1 Introduction

1.1 Motivation

In the recent past, commodities moved in the focus of a variety of different groups ranging from industrial companies over financial institutions to retail investors. For example the prices of industrial metals, which are among the most important input factors for a wide range of industrial products, increased enormously in the past decade. The LMEX index from the London Metal Exchange (LME), which is calculated from the prices of the most important industrial metals, such as aluminum or copper, increased since the beginning of this millennium by more than 200%.[1] One of the main reasons for this can be seen in the fast economic development of emerging economies. Due to this, especially China and India as the largest of these countries had a rapidly growing commodity demand (Radetzki, 2006). Additionally, economic growth in early to medium development stages is much more resource intensive than in later phases (Tilton, 2003). For example large investments in infrastructure projects, typical to this development stage, lead to strong metal demand from the construction sector. But also increased activity of financial institutions in commodity markets are often cited as main cause for rising prices in the past years (Radetzki, 2006). Especially in the last decade it can be observed that commodities are more and more seen as an interesting asset class, attracting considerable amounts of capital investments (McKenzie & Maslakovic, 2011).

Regardless of the true reason of the commodity price boom, this development yields new challenges and opportunities. Industrial producers are confronted with rising and volatile prices of their input factors. Commodity hedging is becoming therefore of critical importance for increasing firm value (Smith & Stulz, 1985). According to a survey of KPMG (2007) among 500 companies, 89% of the survey participants claimed to see a medium to large impact of commodity prices on their costs. As a consequence, 57% planned projects related to hedging of commodity price risk. A very common way to hedge commodity price risk involves the use of financial derivatives. For industrial metals there is a well-organized global exchange trade on a few specialized exchanges, such as the LME or to a smaller extent the COMEX. These exchanges provide market participants with a platform not only for derivative but also physical commodity trading. The former are especially important to industrial companies and commodity producers to hedge their price exposure.

Firms' hedging activities are closely related to activities of financial institutions, such as institutional investors or investment banks, in commodity markets. As counterparty in derivative markets they provide hedging services to the real economy (Keynes, 1930). In contrast to industrial companies these so called non-commercial market participants are usually not interested in the physical commodity (Mayer, 2012 for this and the following). They see commodities as an alternative investment class, for example to stocks or bonds, and desire an exposure to the development of commodity prices. This way, investors can diversify their portfolios and improve the risk-return profile (Geman & Kharoubi, 2008; Belousova & Dorfleitner, 2012). Others engage in speculative trading and take on long as well as short positions, depending on their expectations. Furthermore, investment banks earn fees for commodity market related financial services for firms and private investors. The activities of non-commercial market participants, who are not interested in the consumption of a commodity, have to be carefully evaluated. On the one hand they can be helpful for commodity markets as they e.g.

[1] Short after the price peak in the year 2007 the index level decreased due to the financial crisis. By the end of May 2013 the index was still about 130% above its level from the beginning of the year 2000.

provide additional liquidity, balance differences in supply from producers and demand from consumers, and are the counterparty in hedging activities. However, the fast rising commodity prices together with the strongly increasing number of these market participants lead to the question whether their activities distort market prices (Masters, 2008).

At the same time as many of the aforementioned institutional investors, another investor group became increasingly interested in commodity markets: The retail investors. For them the access to commodity markets is still very difficult, as physical investments, apart from some precious metals, such as gold, are not feasible for them and standard derivatives have very high contract sizes. Hence, retail investors who wish to participate in commodity price developments or diversify their portfolios (Geman & Kharoubi, 2008; Belousova & Dorfleitner, 2012) are obliged to make use of certain kinds of financial intermediation. A very common way to invest in commodities are structured financial products (SFPs). SFPs are derivatives issued from banks, which give the investor the right to receive a payment contingent on the price of a specific commodity. These products allow the investor to directly select a specific commodity. This is especially useful for investors who want to invest only in selected commodities and exclude for example food commodities due to ethical reasons. Like for other non-commercial investors, similar benefits and concerns related to commodity markets arise from activities of this investor class.

For all of these market participants alike, derivatives are of critical importance for their activities in commodity markets. However, there are several differences between derivative markets for standard assets, such as stocks, and commodities, which are subject to research for decades. Therefore, I proceed with a short overview on the most relevant studies from the perspective of this thesis.

1.2 Research on commodity derivative markets and other related topics

Research on commodity derivatives has a very long tradition in the academic literature. One of the first authors to mention is John Maynard Keynes. In his more than 80 years old work “A Treatise on Money” he develops the theory of normal backwardation (Keynes, 1930). In Keynes view, the future price is under rational expectations the expected spot price adjusted by a risk premium, which compensates speculators (i.e. non-commercial traders) for insuring hedgers against price risk. Dusak (1973) extends this model with an alternative explanation approach by proposing that risk premiums are paid for systematic risk of commodity futures. Complementary to the point of view of Keynes, Kaldor (1939) and Working (1948; 1949) suggest the theory of storage, which relates future prices to inventory levels. Despite the fact that a commodity usually does not generate cash flows, it can provide dividend-like benefits to someone having it physically in stock, termed as convenience yield. For example a manufacturer with sufficient inventories can buffer supply shortages of the commodity (Fama & French, 1987). Weymar (1966) suggests furthermore that also future inventory levels influence the future price. Building on these concepts, current research is still focused on explaining commodity price dynamics and commodity future prices (e.g. Gorton et al., 2013).

Furthermore, inventories play a second important role in commodity markets. Commodity prices are subject to the balance of supply and demand. Smaller imbalances are smoothed by sufficiently high inventories, which reduce volatility of prices (Reagan & Weitzman, 1982; Deaton & Laroque, 1992). The resulting negative relationship between inventory and volatility leads to the inverse leverage effect in commodity markets (Geman, 2005), which is opposite to the famous leverage effect in equity markets.

Beginning in the last decade a highly political topic moved in the focus of research on commodity future markets. Fueled by strongly rising prices, researchers and policy makers alike became concerned about the impact of non-commercial trading in commodity prices. Results from research on commodity price bubbles are probably as controversial as the public debate and work is still ongoing (e.g. Stoll & Whaley, 2010; Morana, 2013).

Even though introduced later in the literature, but not less relevant is the research on commodity options. Fischer Black (1976) proposes an adaption of the famous Black-Scholes option pricing model (Black & Scholes, 1973) for commodity future options. Subsequent research introduces other commodity specific stochastic factors to option pricing theory, such as the convenience yield (Miltersen & Schwartz, 1998). Apart from theoretical models of various option types another strand of the literature is related to real option prices. By solving an option pricing model backward one can calculate from market prices the implied volatility. Under certain assumptions, this should be the market forecast of subsequently realized volatility (Canina & Figlewski, 1993; Szakmary et al., 2003). Even though recent research indicates forecast power of implied volatility, volatility risk premiums in commodity option prices (Doran & Ronn, 2008) are documented in the last few years like for other asset classes (Carr & Wu, 2009).
Related to option prices is a new stream of the literature, which is still in its infancy. Instead of predicting financial variables from macroeconomic data, Backus et al. (2011) propose to go the other way round and predict macroeconomic variables, such as economic disaster, from option prices. It seems very promising to adapt this approach in commodity markets because they are shaped to a large extent by fundamental properties.

Finally, there is a huge body of literature on SFPs for retail investors. The focus of researchers is thereby on the hidden fees, which are charged by investment banks for these products. Many studies analyze their determinants with stock underlyings (e.g. Stoimenov & Wilkens, 2005). But surprisingly, there is no research on SFPs with commodity underlyings, even though this offers additional insight into price setting of banks, trading behavior and market understanding of retail investors.

1.3 Research aims of this thesis

The purpose of this doctoral thesis is to answer several research questions building on the fundamental streams of commodity and derivative research mentioned before. At first I focus on commodity future markets and examine the price relation between spot and future prices of a commodity. There are two modeling approaches for commodity future prices in the empirical literature. In the cost of carry valuation approach, which is closely related to the work of Kaldor (1939) and Working (1948; 1949), the future price is derived from the current spot price with arbitrage arguments. Thus, the future price includes interest and storage costs as well as the cost of convenience (as quantified by the famous convenience yield). As an appropriate proxy variable for the unobservable convenience yield I use, in accordance with the theory of storage, the inventory level of a commodity. In the approach of Keynes (1930), the future price is the expected spot price adjusted by a risk premium. Researchers test apart from the existence of a risk premium the forecast power of future prices on subsequent spot prices. For the first time I apply both models in one data set and compare the results from Johansen cointegration tests. This way I answer the question which of the two approaches is more helpful for the modeling of future prices. I am also able to examine some important aspects of the impact of non-commercial market participants on commodity markets. I test under which market conditions their trading activities in the future market can influence spot commodity prices, in which of the two markets price discovery takes place, and how trading volume affects the relationship between spot and future price. Furthermore, I connect the work on convenience yields of Weymar (1966) to the theory of commodity criticality. Based on this, I test hypotheses on the predictive power of

convenience yields on future inventory levels and prices. Hence, I examine whether the convenience yield is an indicator of future supply risk. Even though this part of my research is not related to options, there is also a clear parallel to the approach of Backus et al. (2011) in forecasting macroeconomic data from derivative prices.
Furthermore, I draw from the theory of commodity option pricing. Just like for the convenience yield I examine the implied forward volatility as supply risk indicator, which builds more directly on the work of Backus et al. (2011). Due to the buffering role of inventories, there is a negative relationship between volatility and inventory level (e.g. Reagan & Weitzman, 1982). I verify this with historic volatilities and inventory data. Furthermore, I focus on the implied forward volatility from commodity options, which is under certain conditions the market's estimation of the subsequently realized volatility. My empirical examination of this gives additional insight in the efficiency of the LME commodity option market and the existence of volatility risk premiums. Finally, I synthesize these two theoretical relationships and test whether the implied forward volatility, which should be a forecast of subsequently realized volatility, is also a forecast of the subsequently realized inventory level. This shows whether the implied forward volatility is a measure of future supply risk and whether option prices reflect expectations on future inventory levels.
Finally, I focus on commodity derivatives for retail investors. Especially SFPs allow retail investors to participate in commodity markets in a convenient way. These products are issued by banks and contain usually a non-transparent profit margin. It is very difficult for retail investors to determine the fair value of these often complex products. Hence, the margin is a very important quantity, which determines investors' profits. Being the first to analyze commodity SFPs allows me to gain insight to commodity specific determinants of bank margins, such as fees for the creation of a virtual market access, currency protection, and convenience yield dependent margins. Furthermore, I examine whether retail investors exhibit trend following trading strategies and whether bank margins are adjusted by volatility risk premiums. I draw conclusions on the pricing strategy of the issuers as well as on the behavior of retail investors.

Apart from its academic value, my research helps to gain deeper insight in the pricing of commodity derivatives and gives all market participants a better understanding of mechanisms in international commodity markets. The influence of inventories on commodity spot and derivative prices is of great importance for commodity producers and industrial companies. Especially industrial metals consumers, for example in the electronics or automotive industry, can profit from these results. They are provided with new insights on the mechanics of very important hedging instruments. Furthermore, they can incorporate financial market data in the assessment of commodity supply risk. Financial institutions can introduce inventory data in their valuation and forecasting models. In this context my research contributes to a better understanding of the impact of speculative trading activities on commodity prices. Both groups can profit as well from the knowledge gained on volatility forecasting. Finally, I help retail investors to better understand investments in SFPs on an alternative asset class. This work reveals hidden fees of commodity SFPs, which are usually not transparent to retail investors.

I conduct my research with a sample of industrial metals as they are classical consumption commodities with a clear application area, which are easy to store, and do not deteriorate. They show no strong seasonal behavior like some agricultural or energy commodities. These properties are very favorable from the perspective of scientific analysis and allow empirical examination in a straight forward way. I choose for my analysis industrial metals from the LME, which is the globally leading exchange for these metals. More than 80% of global non-ferrous metal futures are traded at this exchange (LME, 2014). There are various futures and options available for a variety of different maturities, which allow examining the influence of very interesting term structure effects. Additionally, the LME has a global warehouse network with more than 700 warehouses and publishes inventory data with daily frequency (LME, 2014). The total inventory level can amount to some percent of an annual mine production of a commodity, which can be considered as representative for global inventories. This dataset offers a unique setting for my research on commodity derivatives because of the important role of inventories in these markets and the other beneficial properties mentioned before.

Related chapters in this thesis	Derivative type	Practitioners target group	Use of derivative	Research aims & objects
Theory & literature: 3.1 Empirical analysis: 4.1	Futures	• Industrial companies • Banks • Institutional investors	• Hedging • Investment • Speculation	• Modeling future prices • Convenience yield as supply risk indicator • Impact of non-commercial trading
Theory & literature: 3.2 Empirical analysis: 4.2	Options	• Industrial companies • Banks • Institutional investors	• Hedging • Investment • Speculation	• Implied forward volatility as supply risk indicator • Inventory as determinant of volatility
Theory & literature: 3.3 Empirical analysis: 4.3	Structured financial products (SFPs)	• Retail investors • Banks	• Investment • Speculation	• Bank margins of commodity SFPs • Banks' pricing strategy • Retail investors' trading behavior

Figure 1: Overview of the derivative type specific structure of chapter 3 and 4, which reflects the blocks of research fields of this thesis. There are three derivative types in the focus of this work, which have different target groups and uses.

The remainder of this thesis is organized as follows: In chapter 2 I give a general introduction to commodities and to industrial metals, which are in the focus of this work. I explain the role of supply risk in the framework of commodity criticality and present basics of commodity trading. Building on this, I structure my thesis along the three derivative types futures, options, and SFPs, which are very important in commodity markets. This structure is applied to chapter 3 and 4 alike in which I have one subchapter for each derivative type and the related research aims (Figure 1). Chapter 3 contains the relevant theory and an overview of the literature. At the end of each subchapter, I derive research aims and hypotheses related to the respective derivative type. Chapter 4 is dedicated to the empirical examination of the hypotheses. In every subchapter I present the methodology, description of the relevant data, results, and a discussion. I start in chapter 4.1 with the comparison of two future pricing models with cointegration techniques. In the cost of carry model I focus on the approximation of convenience yields with the inventory level of the underlying commodity. The risk premium model, arising from the theory of normal backwardation, allows evaluating the forecast power of the future price on subsequent spot prices. I also test the forecast power of the convenience yield in terms of supply risk and additionally make some observations on issues of non-commercial trading. In chapter 4.2 I examine the forecast power of implied forward volatility on supply risk. Along with this, I also test forecast power on realized volatility and the relationship between volatility and inventories. In chapter 4.3 I examine commodity SFPs for retail investors. I analyze several determinants of the bank margin and draw conclusions on banks' pricing strategies as well as retail investors' trading behavior. Finally, I give a concluding discussion and an outlook on avenues for further research in chapter 5.

2 Commodities and their exchange trade

2.1 Commodity classification

Raw materials are produced from the resources of our environment, which can be divided broadly into renewable and nonrenewable resources (Reller et al., 2013).[2] In the context of financial markets usually the term commodity is used rather than raw material. Even though a clear distinction between both cannot be found in the literature, one can state qualitatively that a commodity has a higher level of added value than a raw material in general and has often undergone several refinement stages. Thus, a commodity of a given quality, which is traded in financial markets, is near to a standardized product without major differentiating features. As the focus of my work is on exchange traded commodities I use, without a loss of generality, the term commodity as far as possible. Because a commodity can be seen as a certain kind of raw material, statements apply in general also to them.

Commodities as a class are very heterogeneous regarding their physical properties and have to be further segmented in groups. Figure 2 presents a classification from a financial market point of view into hard and soft commodities (Fabozzi et al., 2008). Broadly speaking, hard and soft commodities differ among others in their origin from nonrenewable respectively renewable resources. Hard commodities are metals, which are further divided into industrial as well as precious metals, and energy commodities. Soft commodities can be further segmented into livestock (animal products) and agricultural commodities. The latter contain softs as well as grains and seeds. In general soft commodities are perishable and have limited storability in contrast to most hard commodities (e.g. metals). A common characteristic, which they share especially with energy commodities, is that they are consumed and transformed into other substances. In contrast, most metals (given that they do not decay radioactively) are not consumed in their elemental form and their physical quantity remains unchanged. Thus, they can theoretically be recycled to some extent from waste.[3] Among the major limiting factors for this is, however, material dissipation, which means that material is emitted e.g. into the environment in a way that does not allow recycling anymore. For example platinum is dissipated in the atmosphere in cars' catalytic converters (Thorenz & Reller, 2011).

The presented classification is not unique and the listed commodities are not comprehensive. An enhancement of this scheme might be the introduction of a ferrous metals subgroup or a subgroup for minor metals (e.g. cobalt). Alternative classification approaches can be based on the origin of raw materials (e.g. earth crust) or their use (Haas & Schlesinger, 2007). The latter (see Fabozzi et al., 2008) would induce a distinction between input factors for industrial production (e.g. energy or metals) as well as food and consumer products (e.g. corn or tobacco). Furthermore, there are materials which are not associated only with one subgroup. This is the case e.g. for uranium, which is a heavy metal. However, it is used to a large extent as an energy source. Hence, depending on the path of refinement processes, it might be attributable also to the energy commodity subgroup (in the form of yellow cake) from the consumption perspective. The scheme does also not cover alternative energy sources. This

[2] The so called nonrenewable resources are usually products of geologic and astrophysical processes. As the time scale of these processes is far longer than any relevant time scale for human beings, these resources are considered as nonrenewable (Tilton, 2003).
[3] Note that recycling is one way of obtaining closed loop supply chains. Others are reuse of complete products or remanufacturing, which means that components from end of life products are used in new products (Reller et al., 2013).

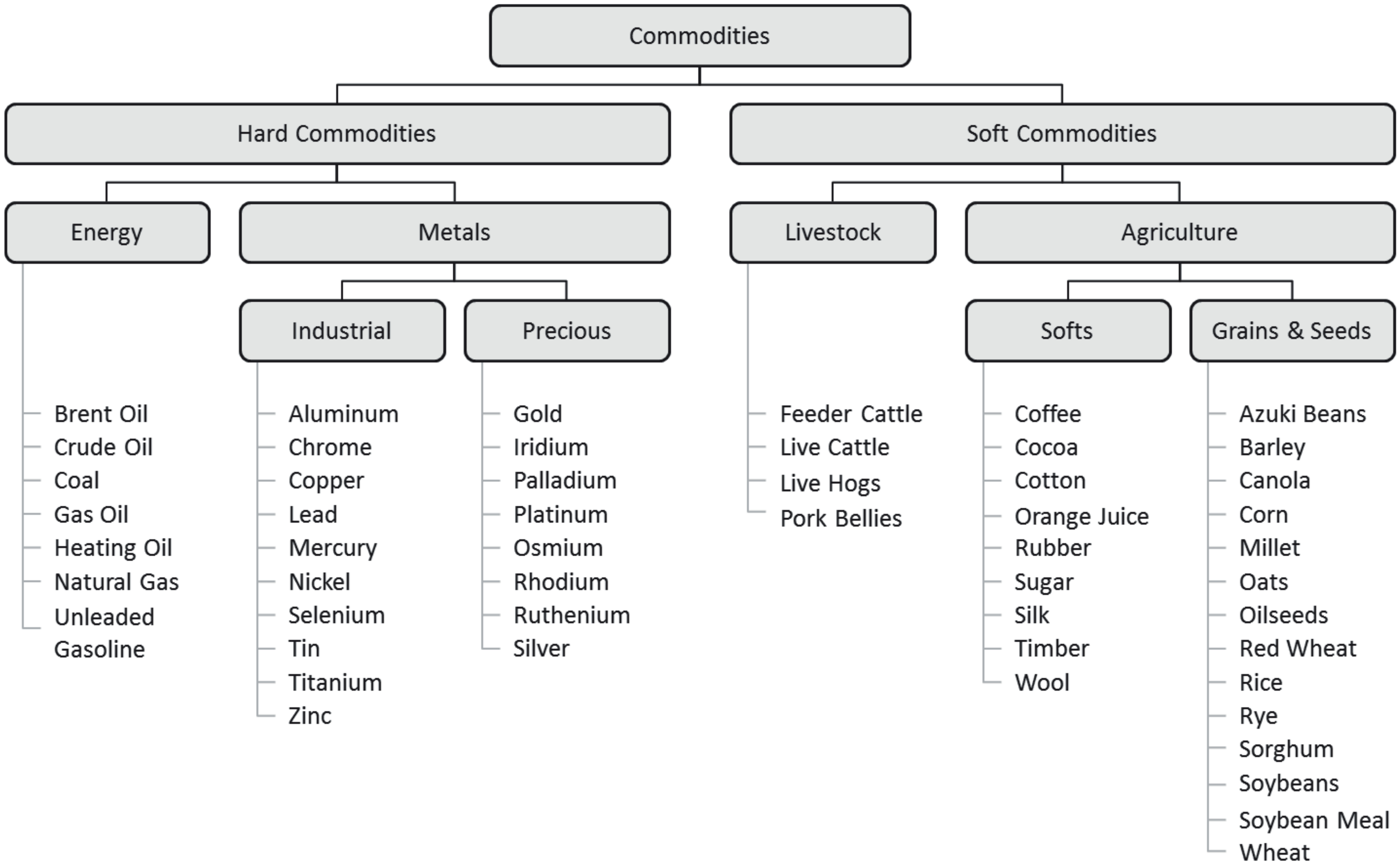

Figure 2: Classification of commodities (adapted from Fabozzi et al., 2008). The figure contains only examples of commodities from the different groups and is not comprehensive.

subgroup contains among others bio mass, which might be attributable to the soft commodity or energy commodity group.

A unique classification appears to be quite difficult as it depends on the perspective. Despite all these drawbacks I use the presented financial market driven classification because it reflects the overall structure of commodity markets reasonably well. This imposes no major limitations for my work because I focus on industrial metals, which can be clearly located in the scheme.

2.2 LME traded industrial metals

As can be seen from the previous discussion, commodities are in general very heterogeneous. For example oil and gas belong both to the group of energy commodities but have quite different properties. There are fundamental differences in transport, storage, and consumption of both commodities. But also from a financial market perspective they differ substantially. Gas forward curves show often a seasonal pattern, which can normally not be observed for oil (Borovkova & Geman, 2006). In contrast, industrial metals as a group are relatively homogenous due to similarity in production and consumption. Additionally, they are easy to store, not perishable, and are usually not subject to strong seasonal patterns. Therefore, industrial metals provide an excellent sample for research on commodity markets and specifically on derivatives.

The remainder of this thesis is focused on the most important market platform for industrial metals' trading, the LME, which was founded in the year 1877 (LME, 2014 for this and the following). The total notional of all trades at the LME in the year 2012 was 14.5 trillion US$ or 3.7 billion tonnes. This amounts to more than 80% of the non-ferrous metals transactions in the world and provides a very good data source for my research. In total, eleven metals are traded at the LME: Those are non-ferrous metals (aluminum, aluminum alloy, copper, lead, NASAAC[4], nickel, tin, and zinc), minor metals (cobalt and molybdenum), and the steel billet. In Figure 3 the shares of single metals from the total turnover in the year 2012 across all contract types of 159.7 million lots (futures and options) are displayed. It can be seen that aluminum, copper, and zinc are the commodities, which are traded most often. Other metals, which are displayed in an aggregated form (others), have a total turnover lower than the one of tin. Consequently, I focus in the remainder of this thesis on the six metals, which have by far the highest turnover. Those are aluminum, copper, lead, nickel, tin, and zinc. For reasons of brevity and consistency with the classification in chapter 2.1, I refer to them in the following also as industrial metals. A detailed description of the metals is given in chapter 2.3.

The major contract types at the LME (2014) are futures, which account for 95.9% (153.2 million lots) of the traded contracts in the year 2012, and options with a share of 4.0% (6.4 million lots). The remaining share is distributed on other minor contract types such as traded average price options (TAPOs), swaps (LMEswaps), and some futures with smaller lot size of five tonnes (LMEminis, not traded in the year 2012).

A future contract is the obligatory transaction of a standardized underlying (metal) at a later delivery date in time (maturity or prompt day) for a predetermined price (future price). Where the buyer (seller) has the long (short) position in the future. LME futures are traded for maturities of up to 123 months. Futures with up to three months maturity expire daily, with up to six months weekly, and monthly for longer contract periods. The prompt day for contracts with weekly expiry is normally Wednesday and for monthly expiry the third Wednesday of the contract month. LME futures are physically settled

[4] NASAAC is the so called North American special aluminum alloy contract.

against the official settlement price. The lot size of one future contract is usually 25 tonnes except for the following metals: Steel billet (65 tonnes), aluminum alloy and NASAAC (20 tonnes), nickel and molybdenum (6 tonnes), tin (5 tonnes), and cobalt (1 tonne).

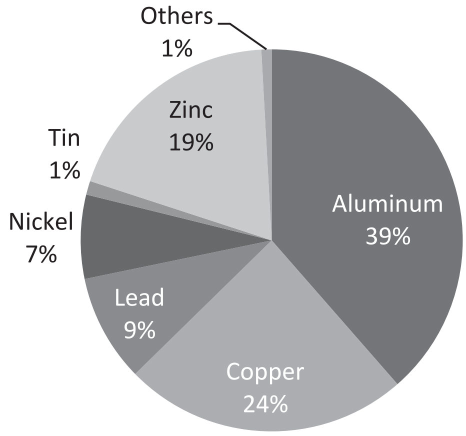

Figure 3: Shares of single metals in the total turnover of traded lots across all derivative types in the year 2012 at the LME (data is obtained from LME, 2014).

The option contracts traded at the LME are American type. An American call option gives the option buyer (long side) the right to buy a standardized underlying (metal) until maturity for a fixed price (strike price) from the option seller (short side). A comparable put option gives the option buyer (long side) the right to sell the underlying until maturity for the strike price to the option seller (short side). In contrast to the future there is no obligation to do so. Options on the LME are traded with maturities of up to 63 months with monthly physical settlement. The settlement day is usually the Tuesday before the first Wednesday of the option's delivery month. The underlying of the option is one future contract with delivery day on the third Wednesday of the delivery month of the option, as specified above.

The LME provides three trading venues, which are partially available at the same time (LME, 2014 for this paragraph). The central venue is the so called ring. It is an open-outcry trading floor where every metal is traded in a trading session of five minutes (futures, options, and TAPOs). The most relevant prices (official, unofficial, and closing price) are determined in this venue. Trading takes place from 11:40 until 17:00 (local time). Furthermore there is an electronic trading system (LMEselect), which operates from 01:00 until 19:00, and the 24 hours inter-office telephone trading.
The LME has a global network of currently more than 700 warehouses in 36 locations (LME, 2014). Inventory volumes of some of the industrial metals are very large, amounting to a few percent of the volume of an annual mine production, and are published daily.

2.3 Description of industrial metals from the LME

2.3.1 Aluminum

I focus in the remainder of this thesis on the metals with the highest turnover at the LME, which I describe briefly in the following. Aluminum (Al, atomic number 13) is one of the three most abundant elements and the most abundant metal found in the earth crust with a mass fraction of 8.2% (Haynes, 2013). This quantity gives information on the physical availability of an element. However, economic mining of a raw material requires usually higher concentrations. In case of aluminum economic production is possible from mass concentrations of about 18.5% (Riedel, 2004), which is called the cutoff grade (Haas & Schlesinger, 2007).[5] It has to be noted that the cutoff grade varies over time e.g. due to technological progress or higher prices. The most important raw material for the production of primary aluminum is currently bauxite (U.S. Geological Survey, 2013b for this and the following). It is the major source for the commercial production of this metal. In the United States (U.S.) for example, bauxite is up to now the only raw material in the commercial production of alumina, which is mostly used for the aluminum production (U.S. Geological Survey, 2013b).[6] Global reserves[7] of bauxite are estimated to 28 billion tonnes in the year 2011 (U.S. Geological Survey, 2013b).[8] The production of aluminum is very energy intensive. For one tonne of aluminum roughly 15 MWh energy is consumed (Riedel, 2004), which accounts for a large part of the production costs. However, there are other raw materials such as clay, which are potential sources for aluminum production in the future (U.S. Geological Survey, 2013b for this and the following). The primary production volume of aluminum amounted to a total of 44.4 million tonnes in the year 2011. The monetary value of the primary production can be estimated[9] with the annual average price of 2389 US$/t at the LME in the year 2011 (price data for all metals presented in this chapter are retrieved via Thomson Reuters Datastream) and amounted to 106 billion US$ (Figure 4).[10] The largest producers[11] in the same year were China with 41% of the global volume, Russia with 9%, and Canada with 7% (U.S. Geological Survey, 2013b). The three major consumers of aluminum in the year 2011 were the transport and the construction sector with 25% of the total industry consumption each, followed by the packaging industry with 17% (LME, 2014).

2.3.2 Copper

Humankind's use of copper (Cu, atomic number 29) has a very long tradition and mining is said to take place for more than 5000 years (Haynes, 2013 for this and the following). It has a mass concentration of $6.0 \cdot 10^{-3}$% in the earth crust. The cutoff grade of copper is about 0.35% (Riedel, 2004) and its global reserves amount to 680 million tonnes (U.S. Geological Survey, 2013b for this and the following). The global production volume in the year 2011 was 16.1 million tonnes with an estimated value of 144 billion US$ (average LME spot price 8948 US$/t in 2011, see Figure 4). The three largest producers were Chile (33% of annual production volume 2011), China (8%), and Peru (7%; U.S. Geological Survey, 2013b). The most important application areas were according to the LME (2014) in electronics (31% of industrial consumption), construction (25%), and so called "consumer & general" applications (17%).

2.3.3 Lead

Lead (Pb, atomic number 82) has a mass concentration of $1.4 \cdot 10^{-3}$% in the earth crust (Haynes, 2013) and a cutoff grade of 4.0% (Riedel, 2004). Reserves amount to 89 million tonnes and the annual production volume in the year 2011 was 4.7 million tonnes (U.S. Geological Survey, 2013b). With an average LME spot price of 2446 US$/t in 2011 the value of the primary production is estimated to

[5] Haas and Schlesinger (2007) provide similar cutoff grade data, but cover not the full range of the metals presented in this chapter. For consistency reasons, I present therefore the data from Riedel (2004).
[6] In this chapter I cite the Mineral Commodity Summaries 2013 from the U.S. Geological Survey (USGS). As they contain only estimated figures for 2012 I use the actual figures for 2011.
[7] Reserves are defined by the USGS as commodity deposits "which could be economically extracted or produced at the time of determination." (U.S. Geological Survey, 2013a, p.194).
[8] In accordance with the USGS data I quote the reserves of bauxite. For the production of one tonne of aluminum roughly four tonnes of dried bauxite are needed (U.S. Geological Survey, 2013b).
[9] This procedure is comparable to the calculation of the U.S. data from USGS. For reasons of consistency I use the LME average prices as this is the only large exchange where all of the presented metals are traded.
[10] The value of the annual gold production in 2011 is for comparison 79.4 billion US$.
[11] Measured by the smelter production.

11 billion US$. The three largest producers accounted for 70% of the annual production in 2011. 50% was produced in China, 13% in Australia, and 7% in the United States (U.S. Geological Survey, 2013b). The major applications of lead were in batteries (80% of industrial consumption), other uses are in coatings or X-ray shields (LME, 2014).

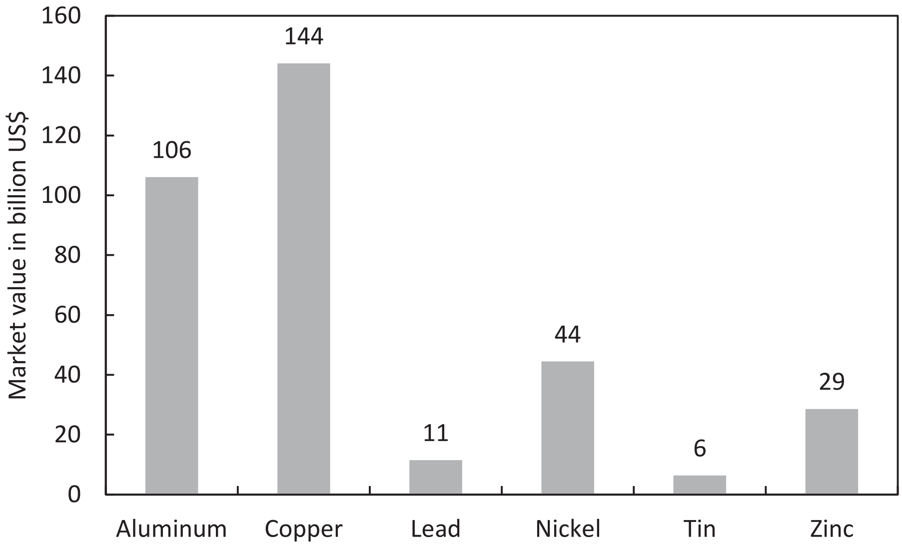

Figure 4: Estimated market value of the primary production in the year 2011 of industrial metals. Valuation with the annual average spot price at the LME. Production volume data is from USGS (U.S. Geological Survey, 2013b) and average prices are calculated from LME price data, retrieved via Thomson Reuters Datastream.

2.3.4 Nickel

In the earth crust a mass concentration of $8.4 \cdot 10^{-3}$% of Nickel (Ni, atomic number 28) can be found (Haynes, 2013). The cutoff grade is about 0.9% (Riedel, 2004) and the reserves are currently estimated to be 75 million tonnes. The mine production in the year 2011 was 1.9 million tonnes (U.S. Geological Survey, 2013b for this and the previous). With an average spot price of 22907 US$/t this amounts to a total production value of 44 billion US$ (Figure 4). The three largest producers had similar shares of the annual mine production in the year 2011 (U.S. Geological Survey, 2013b): Indonesia (15%), Philippines (14%), and Russia (14%). The main use of Nickel was in alloys (90% of industrial consumption; LME, 2014).[12] Another important application was in electroplating (U.S. Geological Survey, 2013b).

2.3.5 Tin

In the earth crust tin (Sn, atomic number 50) can be found with a mass fraction of $0.2 \cdot 10^{-3}$% (Haynes, 2013). It has a cutoff grade of 0.35% (Riedel, 2004) and reserves of 4.9 million tonnes (U.S. Geological Survey, 2013b for this and the following). At an average annual price of 26121 US$/t the mine production in the year 2011 of 244000 tonnes has an estimated value of 6 billion US$ (Figure 4). 78% of the mine production in 2011 was concentrated on the three largest producers: China (49%), Indonesia (17%), and Peru (12%). The major application areas of tin were in the production of solder (52% of industry consumption), in tin plating (17%), and in chemicals (15%; LME, 2014).

2.3.6 Zinc

Zinc (Zn, atomic number 30) is found in the earth crust with a mass fraction of $7.0 \cdot 10^{-3}$% (Haynes, 2013). The economic production is possible from a cutoff grade of 3.5% (Riedel, 2004) and its reserves are

[12] The LME steel billet can contain a nickel concentration of up to 0.2-0.3%. Stainless steel (V 2A) contains for example 8% nickel.

currently estimated to 250 million tonnes. In the year 2011 the total mine production was 12.8 million tonnes (U.S. Geological Survey, 2013b for this and the previous), which is roughly equivalent to 29 billion US$ at an average spot price of 2236 US$/t (Figure 4). The three largest producers (U.S. Geological Survey, 2013b) had a total share of 56% of the mine production in the year 2011 (China 34%, Australia 12%, Peru 10%). Today a large amount of zinc is used as coating of other metals (galvanization e.g. of steel or iron) to prevent corrosion (LME, 2014): In the year 2012 about 55% of the zinc was consumed in galvanization in the United States (U.S. Geological Survey, 2013b). Furthermore, it is used in alloys (LME, 2014).

2.4 Measuring criticality of metals[13]

Industrial metals are important input factors for various industrial production processes. For business activities of all entities of a supply chain it is vital to have a secure commodity supply. Otherwise, their business processes can be disrupted, potentially causing severe economic damage (Fridgen et al., 2012). From the perspective of a single company and also a national economy the availability of a commodity is therefore of very high relevance. Because it is for industrial metals usually not primarily the physical abundance, which imposes risks to commodity supply, a comprehensive assessment methodology has to be applied. This includes many different factors covering the whole life cycle beginning with the extraction of raw material from the ground and ending with end-of-life usage of the final product. But also other factors like the economic importance have to be considered.

Graedel et al. (2012) propose a comprehensive assessment framework for all these factors, which measures the so called criticality of metals along three dimensions: Supply risk (risks that may at least lead to supply disruptions), vulnerability to supply restrictions (at a corporate, national, or global level), and environmental implications (environmental impact of a commodity).

The supply risk dimension consists in the medium term (5-10 years) of three components (Graedel et al., 2012): (1) geological, technological, and economic; (2) social and regulatory; (3) geopolitical. Several indicators quantify each component. Component (1) contains indicators of the time to depletion (e.g. reserves, production, and demand) and interdependencies with by-products. The development level and the impact of public policies on mining projects are included in component (2). Finally, indicators for the concentration of global production capacities (Herfindahl-Hirschman Index) and political stability (Worldwide Governance Indicator) are grouped in component (3).

The vulnerability to supply restrictions comprises different components with different indicators for corporate, national, and global level. On the corporate level, which I explain exemplarily, the relevant components are the economic importance, the substitutability and the ability of a company to innovate. The environmental implications dimension is further broken down into damages to human health and the ecosystem caused, for example, by the toxicity of a commodity or its atmospheric emissions in the production process. This dimension does not cover e.g. actual governmental restrictions to resource production as these are already covered in the regulatory category of supply risk. Much more it measures the actual environmental threat caused by the production and use of a commodity. As it is out of focus from my thesis, I refer the reader to the literature for more details. Throughout the rest of this thesis I use the term criticality as defined by Graedel et al. (2012).

For an overall assessment the indicators are given a score from 0-100 (in almost all cases by a

[13] A large part of this chapter is based on a published work of Prof. Dr. A. Rathgeber, M. Walter, and me (see Stepanek et al., 2013a). The text is rephrased for reasons of consistency in the first person singular and in parts rearranged or slightly adjusted, however, I emphasize that it is partly a collaborative work from my two co-authors and me.

quantitative assessment), where 100 represents the highest risk. For every component an equally weighted average score is calculated. Afterwards these scores are again equally weighted so that a total score per dimension is obtained. If further aggregation of the results is needed, the authors propose to calculate a normalized distance of the commodity in the three dimensional criticality space. The authors furthermore note that users can apply different weighting schemes. They provide an application of such a scheme in an accompanying paper (Nassar et al., 2012) together with an application of the methodology to the metals from the copper family. Additionally, they introduce a Monte Carlo simulation approach to assess the impact of measurement errors in the indicator values on their results.

Rosenau-Tornow et al. (2009) provide another approach to supply risk assessment, which is similar to the components approach of Graedel et al. (2012). They focus on supply risk and describe it using a framework of five so-called main indicators: (a) current supply and demand, (b) production cost, (c) geostrategic risks, (d) market power, and (e) (future) supply and demand trends. These main indicators comprise specific indicators, which are evaluated with a score from 1-9. To aggregate information an average score for every main indicator is calculated and the results are finally displayed in a spider web illustration. I want to emphasize that the indicators correspond in part to those of Graedel et al. (2012). In particular, the main indicator 'current supply and demand' includes the current market balance, calculated as the difference between supply, demand, and the change in the stock level. Market imbalances are as far as possible smoothed by additional supply from inventories or by building up stocks. However, this is only possible, if the stock keeping, which is a second indicator in this main indicator, is sufficiently high. Hence, for producers of industrial goods, a low inventory level bears considerable risk of a supply disruption in the short run, if an excess demand occurs. Therefore, a measure for the inventory of a commodity is a very important short-term (<5 years) indicator in the supply risk dimension. In the Graedel et al. (2012) framework, this would be located in component (1) (geological, technological, and economic) in a short-term perspective.[14] I stress that in the approach of Rosenau-Tornow et al. (2009) market balance and stock keeping are assessed by current values in conjunction with a qualitative outlook. However, for a manufacturer's assessment of the short-term supply risk, it would also be interesting to access more quantitative forward-looking data. How important demand and inventories are for price developments on commodity markets is shown by Radetzki (2006). He analyzes three commodity price booms and states that all three of them are triggered by demand shocks due to strong economic growth.[15] Apart from this, he finds that inventories played in all three boom phases an important role in the up and down of prices. Also Geman and Nguyen (2005) use inventory data to quantify scarcity.

Another well-known approach is the cumulative availability curve, which accounts for dynamic effects (Yaksic & Tilton, 2009) but makes extensive use of data which are difficult to acquire. It incorporates as indicators a measure for the size of the reserves and the price structure of their profitable exploitation. As it reflects depletion risk, it is mainly a long-term assessment tool containing geological, technological, and economic aspects. Another approach for the assessment of changes in the

[14] Note that Graedel et al. (2012) discuss the supply risk only from medium- and long-term perspectives with slightly different components, but the short-term perspective is not presented. They admit that individual indicators can be adjusted if necessary. Hence, users can be provided this way with a short-term perspective.

[15] The first boom analyzed in the study of Radetzki (2006) begins in 1950 and is related to the Korea war. The second boom, beginning in the year 1973, is triggered by crop failures and the price increase of the OPEC cartel. The third boom starts in the year 2004. The author argues that the strong demand from China and India as well as speculative activity in commodity markets are main factors.

production of mineral resources is presented by Mason et al. (2011). They build on the concept of peak oil from Hubbert (1956) and develop a framework for the evaluation of production changes in a mineral resource and a shift to alternatives (recycling or substitutes) on national level. Similar to the dimensions of Graedel et al. (2012) they propose three criteria. In contrast to the other studies presented above, they focus on the supply side of a national economy and the consequences of a decrease in national production rates e.g. due to depletion of reserves or a lack in demand for these products. However, they present neither a quantitative evaluation procedure or aggregation logic nor a clear definition of the term criticality. Thorenz and Reller (2011) propose that apart from resource specific factors also functional aspects of the different applications of a resource have to be taken into account for criticality assessment. They emphasize the importance of covering the complete product life cycle of an application including recycling and dissipation.

Furthermore, the literature provides various other studies published mostly by governmental institutions (e.g. European Commission[16], 2010) or research institutions (e.g. Angerer et al., 2009). These studies are usually more focused on the actual criticality of certain raw materials or raw material groups. As the methodological approach is of greater importance for this thesis I refer to the work of Erdman and Graedel (2011) for an excellent overview of the existing studies on non-fuel minerals in this field.

[16] The widely recognized report of the European Commission ad-hoc working group on defining critical raw materials uses the same three dimensions like Graedel et al. (2012) with slightly different labels (European Commission, 2010). However, their components structure is slightly different.