" shutdown closing closedown) +("illegal mining" mining mine mines) -japan -western -critic* -roundup -insider' | 33 | 6 | similar news within a few days, company-specific news, yearly-reports, general reports, mining in Canada, news about general rare earth demand |
| Holiday | +(Nd neodymium) -after +during +(price prices) +(summer chinese china) +(holiday* festival* national summer) +(sluggish less decreasing low lower) -roundup -insider' | 37 | 7 | similar news within a few days, monthly reports, company-specific news, news focusing on lanthanum |
| Increasing supply - suppliers sell stocks | '+(Nd neodymium) +(price prices) +(high big great large) +(supplier* supply) +domestic +stock* -wait* -Insider -roundup -("prices move higher" "higher prices")' | 22 | 11 | similar news within a few days, monthly reports, news focusing on lanthanum |
| Higher export duties | '+(Nd neodymium rare) +(higher increas* rais* announc*) +export +(duty duties tarif* tax*) -insider -roundup -WTO -europe*' | 42 | 6 | monthly reports, yearly forecasts, strategies and critical news on export duties, similar news within a few days, news about possible duty rebates, company-specific news, news focusing on other countries |
| Holiday before/after | +(Nd neodymium) +(summer Chinese China) +(holiday* festival* national summer) +(after return* from forthcoming upcoming before following shortage) -roundup -insider' | 28 | 6 | similar news within a few days, monthly reports, company-specific news, forecasts ,e.g., for Christmas holidays |

| | | | | |
|---|---|---|---|---|
| Holiday before/after | +(Nd neodymium) +(summer Chinese China) +(holiday* festival* national summer) +(after return* from forthcoming upcoming before following shortage) -roundup -insider' | 28 | 6 | similar news within a few days, monthly reports, company-specific news, forecasts ,e.g., for Christmas holidays |
| Decreasing demand - global crisis | +(Nd neodymium) +(demand* buyer*) +(decreas* less low* sluggish) +(crisis slowdown recession slump demand) +(global* financial economic*) -roundup -insider' | 32 | 5 | similar news within a few days, quarterly analyses, monthly reports, general reports and news, company-specific news, branch-specific news about projects, etc. |
| Decreasing supply - governmental control over production | +(Nd neodymium) +(Chinese China) +produc* +(power* electric*) +(control* limit* cut* reduc* shortage*) -roundup -insider' | 46 | 5 | similar news within a few days, company and branch specific news, news focusing on Canada, news about e-mobility, news about new technologies for neodymium mining |
| Increasing supply - new/more production | +(Nd neodymium) +(China Chinese) +(new restart* start* open*) +(plant* mine* smelter*) +(produc* output) -(festival* holiday*) -"based smelter" -project -roundup -insider ' | 27 | 4 | general reports, planning new mines for the future, interviews concerning other topics, monthly reports, news about company cooperations, fire |
| Decreasing supply - lower production | +(Nd neodymium) +(China Chinese) +(less* decreas* low*) +(production output) -quota* -sideline* -crisis -slowdown -illegal -insider -roundup -goverment*' | 41 | 10 | general reports, similar news within a few days, news focusing on other metal concentrates |
| Decreasing supply - state stockpiling | +(Nd neodymium rare) +(China Chinese) +stockpil* +(state government) -illegal -insider -roundup -concern*' | 28 | 4 | similar news within a few days, critical reports from USA & Japan, company-specific news, yearly forecasts, forecasts and ideas from scientific staff |
| Fire | +fire -insider -roundup' | 11 | 1 | news with other meaning of "fire" |

# Appendix B

| Event | Keywords | Number of news Items | Number of events | Reasons for adjustment |
|---|---|---|---|---|
| Decreasing demand - general | +(In indium) +(china chinese) +("sluggish demand" "decreasing demand" "less demand" "low demand" "weak demand" "clearer market" "has been sluggish" "lack of good consumer") -roundup -insider -crisis -slowdown -holiday*' | 34 | 13 | similar news within a few days, company-specific news, weekly and monthly reports, reviews |
| Decreasing Supply - Speculation for higher Prices | +(In indium) +(sidelines sideline wait*) +(wait waiting forsee* anticipat*) +(higher high) +(price prices) -holiday -roundup -insider' | 38 | 11 | similar news within a few days, company-specific reviews and reports, news, focusing the USA |
| Decreasing demand - Global Crisis | +(In indium) +(China chinese) +(demand* buyer*) +(decreas* less low* sluggish) +(crisis slowdown recession slump demand) +(global* financial economic*) -roundup -insider -stockpile*' | 34 | 9 | similar news within a few days, company-specific news, Quarter and monthly reports, news concerning export taxes, news focusing on other metals, news focusing on the USA |
| Increasing Demand - General | +(In indium) +("more enquiries" "many enquiries" "moving ahead") +(high* increas* grow* ris*) +(demand* buyer* player*) -roundup -insider' | 23 | 9 | similar news within a few days, news focusing on selenium, monthly and weekly reports |
| Increasing Supply - suppliers sell stocks | +(In indium) +(price prices) +(high big large "sold out" "sell their stocks" "sell stocks") +(supplier* supply produc*) +(china chinese) +stock* -wait* -Insider -roundup -("prices move higher" "higher prices" "thin trading") -rise*' | 33 | 11 | similar news within a few days, news about low stocks, company-specific news, reports about long-term projects, news focusing on Japan |
| Decreasing Supply - Governmental Control | +(In indium) +(China Chinese) +(pollut* illegal) +(crackdown shutdown clos* "crack down" small) -"small enquiries" -"small deals" -roundup -insider' | 40 | 9 | similar news within a few days, criticism about control from the USA, reports about other toxic plants, reports concerning the stockpile system, UN reports |

**Table 19** Specific reasons for each event in the case of indium
(to be continues on the following pages)

| | | | | |
|---|---|---|---|---|
| Decreasing Demand - Speculation for lower Prices | +(buyer buyers demand demanders) +(wait waiting postpone postponed push* "no hurry to replenish") +("slow down" "slowed down" lower low "due to high prices" "due to the high prices" "due to softening prices") +(price prices) -"waiting for higher prices" -holiday -roundup -insider' | 36 | 9 | similar news within a few days, waiting for tax announcements, weekly and quarterly reports, company-specific news |
| Decreasing Supply - Less production | +(In indium) +(China Chinese) +(less* decreas* low* reduce* cut* "shut down" shutdown) +(production output) -insider -roundup -government* -slowdown' | 69 | 7 | similar news within a few days, report focusing on the USA, company-specific news, monthly reports |
| Decreasing Demand - announcement export policy | (In indium "minor metals") +announc* +(higher increas* rais* add*) +export +(policy policies quota* duties duty) -insider -roundup' | 40 | 4 | similar news within a few days, report about adaptions in the past, not concerning an announcement, report focusing on Japan, Reports focusing on other metals, company-specific news, monthly and weekly reports |
| Increasing Demand - Positive Outlook | +(In indium) +(positive good strong) +future +(demand demanders buyer buyers "strong market") +(price prices) -"waiting for higher prices" -sideline* -cautious -roundup -insider' | 26 | 9 | similar news within a few days, holidays, interviews with companies (specific) |
| Holiday | +(In indium) -after +(price prices) +(demand* buyer* supply*) +(summer chinese china) +(holiday* festival* national summer "year-end") +(sluggish less decreas* low*) +"Chinese indium" -roundup -insider' | 17 | 5 | similar news within a few days, company-specific news |
| Increasing Demand - Fill stocks after Disaster | +(In indium) +earthquake +(return* "come in" "growing demand") -roundup -insider' | 13 | 3 | similar news within a few days |

| | | | | |
|---|---|---|---|---|
| **Higher Taxes** | **+(In indium) +(higher increas* rais* announc* add*) +export +(tax* duty duties tarif*) -"after duty" -insider -roundup -europe*'** | 12 | 4 | **similar news within a few days** |
| Increasing Supply - Recycling | +(In indium) +"recycled material" -roundup -insider ' | 22 | 6 | news focusing on Korea or USA, similar news within a few days, reports about recycling-companies and strategies |
| **Increasing Demand - Innovation** | **+(In indium) +(China Chinese) +(increas* higher) +solar +demand -germanium -gallium -insider -roundup'** | 16 | 6 | **similar news within a few days, other reports and news about solar technology, company-specific news** |
| Lower Taxes | +(tax* duty duties policy policies) +("support exports" "encourage exports") ' | 2 | 2 | |
| **Unchanged Taxes** | **+(In indium) +(China Chinese) +(tax* duty duties policy policies) +unchange* -roundup -insider'** | 34 | 4 | **similar news within a few days, news focusing on other metals, general reports about taxes** |
| Decreasing Supply - General | +(In indium) +(China Chinese) +(reduc* decreas* ) +"domestic supply" -roundup -insider' | 5 | 2 | reports about quota system, weekly reports |
| **Holiday before/after** | **+(In indium) +(Chinese China) +(holiday* festival* national "new year" "year end") +(after return* from forthcoming upcoming before following shortage) -roundup -insider'** | 50 | 8 | **similar news within a few days, holiday in USA, monthly and weekly reports, general reports, holidays long ago** |
| Increasing Demand - more LCD before FIFA | +(In indium) +demand +(soccer football FIFA "world cup") -roundup -insider' | 3 | 2 | similar news within a few days |
| **Decreasing Demand - Desaster** | **+(In indium) +demand +(earthquake) -roundup -insider'** | 18 | 1 | **similar news within a few days** |

# Appendix C

| Event | Keywords | Number of news items | Number of events | Reasons for adjustment |
|---|---|---|---|---|
| Decreasing Supply - Speculation for higher Prices | +(Ga gallium) (sidelines sideline stable) +(wait waiting "no hurry to sell" "reluctant to sell" "would not sell") +(price prices) -holiday -roundup -insider' | 32 | 11 | monthly reports, general reports with focus on other metals, similar news within a few days, focusing on specific companies, |
| Decreasing Demand - Speculation for lower Prices | +(buyer buyers demand demanders) +(wait waiting postpone postponed push* "no hurry to replenish" cautious) +("slow down" "slowed down" lower low "due to high prices" "due to the high prices" "due to softening prices" "downward trend" "wait and see") +(price prices) -"waiting for higher prices" -holiday -roundup -insider' | 18 | 10 | monthly reports, report focusing on specific companies |
| Increasing Demand - Positive Outlook | +(Ga gallium) +(positive good strong) +(future prospect*) +(demand demanders buyer buyers "strong market") +(price prices) -"waiting for higher prices" -sideline* -roundup -insider' | 29 | 8 | general reports with focus on companies, monthly reports, similar news within few days, focus on Indium and other metals |
| Increasing Demand - LED Technology | +(Ga gallium) +(demand* buyer*) +(increas* grow* high*) +("LED makers" "LED manufacturers" "LED backlightening" "LED chip" "LED lighting" "LED lights" "LED bulbs" "energy saving") -roundup -insider' | 17 | 5 | similar news within a few days, monthly reports, company-specific news, forecasts |
| Decreasing Supply - Low Stocks | +(Ga gallium) +(low sufficient "cannot produce") +(stock* material) -insider -roundup' | 17 | 4 | monthly reports, general reports, similar news within a few days |

**Table 20** Specific reasons for each event in the case of gallium (to be continues on the following pages)

| | | | | |
|---|---|---|---|---|
| Decreasing Supply - Governmental Control over Production (Power) | +(Ga gallium) +(China Chinese) +(power* electric*) +(crackdown shutdown clos* "crack down" shortage limitation) -"small enquiries" -roundup -insider' | 28 | 4 | similar news within a few days, monthly reports, general reports, company-specific, solar- reports |
| **Higher Export Duties** | **+(Ga gallium) +(higher increas* rais* announc* add* rebat*) +export* +(tax* duty duties tarif*) - "after duty" -insider -roundup - europe*'** | 3 | 2 | **only discussion about gallium** |
| Decreasing Demand - Global Crisis | +(Ga gallium) +(demand* buyer*) +(decreas* less low* sluggish weak) +(crisis slowdown recession slump "weak demand" "sluggish demand" "poor economic") +(global* financial economic*) -roundup - insider' | 17 | 3 | monthly reports, focus on indium, company-specific news |
| **Holiday before/after** | **+(Ga gallium) +(Chinese China) +(holiday* festival* national "new year" "year end") +(after return* from forthcoming upcoming before following shortage) -roundup - insider'** | 23 | 4 | **similar news within a few days, monthly reports, general forecasts,** |
| Increasing Demand - announcement export duties | (Ga gallium) +announc* (high* increas*) +export +(duty duties tarif* tax*) -maintain -package - roundup -insider' | 11 | 3 | general reports about taxes, taxes on Si and Co, monthly reports, company-specific news, unchanged duties |
| **Decreasing Supply - General** | **+(Ga gallium) +(China Chinese) +(reduc* decreas* rise*) +"domestic supply" -roundup - insider'** | 11 | 3 | **monthly reports, holiday reports, report about quota system, similar news within a few days** |

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| Decreasing Demand - General | +(Ga gallium) +(china chinese) +("sluggish demand" "decreasing demand" "less demand" "quiet demand" "low demand" "weak demand" "clearer market" "has been sluggish" "lack of good consumer") -roundup -insider -crisis -slowdown -holiday*' | 17 | 4 | similar news within a few days, monthly reports, company-specific news, |
| Decreasing Demand - Big Stocks | +(Ga gallium) +(demand* buyer*) +cautious +(replenish* restock*) +stock* -roundup -insider' | 6 | 2 | similar news within a few days, monthly reports |
| Decreasing Supply - State Stockpiling | +(Ga gallium) +(China Chinese) +stockpil* +(state government) -illegal -insider -roundup -concern*' | 14 | 4 | monthly reports, general reports, focusing on indium, forecasts |
| Holiday | +(Ga gallium) -after +(price prices) +(demand* buyer* supply*) +(summer chinese china) +(holiday* festival* national summer "year-end" season) +(sluggish less decreas* low*) -roundup -insider' | 37 | 5 | monthly reports, reports for stockpiles, focus on indium, general reports |