Analysis of Environmental and Economic Aspects of International Pellet Supply Chains

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Abstract

Biomass plays a key role to achieve the EU's 20-20-20 energy and climate targets. Because of rising European demand and limited domestic resources, the EU relies on worldwide imports.

Given this framework, the present thesis explores the influences on wood pellet supply chains considering different environmental policies, price risks and the effect of torrefaction pretreatment. The examinations refer to three real case studies for pellet trade from Australia, Canada, and Russia to Europe.

In the first investigation, the efficiency of co-firing imported wood pellets in terms of CO_2 savings and related subsidy schemes is analysed. Scenarios show that co-firing biomass is efficient to contribute to the EU energy targets. Though, policy makers could use these instruments more effective when directing sourcing decision towards options with even less environmental impacts.

The second analysis explores the influence of statistically derived price risks on total supply chain economics. It is shown that price risks can effect strong fluctuations in the short term, which seriously affect the profitability of individual trade routes. Securing the supply chain is mainly based on individual producer-buyer agreements, personal branch experiences and fast reactions on the subsidy system. Systematic evaluation of supply chains could contribute to a more reliable market and thus foster investment decisions.

In the last investigation, the economic and environmental performance of potential torrefaction-based supply chains is assessed. As a result, torrefaction-based supply chains turn out to be a certain alternative to conventional ones. Though, still huge research efforts and industrial demonstration are required to make torrefied biomass a real alternative on the market.

Zusammenfassung

Biomasse spielt eine Schlüsselrolle bei der Erfüllung der EU 20-20-20 Energieziele. Aufgrund des steigenden Bedarfs bei gleichzeitig limitierten einheimischen Ressourcen ist die EU auf weltweite Biomasseimporte angewiesen.
In diesem Rahmen untersucht die vorliegende Arbeit die Einflussnahme unterschiedlicher Förderungen, Preisrisiken und die thermische Vorbehandlung durch Torrefizierung auf Pelletsversorgungsketten. Die Analysen basieren auf drei realen Fallstudien für Pelletshandel von Australien, Kanada und Russland nach Europa.

In der ersten Untersuchung wird die Kofeuerung importierter Pellets auf ihre Effizienz hinsichtlich CO_2 Einsparungen und verbundener Förderungen evaluiert. Szenarien zeigen, dass Biomasse-Kofeuerung einen effizienten Beitrag zur Erfüllung der EU-20-20-20 Ziele leisten kann. Dennoch könnten die Fördersysteme noch wirksamer auf die Versorgungsoptionen mit geringstem Umwelteffekt abzielen.

Die zweite Analyse untersucht den Einfluss von Preisrisiken auf die Wirtschaftlichkeit der Versorgungsketten. Es wird gezeigt, dass Preisrisiken extrem starke wirtschaftliche Schwankungen über einen kurzen Zeitraum verursachen können. Die Absicherung der Versorgungskette geschieht oft über bilaterale Verträge, persönliche Erfahrungen und schnelle Anpassungen an das Fördersystem. Dabei könnte ein systematisches Monitoring dazu beitragen, den Markt verlässlicher zu gestalten und Investitionsentscheidungen zu erleichtern.

In der letzten Untersuchung werden die Vorteile von Versorgungsketten auf Basis torrefizierter Pellets bewertet. Im Ergebnis zeigt sich, dass torrefizierte Pellets einen gewissen wirtschaftlichen und ökologischen Vorteil ermöglichen können, es aber noch Forschungsbedarf hinsichtlich der Technologieumsetzung und Marktimplementierung gibt.

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Furthermore, I want to thank the interviewees and many other not explicitely mentioned branch actors who were available for discussions and feedback. They gave me valuable insight and information about actual processes and mechanisms in the biomass supply chain market.

Finally, I want to acknowledge the great support by my family, with particular thanks to Gertraud, Hartmut and Rafael, who steadily encouraged me in this time.

List of related publications

This thesis is based on the following publications:

Publication I:
Ehrig, R., Behrendt, F., Co-firing of imported wood pellets - An option to efficiently save CO_2 emissions?, In: *Energy Policy* 59 (2013), p.283-300 [1]

Publication II:
Ehrig, R., Behrendt, F., Strasser, C. and Wörgetter, M., Economics and price risks in international pellet supply chains, *submitted journal paper* (2013) [2]

Publication III:
Ehrig, R., Gugler, H., Kristöfel, C., Pointner, C., Schmutzer-Roseneder, I., Feldmeier, S., Kolck, M., Rauch, P., Strasser, C., Schipfer, F., Kranzl, L., Wörgetter, M., Economic comparison of torrefaction-based and conventional pellet production-to-end-use chains, Proceedings of the *21st European Biomass Conference & Exhibition*, Copenhagen (2013) [3]

Related publications including results of or input data for this thesis:

Kranzl, L., Bienert, K., Chand, T., Ehrig, R., Majer, S., Matzenberger, J., Meyer, M., Priess, J.,Svanberg, M., Description of the relevant biomass-to-end-use chains, including torrefied biofuels. Deliverable No. D9.1 in frame of FP7 project Sector *"Production of solid sustainable energy carriers from biomass by means of torrefaction"* (2012)

Schipfer, F., Bienert, K., Ehrig, R., Kranzl, L., Majer, S., Deployment scenarios and socio-economic assessment of torrefied biomass chains. Deliverable No. D9.3 in frame of FP7 project Sector *"Production of solid sustainable energy carriers from biomass by means of torrefaction"*, (2013)

Pointner, C., Feldmeier, S., Schmutzer-Roseneder, I., Kristöfel, C., Ehrig, R., Schwabl, M., Wörgetter, M., Strasser, C., Torrefied pellets for domestic use – production, properties and utilisation, *submitted journal paper*, (2013)

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Chapter 1

Introduction

1.1 Role of biomass and wood pellets in Europe

Biomass plays a major role to fulfil the EU's energy targets for 2020 [4]. The EU's 20-20-20 targets aim for a 20 % reduction of greenhouse gas emissions from energy, a 20 % increase in efficiency and a 20 % increase of renewable energy sources in energy consumption by 2020 compared to 1990 levels. Up to now, renewables take a share of around 13 % of the EU27's energy consumption, whereas most comes from woody biomass, see Figure 1.1. Not only today, but also for the 2020 targets, biomass should contribute much more than 50 % to the EU's renewable energy consumption and 19 % (or 16 % solid biomass) to the EU's renewable electricity production [5,6], see Figure 1.2.
In 2011, around 3300 PJ primary energy of biomass was produced in the EU, whereas slightly more solid biomass (3383 PJ) was consumed [7]. That means 66 % of the EU's primary renewable energy production comes from biomass [8]. Thereby, currently 72 % of biomass is used for heating and cooling, about 15 % for transportation and 13 % for electricity use [5]. In 2010, most electricity from biomass was produced in Germany with 30,000 GWh/a, followed by Sweden, the UK, and Finland. For this electricity, forestry in terms of wood and wood waste is the main supply sector. According to EU estimations, forestry will remain the main supply sector for the EU's solid biomass supply by 2020 [5].

With tenfold increase in production, wood pellets have demonstrated the strongest growth of solid biofuels within the recent 10 years from 1.6 million tons in 2000 to 15 million tons in 2010 [9]. Thereof 61 % (9.2 million tons) biomass originated in Europe. In the same period, EU pellet consumption increased by 44 %, which

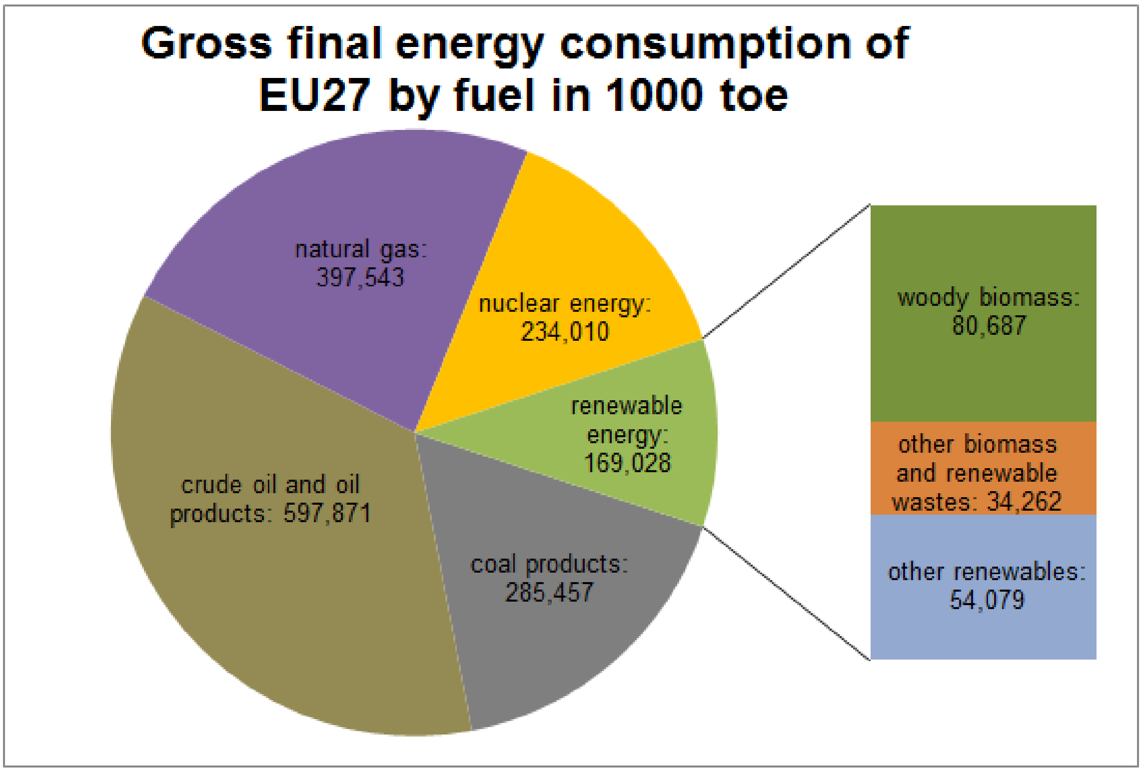

Figure 1.1: *Gross final energy consumption of the EU27 by fuel in 1000 ton of oil equivalents (toe) in 2011*
Source: [8]

was more than 11.4 million tons in 2010 (85 % of global wood pellet demand) [10]. The surplus 20 % demand on pellets in Europe are covered by imports from non-EU countries [9].
Currently, the EU27 produces only 46 % of it's energy needs [8]. The energy dependency is particularly high for fossil fuels with 62 % for hard coal, 85 % for crude oil and 67 % for natural gas, whereas only 7 % of consumed renewable energy (which is solely biomass) is imported to the EU. Within renewable energy resources, wood pellets are predestined for long distance transportation due to their high energy density, storage properties and flexible utilisation options. Within the recent years, the EU pellet production tripled from 3.5 million tons in 2006 up to 10 million tons in 2012. The bulk share of pellets imports still takes place between EU member states, which are mainly destined for the large residential pellet market.
Nevertheless, in the period 2006 to 2012, imports from outside the EU rose five times from 800,000 tons in 2006 to 4.4 million tons in 2012 [11]. So far, most of these extra-EU imports are used for industrial use. In a business-as-usual scenario, Junginger [12] estimates that the EU pellet demand will rise to between 20 and 50 million t by 2020, which means a sharp increase of almost 16 million t biomass

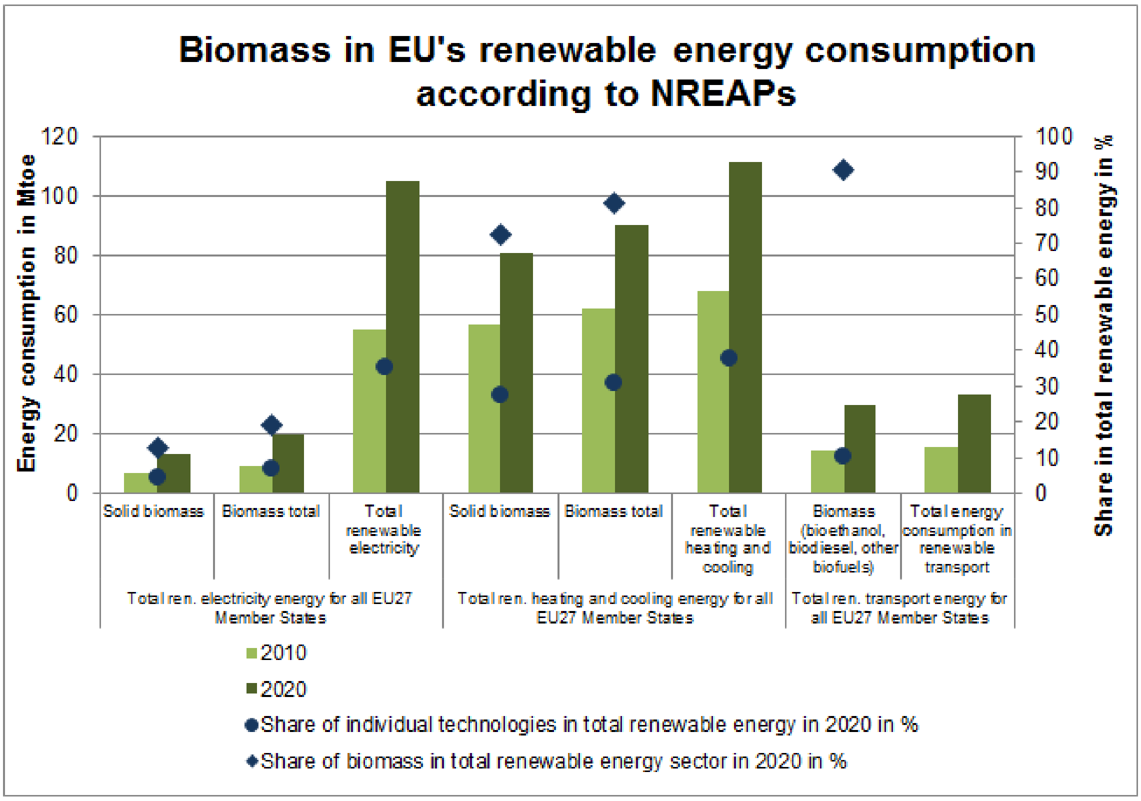

Figure 1.2: *Contribution of biomass to EU27 renewable energy consumption in 2010 and 2020 according to National Renewable Energy Action Plans (NREAPs)*
Source: [6]

imports (280 PJ) to the EU.
As shown in Figure 1.3 and Table 1.1, in 2011 most imports are from Canada and the USA with each more than 1 million t pellets in 2011, 0.5 million t from Russia and some volumes from Eastern European neighbour countries. Other pellet exporting countries far away from Europe are South Africa with 43,000 t imports to the EU, New Zealand with 30,000 t and finally Australia with 14,000 t in 2011 (Australian-European trade reached a high with 66,000 t in 2010) [11]. According to estimations by the International Energy Agency in 2011, the main sourcing countries for imported pellets to the EU by 2020 will be the USA, Canada, Russia, Brazil, but also Australia and New Zealand [10]. One of the main drivers for imports to the EU is the relatively high costs of wood pellets in Europe. In addition, large pellet producers in the EU, such as in Germany, Sweden, and Austria, have either slowed down or decreased their production. The consequence is that in 2012, intra-European trade of pellets declined by 12 % and purchases from North America increased by 44 % [13]. As shown in Table 1.1, most import volumes are destined for industrial pellet markets in Northwest Europe, especially those sourced from overseas regions. Until now, most pellet imports to the EU are destined for co-firing in coal power plants [9, 10]. The reason for that is that co-firing of industrial wood pellets represents one of the most cost-efficient and easy-to-adopt technologies to produce renewable electricity [14]. It is widely implemented throughout EU countries like the Netherlands, Belgium, UK and Scandinavia [15]. During co-firing, pellets are co-combusted in a pulverised coal power plant. Due to its robustness, co-fired pellets can be of lower quality, meaning they can have a higher ash content and higher impurity and can contain more fines. These industrial pellets are classified as B quality according to the European standards EN14961 [16]. Besides, there is an increasing trend for premium pellet imports from Eastern European countries to meet increasing demand in Central Europe. Premium pellets are usually destined for residential heating in small-scale appliances and need to fulfill high quality standards. Also North American pellet exporters make efforts in producing premium pellets for the European market [17, 18], conforming the European premium EN plus A classification according to the EN14961 standard [16].
Trade with imported (industrial) pellets typically takes place at the large European import harbours like Rotterdam, or through the trade departments of energy utilities in demand. Since a few years, industrial pellets are traded via energy exchanges like APX-ENDEX, whose price setting serves as reference for the European market [19].

Table 1.1: *Pellet imports to EU27 by main exporting countries in 1,000 tons (Eurostat category CN 44013020)*
Source: [11]

Pellet exporter	**2009**	**2010**	**2011**	**EU destination countries**	**Pellet quality**
Canada	520	983	1160	IT, DK, BE, IR, NL	industrial, increasingly premium
USA	535	763	1001	NL, UK, BE, SE, DK	industrial, increasingly premium
Russia	379	396	477	NL and re-export to EU	industrial
Ukraine	30	57	150	DK, IT, ES	premium
Belarus	75	90	101	UK, NL, BE, SE, DK, IT	industrial
Serbia	18	26	47	IT, DE, AT	premium
Bosnia Herzegowina	54	44	47	NL, IR, UK	premium
South Africa	42	25	43	SE, DK, BE, FI, NL, DE	industrial
New Zealand	0	21	30	DK, IT, DE, LT, HU, DE, BE, EE, AT	premium
Australia	9	66	14	IT, SL, AT	industrial
Argentinia	10	9	6	LT, DK, DE	industrial
Switzerland	6	15	5	NL, UK, BE	premium

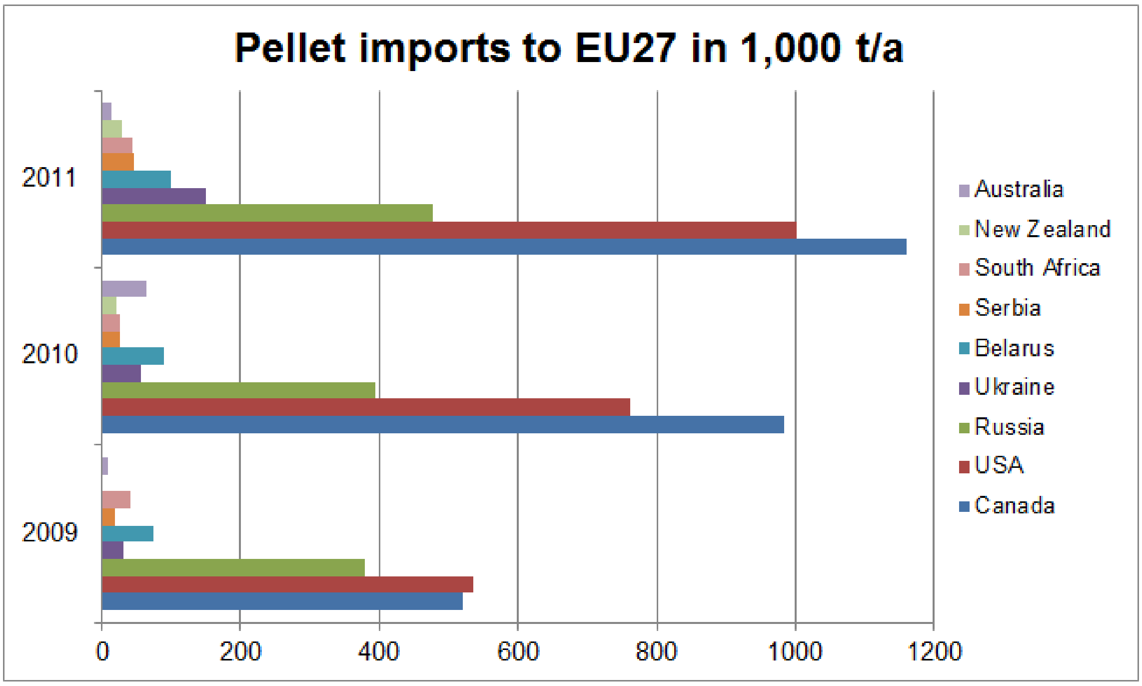

Figure 1.3: *Pellet imports to EU27 by main exporting countries*
Source: [11]

Although overseas pellet imports to the EU are profitable for energy utilities and biomass traders, these pellet imports can have notable carbon and energy footprints, resulting from the production, pretreatment, transport and logistics along the supply chain to Europe.

Related to energy security, large pellet consumers such as electric utilities rely on large volumes of biomass imports, a long-term and just-in-time supply as well as a secured price range over the life cycle of their investments [20]. While the international market for wood pellets has just aroused over the last 10 to 15 years, pellets are yet traded on stock exchanges like APX-ENDEX or FOEX and are on the way to becoming a global commodity [21]. At these exchanges, a market driven pellet price is set. Though, pellet pricing is characterised by a complex pattern of multiple market actors, interconnections and dynamics in the entire supply chain, which are widely non-transparent and still widely intangible to allow for reliable, long-term project and investment planning (see also Section 2 and [20]).
This thesis is addressing this research gap by exploring crucial influences and interconnections in the supply chain based on three exemplary case studies.

Torrefaction is one of the most promising and discussed pretreatment technologies for biomass. Experts estimate that torrefied biomass can relevantly reduce biomass trade costs and thus energy costs for the end-user. These advantages could further enhance biomass trade and make biomass imports and use even more attractive for European consumers. Related cost and environmental estimations for the production, transport and logistics of torrefied biomass have been published before [22–24], but with few background data on fuel and technology data and with extremely diverging values (see Section 2.3 for more details). Furthermore, the data are often estimated by the torrefaction plant operators themselves or by associate organisations. This research need is addressed by the present thesis, analysing advantages of torrefied pellets versus conventional ones by evaluating up-to-date processing data and research results on torrefied biomass.

1.2 Current European policies related to biomass use and trade

The demand for biofuel is driven by the European renewable energy targets for 2020 and beyond. These have been introduced to implement the targets set in the Kyoto Protocol to the United Nations Framework Convention on Climate Change, and in connected international greenhouse gas emission reduction commitments [4]. Main aims and elements of the European energy policy are, within the context of stronger economic growth:

- the need to reduce energy demand,
- to increase reliance on renewable energy sources, given the potential to produce them domestically and their sustainability,
- to diversify energy sources,
- and to enhance international cooperation [25].

The current EU policies related to biomass imports and use are characterised by the following legislations and EU documents:

- The European Renewable Energy Directive (RED - Directive 2009/28/EC) [4], giving a common framework for the use of energy from renewable sources in order to limit greenhouse gas emissions and to promote cleaner transport. It gives binding guidelines for the sustainable production and use of liquid biofuels.
- A non-binding recommendation by the European Commission on sustainability requirements for solid and gaseous biomass (COM(2010)11 final) [26].

- The National Renewable Energy Action Plans (NREAPs) and subsequent National Biomass Action Plans [6, 25], determining the Member States' national targets and measures to contribute to the EU's 20-20-20 targets. The Action Plans set the share of energy from renewable sources consumed in transport, as well as in the production of electricity and heating by 2020. With these, the Member States should also establish procedures for the reform of planning and pricing schemes and access to electricity networks, promoting energy from renewable sources [4].

Consequently, main drivers for the EU biomass demand are incentives to implement national policies and support measures for biomass use. These are e.g. policies on co-firing in the UK, Netherlands, Belgium, and the combination of market dynamics for coal plus CO_2 emission allowances. Furthermore, the continuity of biomass support are crucial for the uptake of biomass markets, particularly for small-scale biomass appliances, the price of fossil fuels and related attractiveness to switch from fossil fuels to biomass for end-users [12].

This legislative framework reinforces the increasing biomass imports from outside Europe (cp. [9] and Section 1.1). In this framework Hewitt (2011) [27] stated that a consequence of satisfying the EU's 2020 objectives – a decrease of carbon emissions – could result in an actual increase of the EU's own carbon footprint.
So when discussing the further increase of biomass use in Europe, a great controversy remains around the questions which biomass supply chains can be seen as sustainable and how to effectively and efficiently increase the share of electricity from renewables.
Starting with the massive imports of liquid biofuels from all over the world, the debate began on how environmentally justifiable imported biomass is. For liquid biofuels, obligatory emission thresholds and environmental indicators in the origin country are manifestated in the EU Renewable Energy Directive [4]. In 2010, the European Commission (EC) made recommendations for estimating and meeting sustainability criteria for solid biofuels [26]. These are already obeyed by many market actors and national authorities. As a preliminary approach, the EU Directorate Energy has recognised 14 voluntary evaluation schemes for sustainability criteria of solid biomass [28], which are in line with the EU legislations mentioned above. As the public debate on sustainable solid biomass is persistent, the EC is working on a directive introducing EU harmonised, binding sustainability criteria for solid biomass [29, 30].

In turn, the Member States are responsible to set the framework and incentives to promote the use of low-emission energy pathways. Indeed, since several years, a couple of Member States - especially those with low domestic biomass potentials - like the Netherlands, Belgium, the UK or also Scandinavian countries, successfully applies this model by having effective co-firing subsidies [10, 14]. Up to now, no legally binding sustainability requirement exists for supporting the use of solid biomass in conversion plants, except from Belgium and the UK [26, 31]. In Belgium, the upstream energy or CO_2 balance of supplied biomass is assessed and included in the calculation of creditable co-firing subsidies [32, 33]. The UK has introduced binding sustainability criteria on the biomass upstream emissions in early 2013, which are obligatory to receive support for co-firing [34, 35]. These subsidy models could be exemplary for other countries considering the support of biomass co-firing. For inland European countries like Germany, increased use of imported biomass, amongst others for co-firing in existing coal plants, is already recognised as an interesting and cost-effective option to reduce CO_2 emissions [36, 37].
On the one hand these environmental requirements gain more and more importance for biomass imports to Europe. On the other hand, national subsidies and obligations are currently the main incentives for using imported biomass. Connecting both aspects, this thesis explores how they contribute to sustainable and economic biomass use in Europe.

1.3 Outline of the thesis

The thesis is structured as follows: Chapter 2 outlines the scientific disciplines and specific topics the thesis is dealing with. After that, Chapter 3 determines the research problem, general and specific objectives of the thesis. In Chapter 4, data used and the methodology for the investigations are explained. Respective results are presented and discussed in Chapter 5. Finally, the findings and answers on the research questions in Chapter 3 are concluded in Chapter 6. Additional data extracts and information are given in the Appendix in Chapter 7.

Chapter 2

State of Research and Technology

2.1 Overall scientific scope of the research topic

This thesis deals with a topic, which encompasses various scientific issues and management disciplines ranging from the "triangle" natural resource sciences and biomass technology and entrepreneurial management to energy and environmental policies, see Figure 2.1.

In the following, most relevant methods, theories and existing models related to and applied in this thesis are outlined and discussed.

2.2 Biomass supply chain models

Since the last ten to fifteen years, several studies have been dealing with modelling and optimisation of particular biomass supply chains using geograhical information system (GIS) models, linear and mixed integer modelling (see e.g. [38]. These all have a specific focus (e.g. optimisation of logistics, costs or allocation of resources), and respond to a given framework and several assumptions, e.g. a local logistics network, specific transportation means, or the allocation of resources for specific end-use demand. Though, these models give limited representation of the actual market situation. More focussed on actual trade flows, a comprehensive model on biomass supply chains was accomplished by Hamelinck et al. (2005) [39] comparing different international bioenergy chains to Europe with focus on logistics. An evaluation of supply costs from Argentina to the Netherlands was done by Uasuf [40]. Costs for the pellet supply from British Columbia to the EU has been assessed before by Sikkema et al. [41].

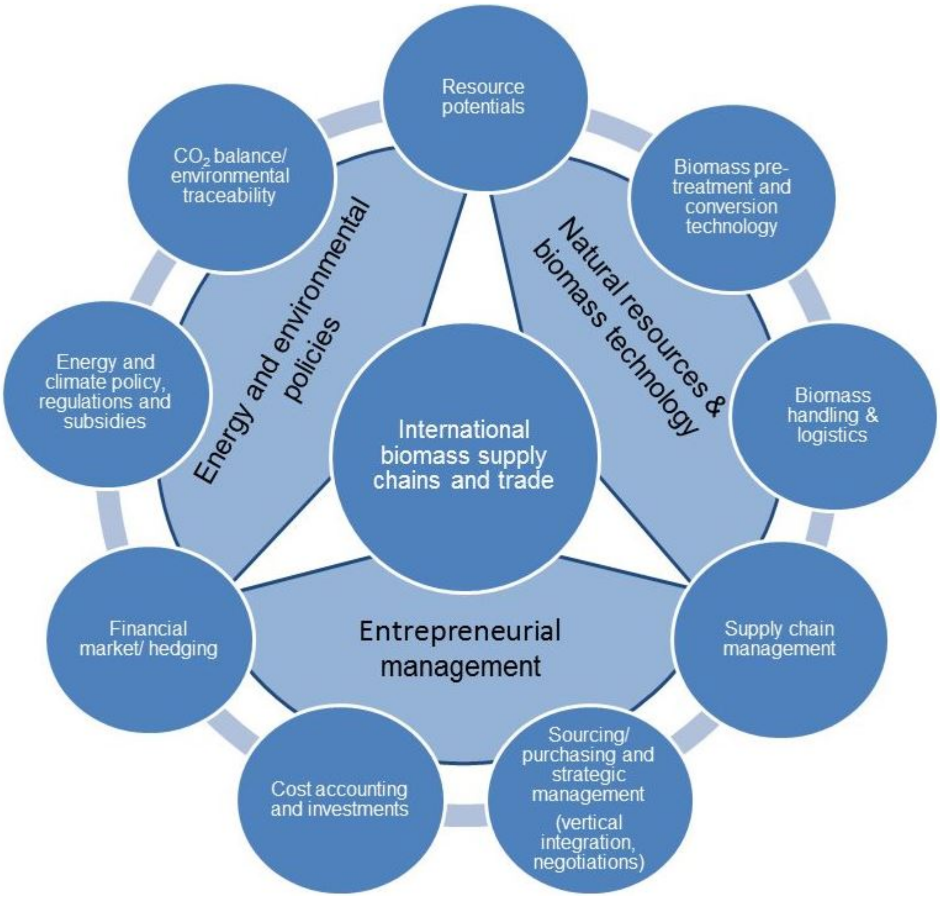

Figure 2.1: *Scope of disciplines ("triangle" natural resources and biomass technology, entrepreneurial management, energy and environmental policies) related to biomass supply chains and trade*

In several market reports, the given framework for international biomass trade and specific aspects like shipping [42] or equity and investments [43] are discussed. Moreover, in a scenario-based study Heinimö (2011) determined critical factors for the future development of the global (solid) biomass market [44], which are:

- Price competitiveness of bioenergy,
- Energy policy (subsidies, research and development),
- Imbalance between supply and demand of bioenergy (sources),
- International agreements,
- Sustainability issues to the utilisation of biomass.

Based on these existing studies, this thesis presents new investigations, which combine an analysis of real case biomass supply with a detailed assessment of individual variables underlying actual market, regulatory and technology actions.

2.3 Biomass pretreatment and supply chain operations

Biomass is used in a broad range of pretreatment, logistics and conversion technologies to convert the chemical energy stored in biomass into fuels, heat or electricity (see Figure 2.2). In this thesis, the research focus for the different pathways begins with different solid biomass resources, and continues with the collection, preparation, logistics and transportation up to combustion and the conversion into the final product electricity.
Comprehensive assessments of biomass supply chain operations from harvesting, preparation including grinding of the material, logistics and transportations as well as their technology processes and respective energy demand and costs have been conducted by researchers like Suurs (2002) [45], Kaltschmitt et al. (2009) [46] or Obernberger and Thek (2010) [47]. Specific logistical requirements for planning biomass supply chains are summarised by Svanberg and Halldorsson (2013) [48].

Pelletisation is a mature technology for densification of biomass and resulting favourable conditions for storage, handling and logistics. Since the last 15 years, pellet plants are operated worldwide, while many technology providers and manufacturers are based in Europe. Currently, most pellet plants are operated in Europe and North

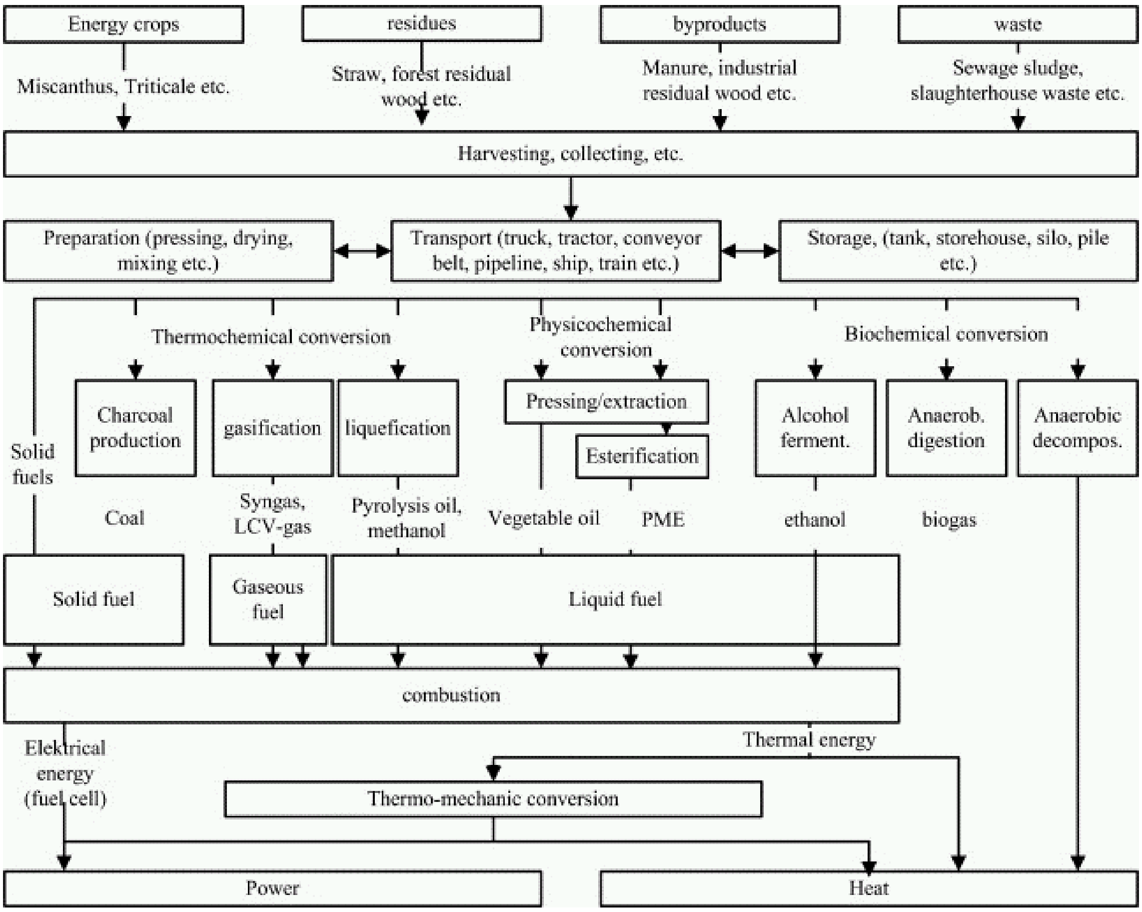

Figure 2.2: Overview of energy conversion pathways from biomass sources
Source: [49]

America [10, 50]. The pellet production process is a mature technology, described thoroughly by e.g. Obernberger and Thek (2010) [47]. It usually consists of a dryer for reducing moisture content of the raw material, one or more grinding units to make the raw material suitable for further processing, a pellet mill to densify the material to pellet dimensions and a cooler to decrease temperature of the pellets after pressing. Additional equipment are storage systems for raw material and pellets, and the peripheral equipment for conveyors and the construction of the plant. Usually the raw material is wood residues (sawdust, shavings), which often is a low-cost by-product of the nearby wood industry. Synergies with the co-located wood industry are also common for supplying the pellet plant with heat or low-value biomass residues (bark, wood chips, sawdust) for drying [10, 47, 51]. In case of lacking wood residues or low market prices for wood assortments of higher value, also wood logs are used for pellet production. As an example, typical pellet production processes for both sawdust, wood chips and for wood logs by plant manufacturer Andritz are shown in Figures 2.3 and 2.4 [52].

The torrefaction technology process is a mild pyrolysis (thermochemical pretreatment) of biomass in absence of oxygen at temperatures between 200 and 320 ℃ over a time period of 10 to 30 minutes [53]. As a result, the biomass is expected to obtain a better fuel quality with higher energy density, hydrophobic characteristics, easy handling and better grindability. Objective of current research projects is to upgrade biomass via torrefaction into a fuel with properties similar to coal. A general framework for the fuel characteristic ranges is currently given with the draft ISO 17225 standard for graded torrefied pellets [54].
With the promised advanced fuel characteristics, torrefied biomass should be suitable for existing combustion and gasification applications such as for coal co-firing plants. So, in many research papers, torrefied biofuels are expected to relevantly reduce biomass trade costs and thus energy costs for the end-user [22–24, 48, 55]. Though, there are no commercial torrefaction plants, but only pilot plants in operation yet. That makes it difficult to judge about the actual production, operational costs and energy balances in the processes and allows for approximations only. Several cost estimations for the production, transport and logistics of torrefied biomass have been published before [22–24, 55], but with few background data on fuel and technology data and with extremely diverging values. A review on the torrefaction process by 2011 is presented by Stelt et al. (2011) and Ciolkosz and Wallace (2011) [56, 57]. The properties of torrefied biomass for co-firing in coal plants has been reviewed by Agar and Wihersaari (2012) [58]. They find, that trade-offs in the

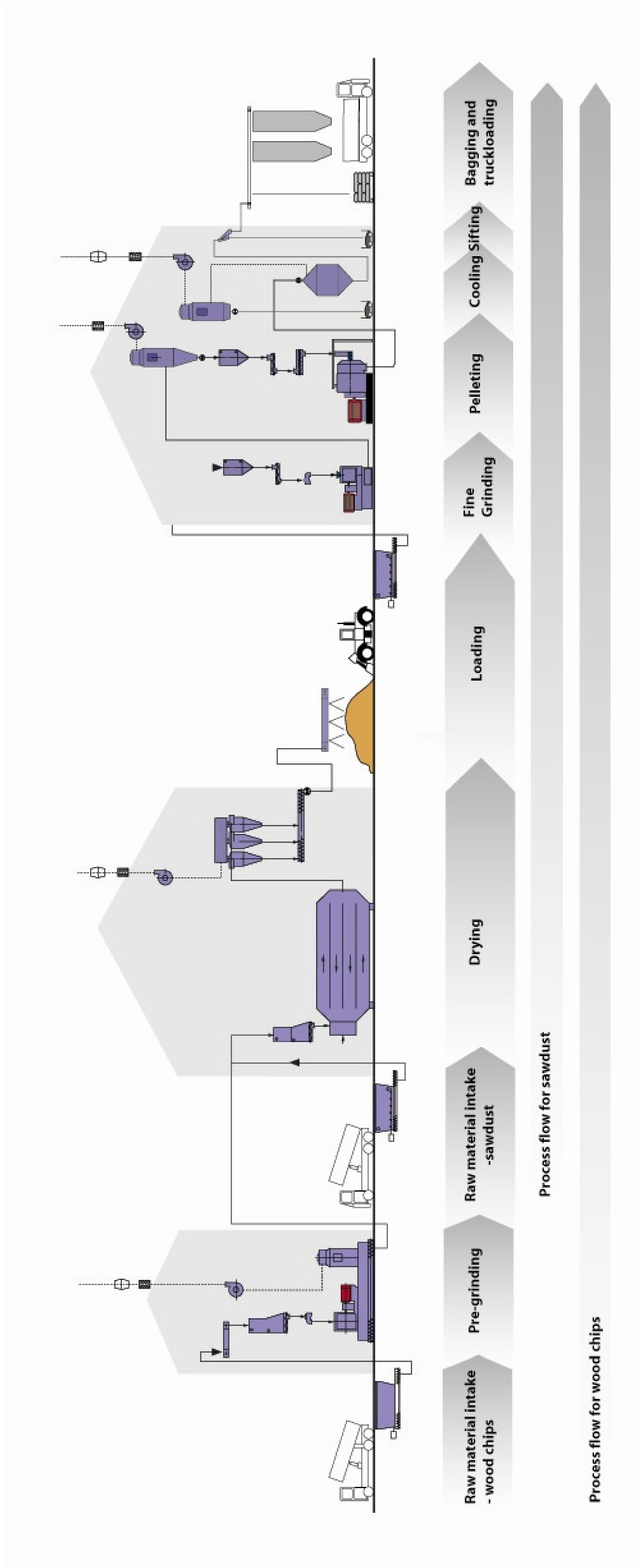

Figure 2.3: *Process flow for conversion of wood chips and sawdust into wood pellets*

Source: [52]

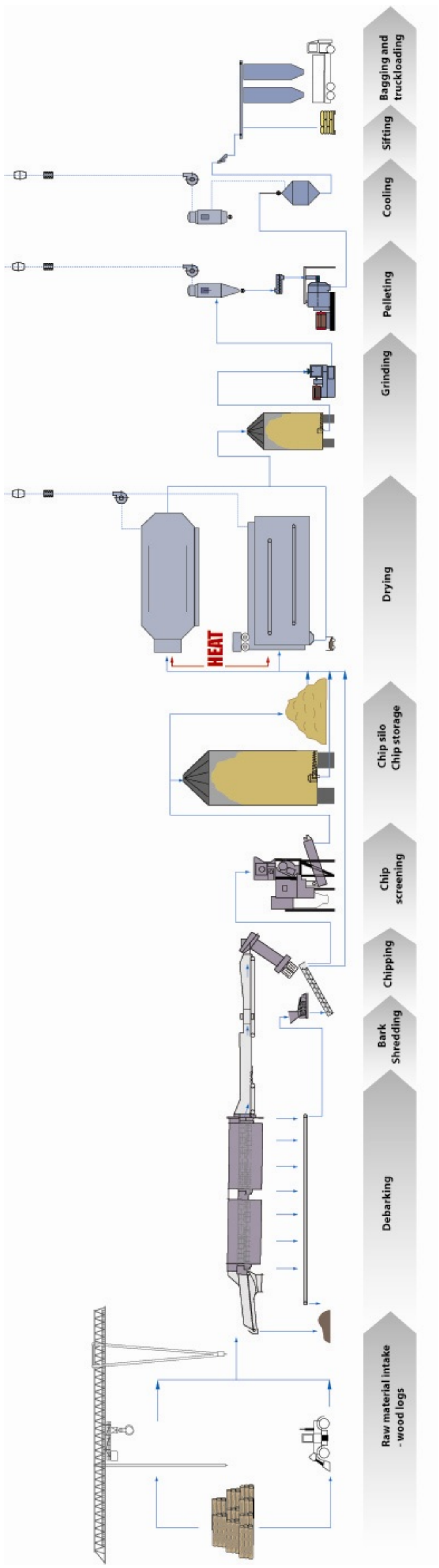

Figure 2.4: *Process flow for conversion of wood logs into wood pellets*
Source: [52]

energy balance occur when achieving favourable properties of the torrefied fuel.
Evidence is given by several publications that the quality and energy density of torrefied biomass increases with higher temperatures and longer residence time in the torrefaction reactor [59–63]. The possibility to densify torrefied biomass was proven in studies by Wang et al. (2013) [64], Stelte et al. (2012) [65] or Pointner et al. (2013) [66]. Favourable end-use properties of torrefied biomass when combusted in a pulverised coal boiler has been proved by Li et al. (2012) [67]. Pirraglia et al. (2013) recently provided techno-economic results when modelling the production of torrefied pellets in the US [60]. A first analysis of supply chain costs for torrefied pellets is accomplished by Chieuh et al. (2012) [68]. It includes a cost and carbon emission analysis of a torrefaction supply chain with focus on variating operations in logistics and transportation. Svanberg et al. (2013) [69] conducted an advanced study. Here, a Swedish resource-to-end-use chain is analysed with variation of different processing and operational parameters. So far, there is a lack of realistic data on the current fuel and technology status. Especially, evidence is not provided on the overall energy balance of the torrefaction process. Furthermore, the data are often estimated by the torrefaction plant operators themselves, as in the studies mentioned above. Also, few fuel specific, economic and environmental assessments of torrefaction carriers consider the reference carriers with conventional biomass from the same origin material.
Thus, the present study addresses the research gap when proving the realistic eligibility of torrefied pellets for different production and supply chain options as well as compiling relative advantages of torrefied pellets compared to conventional ones. Given the current technology and market development stage, this thesis can provide a basis for practical proof on the techno-economic feasibility of torrefaction.

2.4 Environmental and economic assessments along biomass supply chains

A comprehensive analysis of different global biomass supply chains in economic and environmental terms has been conducted by Hamelinck et al. (2005) [39]. This is partly based on detailed investigations of the logistics and transportation processes for different biomass assortments by Suurs (2002) [45]. One of their results is that long-distance supply is necessary to meet the demand of importing regions like Western Europe. This is connected with extra costs, energy consumption and material loss. They conclude that densification of biomass, ship transportation and economies of scale are crucial for international trade as this reduces much the transportation efforts in costs and energy expenses. More up-to-date, in his PhD thesis, Uasuf (2010) [40] handled an energy, CO_2 and cost focussed assessment of Argentinian pellets exported to Europe. He concluded that the trade is profitable from the supply cost perspective, and trade economics are most dependent on raw material prices and competition of wood resources in the origin country. He found that most emissions are associated with the production and transportation of wood pellets from Argentinia to Europe, but generally result in a positive energy balance. With focus on a particular trade route and environmental impacts, Magelli et al. (2009) [70] came to similar results applying a life cycle analysis for pellets produced in Canada and shipped to Europe. Sikkema et al. (2010) [41] have presented the environmental and economic balance for this Canadian chain to Europe as well as two other intra-European pellet supply chains for premium pellets. They emphasized that drying with biomass has crucial greenhouse gas saving potentials for Europe. So they came to a total of 12.6 million t CO_2, which have been saved by 8.2 million t pellet consumption in the EU 27. Finally, they concluded that using low quality logs as pellet raw material could exceed the raw material base, whereas policy makers have to decide whether to focus on most GHG emissions avoided (favoring co-firing) or to focus on lowest costs for GHG emissions (favoring heating oil replacement). Further environmental and economic assessments of individual intra-continental European biomass supply chains have been investigated by van Dam et al. (2009) and Maderthaner (2012) [71, 72]. A general evaluation and comparison of the UK's and German subsidy systems have been given by Mitchell et al. (2006) [73]. As a result, the requirements for an economic operation of international biomass supply chains can be summarised as follows:

- Biomass supply is strongly driven by the resource production costs (availability, productivity, short delivery distances).
- Efficient infrastructure for transport & logistics of biomass is key for long-distance biomass trade.
- Overseas shipping of large volumes of biomass is profitable, given high, cost-efficient supply in the exporting and high demand and subsidies in the importing countries.
- Continuous optimisation of economies of scale and of the pellet plant operation is necessary to compete on the global market.

In terms of environmental impacts of biomass supply chains, the following can be concluded:

- Depending on the supply chain, long-distance trade with biomass can be as sustainable (concerning energy demand and emissions) as regional biomass supply.
- Most crucial environmental impacts result from the pretreatment of biomass and transportation.
- Environmental impacts can be reduced when chosing renewables in place of fossil fuels and achieving high efficiencies in conversion systems.
- Compared to fossil fuels, much favourable environmental balances can be reached by imported biomass.

Nevertheless, few studies consider alternative raw material and the overall framework conditions for profitable, sustainable biomass supply chains. Also, biomass supply chains from Australia and Russia to Europe have not been investigated before in environmental and economic terms.
Supplementary to these existing studies, the present thesis investigates how specific regulatory measures (co-firing subsidies), market actions (price fluctuations) and the introduction of torrefaction technology are influenced by specific biomass supply chain designs.

2.5 Price risks and security in biomass supply chains

Price risks in energy projects can be described as negative (or positive) impact on the financial value of an investment [74]. Risks are related to uncertain future events and thus play a dominant role in investment decisions and implementation of investment projects. Cleijne and Ruijgrook (2004) classify them into three categories: I) regulatory risks, II) market and operational risks, and III) technological risks. Security of energy supply and related risk can be analysed by applying different methods like scenario analyses, sensitivities, multi-criteria analyses, calculating the correlation amongst different factors, the price elasticities, the real option value or value at risk (see e.g. Kruyt et al. (2009) [75]). For measuring risks, crucial requirements are the applicability of the method for the investigated subject as well as available data and information on the probability and distribution of uncertainty. For instance, the increasingly popular Real Options Approach [76, 77] is an extension of the traditional net present value calculation. It allows investors to account for the value inherent in the flexibility to delay an irreversible investment into the future [78]. But few studies actually apply this complex approach in the field of biomass (amongst the few Fuss et al. (2009) [79]), as it requires extensive data or assumptions on the uncertainty of investigated aspects. Also, there are few attempts to combine individual uncertainties for a comprehensive, but practically relevant risk accounting. Among these are Adkins and Paxson (2011) [80] combining forest growth and timber prices, or Wieland and Wallenberg (2012) analysing risk management strategies in supply chains [81]. Other studies as by Cavallaro (2005) apply a multi-criteria analysis to assess energy options via a ranking of investor's preferences for different aspects [82] or for assessing the sustainability of bioenergy systems [83]. Besides, Olsson (2009) found that although biomass price differences in different European markets have decreased with more trade, there is still no completely integrated, European biomass market [84]. Moreover, Dahlberg (2010) has interviewed European biomass importers regarding the chances and challenges in international trade [85]. He found that strongly increased imports from outside the EU may have an effect on European biomass prices. Nevertheless, he concluded that in the same time there are barriers and uncertainties, which limit the expanding trade from countries like Russia or from overseas.

There have been selected sensitivity analyses [41] or discussions of market impacts and uncertainties in the pellet market [86, 87], but no concrete evaluation of several price risks along real biomass supply chains. Few studies and reports are available on the management practice for fossil supply chains, related price formation and security aspects. Joskow (1985) has provided fundamental knowledge on vertical integration and pricing provisions for coal supply agreements, which are still widely valid [88]. Ritschel and Schiffer (2007) have thoroughly analysed price setting mechanisms in the world coal market, exemplary coal supply costs, their dependence on regional trade developments, and individual reasons for regional and global trends in the coal market development [89].

Nevertheless, hardly any approach comprises a biomass related supply chain process and is suitable for available data on biomass trade. Also, biomass supply patterns do not follow a standard, but are dependent on the biomass source, the countries involved and the particular regulatory framework. Even more important, there is hardly any internationally relevant data series having a high resolution, but covering partly annual or partly quarter data. Specific biomass data are available only for the last few years, which makes an application of complex theories like real option calculation insignificant.

The present thesis responds to the given framework in biomass supply chain markets and applies an empirical-statistical analysis to assess recent regulatory risks (subsidies) as well as market and operational risks (price fluctuations and introduction of torrefaction technology).

Considering different real case biomass supply chains and actual market dynamics, the following analyses of environmental and economic aspects represent a novel approach. Particularly, the impact of exchange rate fluctuations on pellet trade is not yet explored in a precise, empirical way and thus is handled in this thesis.

Chapter 3

Aims and objectives

3.1 Problem outline and need for research along real biomass supply chains

This thesis addresses the research problem, how the EU's energy targets can be economically and sustainably achieved by international pellet supply chains on the real market. Particularly, the investigations should clarify in which way dedicated subsidies for using imported pellets make sense, which risks can influence international supply chains and how to manage these, and if torrefaction-based supply chains can be a reasonable alternative to efficiently import biomass to the EU.

The design and arrangement of the supply chain from biomass production, pretreatment, logistics and transportation to end-use is highly complex. Both aspects depend on the particular market and countries involved and include a number of different market actors with different focus and interests. The spectrum of stakeholders ranges from forest or land owners, plant operators for pretreatment technology, logistics and transportation operators, and trading companies up to small- to large-scale end-users. This makes biomass trade, but also research on it complicated. Likewise, the strategy of the International Energy Agency sees strong demand to deal with sustainable biomass supply chains, their identification and implementation with the aim of higher mobilisation of biomass. Particular actions are required to make the market and its dynamics more transparently, as reported in documents like the World Bio-trade Equity Fund Study [43] and in an inter-task strategic working document [90].
A thorough, detailed analysis of technical, economic and environmental supply chain parameters and subsequent policy and price risk investigation makes it inevitable to

set-up a targeted, own calculation and dedicated analyses along case study supply chains. As additional aspect, the option to torrefy biomass and to trade it more efficiently has raised great awareness within the last years. These issues are addressed in the present thesis.

3.2 General and specific objectives

Main aim of this thesis is to investigate the economic influences on pellet supply chains considering different environmental policies and subsidies, price risks and the effect of torrefaction pretreatment.
In particular, this thesis deals with the comprehensive assessment of three real case studies on pellet trade from Australia, Canada, and Russia to Europe (see Figure 3.1). With these as starting point, on the one hand their environmental balance and the economic impact on related subsidies are investigated. On the other hand, the supply chain economics are directly explored to gather basic supply costs along the case studies and to determine main price drivers along the supply chains. Based on these, underlying price risks for the case study supply chains and general de-risk strategies are investigated. Furthermore, an economic and environmental assessment is carried out for torrefaction-based supply chains using latest processing and fuel data. Using the design of the three case studies, the relative performance of torrefaction-based versus conventional pellet supply chains is estimated.

To tackle these topics, a series of key questions is raised and answered.

Concerning the impact of co-firing imported wood pellets in Europe the following questions are examined:

- How is the most sustainable biomass supply chain for import characterised, regarding the three real case studies (Australia, Canada, Russia)?
- Is co-firing of imported wood pellets efficient in terms of CO_2 equivalent (CO_{2eq}) savings?
- How do existing co-firing support schemes as in Belgium and the UK respond to the environmental footprint of concrete biomass imports? Which are the impacts on supply chain decisions?
- Under which conditions is co-firing of imported biomass cost-effective for inland countries like Germany and Austria?

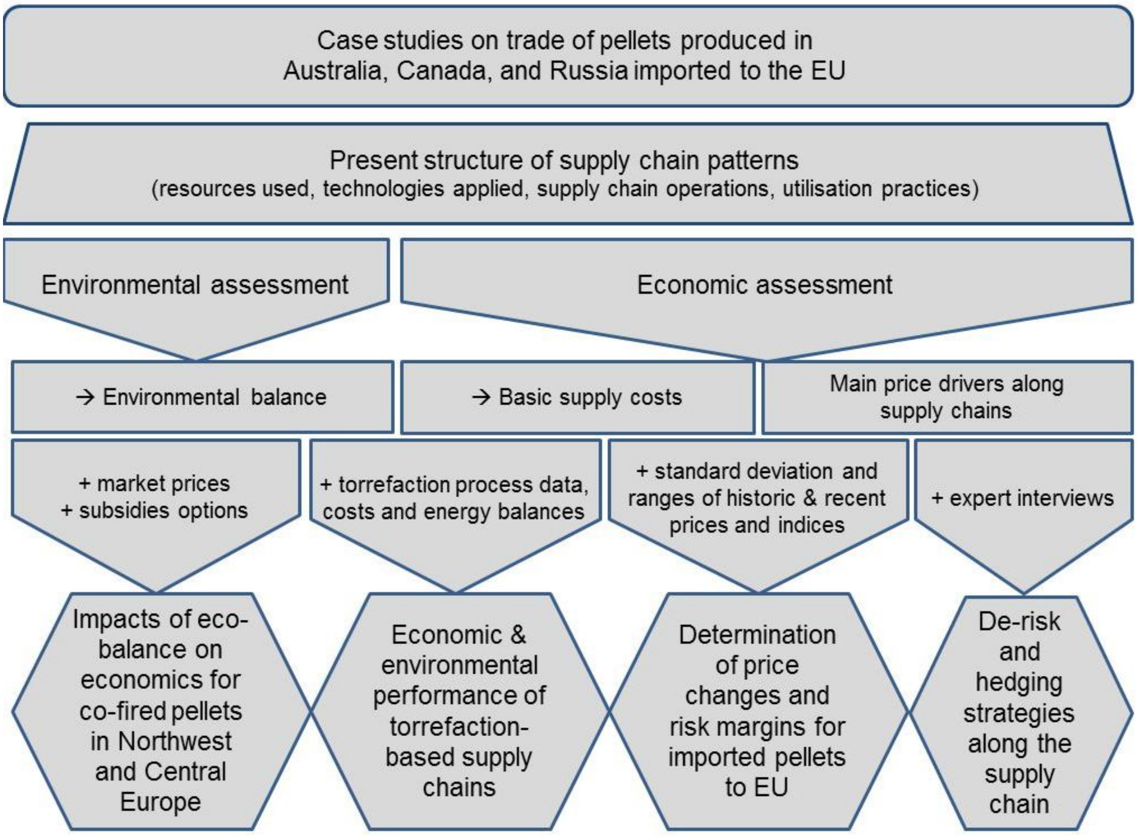

Figure 3.1: *Research outline of this thesis*

Concerning price risks, the thesis deals with the following central issues based on the three case studies on pellet trade from Canada, Australia and Russia to the EU:

- Which price fluctuations have the biggest influence on pellet supply costs and thus on the import price? How do they affect electricity production costs during co-firing?
- What is the magnitude of pellet price volatility over typical supply contract periods?
- In which way do pellet importers face and handle price variations and de-risk the supply chain within contractual relationships?

Considering the future option to produce and use torrefied pellets along the three supply case studies, this thesis deals with the following questions:

- What is the economic and environmental advantage of supply chains with torrefied pellets compared to conventional ones?
- Which are critical cost and environmental aspects making torrefied pellets competitive to conventional ones?
- Which general technical and market issues have to answered and solved to make torrefied biomass a success?

These questions, analysed and answered on the basis of three case studies, allow for further and general conclusions on market drivers in pellet supply chains. Underlying methods and data are defined in Chapter 4. The results of the analyses are presented and discussed in Chapter 5. Final conclusions and answers can be found in Chapter 6.

Chapter 4

Methods and Data

4.1 Supply chain model for case study compilation

Biomass supply chains and related market effects comprise a complex pattern of various market mechanisms and numerous actors (cp. Section 2). These interdependencies are highly individual for different markets and operations in the supply chain. Furthermore, the worldwide biomass market is quite young and still underlies quick changes, many trials and errors and is highly characterised by the regions involved. Trying to construct a too generic model on supply chain processes would not allow much conclusions on the real market. This is why in this thesis, a case study approach is applied, which gives a realistic picture of occurences in the international biomass market.

Three different case studies for pellet imports to Europe are investigated for associated supply costs from resource origin to end-user in the EU, following the pattern in Figure 4.1. Studied phases include the raw material production and delivery, pellet production, transport to Europe, as well as delivery and conversion in a coal based co-firing power plant, located 75 km from EU import harbour (for the subsidy analysis more locations are considered, see 4.4.2). Because of increasing biomass resources and recent dominance over pellet imports into the European market, British Columbia (Canada), Western Australia, and Northwest Russia are chosen as the case studies [9,12,91]. They further offer a good comparison as they differ significantly in biomass source, distance and region. Existing studies in the field of biomass supply chains serve as a profound reference and for comparison of assessed supply chains in this study. The present study reassesses the Canadian case due to its prominent role in pellet exports to the EU and also for evaluating new issues, such as the effect of co-firing policies, price risks and torrefaction-based supply chains. In terms of the environmental balance, this study includes the evaluation of the fossil fuel input, which has not been assessed before along biomass supply chains, and further considers different sourcing options. Comparable evaluations of the Australian and Northwest Russian pellet chains do not exist in literature and therefore are new in this study. For all calculations spreadsheet models are developed and used. Even if every real case supply chain has unique properties and settings, the spreadsheet model allows to flexibly handle process and input variations in the supply chain pattern. With that, it allows to set-up new scenarios and analyse variations of the base case situation.

For analysing the co-firing policy options, two different kinds of feedstock for each export country are considered, i.e. the 'standard' one consisting of sawmill or wood residues, and an 'alternative' one consisting of forest residues, plantation logs or roundwood. The latter one is used occasionally in the export countries in case of lack of standard feedstock or high competition with other sectors. The standard feedstock is included in all environmental and cost assessments. That means, for the standard environmental cases the same supply chain pattern as for the basic supply costs are followed. The alternative one is considered in all environmental and policy analyses. In economic terms, different biomass options and related prices are considered in the analysis of price variations, see Section 4.5.3.

As result, a detailed description of the three pellet supply cases from resource origin to conversion plant in Europe is presented in Section 5.1.

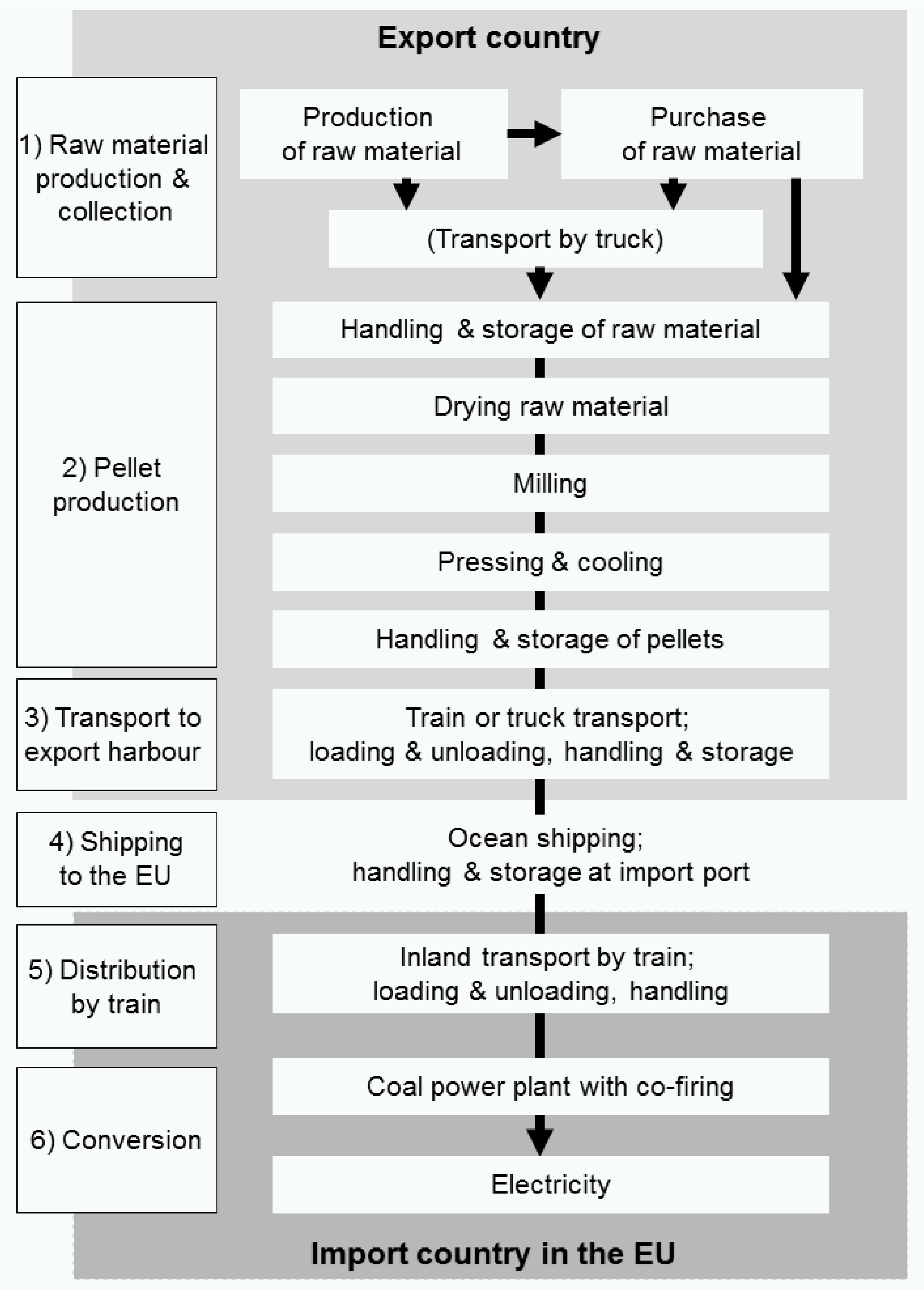

Figure 4.1: Outline of supply chain model

4.2 Processing parameters for supply chain operations

4.2.1 Pellet supply chain processes and characteristics

The pellet production phase and logistic operations are based on typical capacities and on technology in use in the respective countries. The raw material considered is country specific as well as defined in Sections 4.3.2 and 4.4.1 and analysed in the resulting Section 5.1. The standard raw material consists of typical biomass residues from wood industry, forest management or plantations. Alternative raw material is assessed for the policy and price risk assessments. For the standard resources in the environmental and cost assessment, two fuel options are distinguished for drying the raw material: biomass (Bio) and natural gas (NG). The most common fuel during pellet production is bark or other wood residues [10]. Nevertheless, the option natural gas is considered in order to demonstrate the impact of increased fossil fuel use. The pellet production phase is based on typical plant size capacity, on technology in use and on fuel specific energy consumptions which were based on the data by Obernberger and Thek (2010) [47]. Respective technology and cost parameters used for the pellet production phase are listed in Appendix 7.1. Country specific costs for employment of staff, electricity, fuel and biomass are summarised in Appendix 7.2. From the production site it is assumed that the pellets are transferred by train or truck to the export harbour of the respective country. From there, the pellets are shipped by bulk carrier (ocean) vessels to Western Europe. The inland delivery to the conversion plants is assumed to be by train. For Belgium and the UK similar logistics and prices are considered. Finally, the imported pellets are assumed to be co-fired in a 800 MW_{el} coal power plant located in Belgium, UK, Germany, or Austria (see Section 4.4 for economic details). Due to high ash contents caused by bark or other impurities, the considered pellets fulfil the B category according to the current standard for wood pellets [16]. Thus, the pellets are suitable for industrial use only.

All information and calculations in this paper are based on the net calorific value of fuels, which is 4.9 MWh/t for pellets with 6 % moisture content (mc) delivered at the conversion plant. This conforms the elementary analysis calculations based on the B category of the pellet standard [16]. For hard coal a net calorific value of 7.8 MWh/t with $\leq$ 2 % mc is used. These specifications reflect average values for the considered fuels.

4.2.2 Processes and characteristics of torrefaction-based supply chains

The analysis of torrefaction-based supply chains is based on the same production capacities and supply chain settings (raw materials and their origin, transport distances, end-use location and product) as analysed for the conventional pellet cases from Australia, Canada or Northwest Russia to Northwest Europe. This allows for a step-wise comparison of production and supply costs as well as environmental balance of torrefaction-based pellet chains with conventional ones.

The regarded torrefaction unit of 40,000 t/a or 120,000 t/a production capacity is based on a rotating drum reactor, belt dryer, heat generator for torrefaction and drying, conveyor system, storage, cooling and grinding as described in frame of the TorrChance project [92]. A schematic outline is given in Figure 4.2. This corresponds to technologies applied e.g. at the Andritz pilot plant in Frohnleiten (Austria) [93].

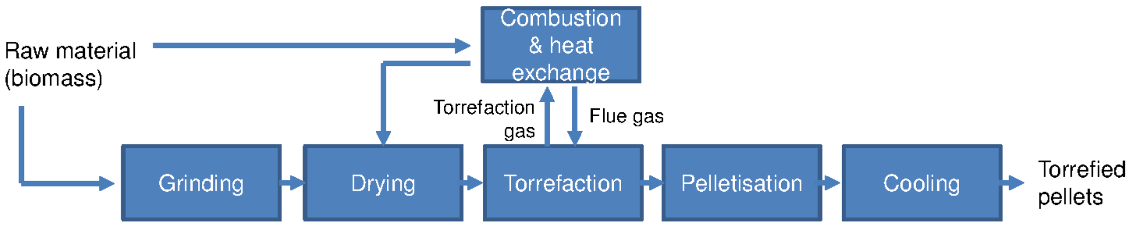

Figure 4.2: *Outline of the torrefaction and pelletisation concept*
Source: own illustration based on [22, 61, 93]

In the defined technology concept, the torrefaction reactor is fed by flue gas from a biomass furnace. Biomass is torrefied for a residence time between 10 to 30 minutes under homogenuous conditions and under temperatures between 250 and 350 ℃. Natural gas as process fuel is not considered in the torrefaction cases. In a 40,000 t/a torrefaction plant, the torrefaction gas provides around 2.7 MW thermal capacity and can be partly used for drying the raw material to a moisture content $< 5\,\%$ mc [92]. The rate of exothermic operation is depending on the moisture content of raw material and the torrefaction temperature and respective torrefaction degree, whereas for the latter factor just individual definitions exist [94]. The standard overall thermal efficiency of the plant is assumed to be 84 %. Because of decomposition of hemicelluloses during torrefaction, it is assumed that the process requires 1.25 t_{dry} raw material input for 1.0 t_{dry} output of torrefied pellets. This corresponds to data in literature as reviewed by van der Stelt et al. (2011) [56]. As this input-output ratio is quite optimistic, the alternative ratios 1.5:1 and 2:1 are considered as well in the economic and environmental analyses. While this raw material demand is considered as additional fuel input, there is no change of any other process or output parameters. These higher input volumes demonstrate the requirement of more biomass raw material required for torrefying the biomass, as additional process fuel (biomass for combustion and heat generation) or more material loss during the process. A full energy balance with variating parameters cannot be undertaken, as data are not available or insufficient yet. The kind of raw material considered corresponds to the same kinds as defined for the conventional pellet chains (biomass residues). Biomass of lower quality is not considered for achieving the same output quality, as existing investigations have shown that torrefaction cannot turn low quality biomass into high quality fuel [66].

The characteristics of the torrefied biomass product depend very much on the technology procedure (residence time, torrefaction temperature, input material). So far, there are no consistent data available on how these parameters influence each other. Thus, the process and corresponding data as defined in TorrChance project [92] are considered to be constant for all considered scenarios. Assumed production costs, as well as calculated energy and raw material inputs are based on the assumed configuration and mass balances of the torrefaction plant design [92] in frame of TorrChance project, which are based on the engineering and set-up of a pyrolysis plant in Dürnrohr (Austria) with similar technology and literature data. The basic configuration, investment and operational costs are confirmed as realistic by a torrefaction pilot plant operator.

For the pelletisation process, standard equipment is considered as for the cases with conventional pellets [47]. The technical feasibility of grinding and pelletising at laboratory scale shown by Pointner et al. (2013) [66] and the related energy input during grinding and densification are compared with those for conventional wood biomass. Resulting findings on specific operational costs and energy demand are considered as input data for the combined torrefaction and pelletisation concept.

The torrefied pellets end-product is defined by current fuel specifications of torrefied biofuels according to European standards for solid biofuels (e.g. EN 14775 - Solid biofuels - Determination of ash content, EN 14918 - Solid Biofuels - Determination of calorific value, EN 15103 – Solid biofuels – Determination of bulk density), which were accomplished by TorrChance project [66] and other studies [95]. Accordingly, torrefied biomass and pellets originating from the considered woody raw material are assumed to have a 10 % higher net calorific value compared to the conventional wood pellets, both on dry basis. This increase corresponds to the maximum or average value results on fuel analyses by Bridgeman et al. [59], Agar et al. [58], Wang et al. [64] Wojcik and Englisch [95]. According to this assumption, torrefied pellets have a net calorific value of 5.52 MWh/t considering a 4 % moisture content and a bulk density of 705 kg/m^3. More energy increase is partly demonstrated at higher torrefaction temperatures and longer residence time in the torrefaction reactor, so by Chen et al. (2011) [63]. These are likely to have significant negative influence on the economies and the process design [58]. Due to still lacking data evidence on effects concerning energy balance and process parameters, this variation of fuel output properties cannot be covered by the present analysis. In terms of logistics and transport, the basic assumption in available studies [22–24, 48, 96] is that torrefied biomass is hydrophobic and stable and thus suitable for outdoor storage, which relevantly reduces transport and logistics costs compared to conventional wood pellets. Nevertheless, so far no evidence is given on that. Within TorrChance project, the durability related fuel properties have been analysed in frame of outdoor storage tests with 4 t torrefied pellets in Austria [97]. According to these tests and experiences made by individual biomass traders and actors (see interview guidelines in Appendix B.1), up-to-date conclusions are made concerning the suitability of logistics and transportation means for torrefied fuels on the market.

For the end-use of torrefied pellets – as for the conventional pellet cases – a 10 % co-firing in a coal power plant is considered. That allows a direct comparison of conventional with torrefaction-based supply chain parameters. Due to torrefaction, the relative proportion of the elements C and O is changed. The torrefaction of biomass increases the content of carbon, while the oxygen content decreases due to the torrefaction procedure, and the ash content is relatively increased [66]. As even the use in small-scale appliances is generally possible with minor adaptions [66], it is expected that torrefied pellets can be used without major adjustments or problems in large-scale coal power plants. As well, the combustion efficiency corresponds to those of pure coal firing according to simulation results by Wielen et al. (2013) [53]. Relevant adaptions of the conversion plant regarding grinding and combustion are drawn from available testings [66, 67] and interviews with technology and plant operators (see Appendix B.1).

The findings and cost data on production, supply and end-use of torrefaction-based pellet production-to-end-use-chains are compared with existing conventional pellet chains, as outlined in Section 4.2.1 and described in Section 5.1. For all cases, the raw material taken into account comprises of either sawmill or forest residues (standard biomass), which is the most common input material.

4.3 Environmental impact assessment

4.3.1 Methods

For assessing the environmental and sustainable impact of imported biofuels, the fossil and primary energy balance and CO_2-equivalent (GHG or CO_{2eq}) emissions are calculated. The direct energy input from all supply chain processes is considered, which is derived from technology, logistic and process data.
For that purpose, the greenhouse gas emissions from the production of solid biofuels, before conversion into electricity, are calculated according to the guidelines by the European Commission [26] in Equation (4.1):

$$\mathrm{E} = \mathrm{e_{ec}} + \mathrm{e_{l}} + \mathrm{e}_p + \mathrm{e_{td}} + \mathrm{e_{u}} - \mathrm{e_{sca}} - \mathrm{e_{ccs}} - \mathrm{e_{ccr}} \tag{4.1}$$

where E are the total emissions from the production of the fuel before energy conversion, $\mathrm{e_{ec}}$ are emissions from the extraction or cultivation of raw materials, $\mathrm{e_{l}}$ are the annualised emissions from carbon stock changes caused by land use change, e_p are emissions from processing, $\mathrm{e_{td}}$ are emissions from transport and distribution, e_u are emissions from the fuel in use that is greenhouse gases emitted during the combustion of solid and gaseous biomass, $\mathrm{e_{sca}}$ is the emission savings from soil carbon accumulation via improved agricultural management, $\mathrm{e_{ccs}}$ are emission savings from carbon capture and geological storage, and $\mathrm{e_{ccr}}$ are emission savings from carbon capture and replacement.
Emissions from the manufacture of machinery and equipment are not taken into account. The emissions from biomass combustion (e_u) are set 0, according to the Renewable Energy Directive of the EU [4]. The following assessments assume that the effects of carbon stock changes caused by land use change and the savings from soil carbon accumulation via improved agricultural management should be offset. That means, it is supposed that the removed carbon stock, dedicated for pellet production, regrows under approved forest (or land) management practices (cp. Section 6.1 for further discussion). Measures for carbon capture, storage or replacement ($\mathrm{e_{ccs}}$, $\mathrm{e_{ccr}}$) are not considered in the further assessments.
The emissions from the use of solid biomass in producing electricity, including the energy conversion to electricity, is calculated as described in Equation (4.2) [26]:

$$\mathrm{EC_{el}} = \frac{\mathrm{E}}{\eta_{\mathrm{el}}} \tag{4.2}$$

with $\mathrm{EC_{el}}$ the total greenhouse gas emissions from the final energy commodity (electricity), and η_{el} the thermal efficiency, defined as the annual useful heat output that is heat generated to satisfy an economically justifiable demand for heat, divided by the annual fuel input.

The finally allocated CO_2 emissions from combustion are calculated according to the EU's emission trading system [98], as described in Equation (4.3):

$$CO_2\,\text{emissions} = E_{fuel} \cdot H_{u,fuel} \cdot EF \cdot OF \tag{4.3}$$

where CO_2 emissions is the annually emitted amount of CO_2, E_{fuel} is the fossil fuel consumed per year, $H_{u,fuel}$ is the net calorific value of the fossil fuel, EF is the emission factor, which is 353 kg CO_{2eq}/MWh_{fuel} for hard coal, and OF is the oxidation factor, here: 1. For the sake of simplicity, only electrity output is considered for the conversion step. Possible heat extracts during conversion are not taken into account. The resulting energy inputs and GHG emissions are presented in kWh direct fossil or primary energy and kg/CO_{2eq}, each per ton or MWh fuel of pellets or torrefied pellets (for easy comparison of data, MWh or kWh are used consistently also for the fuel). Taking the net efficiency of the conversion system into account, the energy input and emissions per MWh_{el} are derived. The subsequent listing of energy consumptions and CO_2 effects for wood pellets in Section 5.2.1 follows a structure similar to Sikkema et al.(2010) [41].

4.3.2 Data

Conversion factors and the process efficiency in each supply step, the fuel and country specific emissions and the primary energy factors are extracted from the GHG databases Ecoinvent, accessed via software Gabi 4.4 [99], and GEMIS 4.7 [100]. For cross-border transports and logistics within the EU, the energy and emission factors for the EU's electricity or fuel mix are assumed. The greenhouse gases CO_2, CH_4, N_2O, perfluormethan and perfluorethan [99, 100] are considered in the CO_{2eq} calculations. Resources originating as a by-product from the wood processing industry or forestry are considered as CO_2-neutral up to the process of collection [4]. For primary biomass resources the energy input during production of biomass is included. This assessment widely conforms to the recommendations by the EU [26]. Respective mass balances and biofuel characteristics are taken from the biofuel database of University of Technology Vienna [101]. This approach is common and has been applied in numerous studies [39–41, 70].

4.4 Economic assessment of pellet supply and energy production costs, co-firing subsidies and torrefaction-based supply chains

4.4.1 Basic costs for pellet supply to end-use

Methods

For evaluating the pellets production and end-conversion in power plants, a full cost account on annual base according to VDI 2067 [102] is applied. This allows to consider different options for raw material, and fuel use and varying other parameters. Corresponding technology and cost parameters for a 40,000 t/a or 120,000 t/a pellet plant and a 800 MW_{el} coal power plant are based on acknowledged research analyses [47, 103] and are outlined in Tables 4.1 and Table 5.12 in the results). For both pellet plants and final conversion plant, the annual capital costs are calculated according to Equations (4.4) and (4.5):

$$\mathrm{C_C} = \mathrm{I_0} \cdot \mathrm{CRF} \tag{4.4}$$

where $\mathrm{C_C}$ is the capital costs, $\mathrm{I_0}$ the initial investment costs and CRF the capital recovery factor,

$$\mathrm{CRF} = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{4.5}$$

with i the interest rate of the project, and n the life time of equipment. The electricity production costs (without heat extracts) are calculated according to Equation (4.6):

$$\mathrm{C_{el}} = \frac{\mathrm{C_C} + \mathrm{OM}}{\mathrm{E}} + \frac{\mathrm{C}_F}{\eta_{\mathrm{el}} \cdot 0.0036} + \mathrm{CO_2\,costs} \tag{4.6}$$

where $\mathrm{C_{el}}$ are the levelised costs of electricity [€/kWh], OM are the annual costs for operation, maintenance and other costs [€/a], calculated as relative share [in %] of investment costs, E is the annual electricity production [kWh], CF are the annual fuel costs [€ per primary GJ], η_{el} is the efficiency of the plant [%] and CO_2 costs are the charged EU emission allowances for combusting the used fuel [€/kWh]. A 10 % co-firing of torrefied or conventional pellets (80 MW_{el} installed biomass capacity in a 800 MW_{el} hard coal power plant) is regarded as technically viable [62].

Data

The specific supply costs for transporting the pellets from origin country to the EU are derived from current market and country related data. This approach has been applied in several other studies [39–41]. Thereby, costs of raw material delivered to the pellet plant, transport rates and logistic costs, common for the specific chain, are requested from transportation operators, bioenergy traders and experts. The cost term refers to the costs, which occur from the end-user perspective. By nature, these costs are also composed of prices, such as for feedstock, fuels or freight rates. Thus, the price influence on costs is examined subsequently (see 4.5). For the final use of pellets, the 800 MW_{el} power plant serves as basis, which is a standard technology in Europe [103]. Relevant technology and economic parameters including additional costs for the preparation and co-firing of pellets are summarised in Table 4.1.

Table 4.1: *Key parameters for a new coal power plant with steam turbine*
Sources: [37, 58, 67, 98, 103–105]

Parameter	**Specification**
Average nominal capacity	800 MW_{el}
Basic investment	1040 million €
Net efficiency	46 %
Average operating hours	5000 h/a
CO_{2eq} emissions for coal	768 g/kWh_{el}
Deprecation time	25 a
Interest rate	6 %
Specific investment costs	1,300 €/kW_{el}
Operating costs	2 % of investment costs/a
Additional investment costs for direct co-firing of wood pellets	300 €/kW_{el} for separate feeding and grinding unit
Additional operation costs during co-firing of wood pellets	3 €/kW_{el} due to increased pretreatment efforts
No additional costs for co-firing torrefied pellets	

The underlying cost data for energy conversion are adjusted using current fuel prices [106, 107]. The allocated CO_2 emissions from combustion of hard coal are calculated according to the EU's emission trading system (see 4.3). All calculations are estimated in Euro using the annual average exchange rates for 2011 (see Table 4.2). VAT, profit margins or supply charges are not included. The results are presented either in €/t pellets (delivered at import harbour or conversion plant) or in €/MWh_{el} converted energy. The resulting structuring of cost data along the supply chain in Section 5.3 is inspired by Sikkema et al. (2010) [41].

Table 4.2: *Currency exchange rates to Euro for the year 2011 (annual average)*
Source: [108]

1 € corresponds to	
1.35	Australian dollar: AUS-$
1.38	Canadian dollar: CAN-$
40.88	Russian rouble: RUB
1.39	US dollar: US-$

4.4.2 Electricity production costs under co-firing policies

Methods

The derived pellet supply costs are evaluated under the effect of different co-firing subsidies, dealing with the subsidy schemes in Belgium and the UK. These subsidy schemes are analysed with respect to the current and future financial support for co-firing. Considering the three different supply chain designs in this work (Australia, Canada, Russia to the EU), the support options for co-firing are compared and their application to inland locations in Germany and Austria is investigated. For these countries, the electricity production costs, the financial gap of co-firing and CO_2 mitigation costs are modelled in different fuel and emission allowance price scenarios, which are defined below.
A comparison with current costs for other renewables proves the financial performance of co-firing pellets. This type of policy evaluation is new and allows for new findings on effective strategies to reduce CO_2. The analysis is conducted for all supply cases for conventional wood pellets. Torrefied pellets demonstrate innovative biofuels under development, which are not yet mature for the market and thus should not be considered in these investigations.

Based on the electricity production costs of coal and those including 10 % co-fired pellets, the respective financial gap can be assessed, as described in Equation (4.7):

$$\mathrm{FG} = \frac{\mathrm{C}_{\text{co-firing}} - (0.9 \cdot \mathrm{C}_{\text{coal}})}{0.1} - \mathrm{C}_{\text{co-firing}} \tag{4.7}$$

where FG is the financial gap, $\mathrm{C}_{\text{co-firing}}$ are the electricity production costs for 90 % coal and 10 % pellets firing (constant for all considered scenarios), and C_{coal} are the electricity production costs for coal only [each in €-Cent/$\mathrm{kWh}_{\mathrm{el}}$]. The financial gap indicates the difference in €-Cent/$\mathrm{kWh}_{\mathrm{el}}$ of electricity production using either co-fired pellets and coal (10 % pellets, 90 % coal) or 100 % coal. That means, the lower the pellet fuel price compared to the coal price, the lower will be the electricity production costs for co-firing compared to electricity production costs using 100 % coal. As a result, a low financial gap induces higher profitability of co-firing, and electricity costs are closer to those from coal only. The more the financial gap turns negative, the higher is the cost advantage of electricity costs from co-firing against those from coal firing only.

The CO_2 mitigation costs specify, how much € have to be spent to avoid one ton of CO_2. They are a measure to compare the efficiency of a technology's CO_2 reduction potential applied in research and policy (see examples in [109–111]. Moreover, CO_2 mitigation costs offer a reference value to compare renewable energy technology with alternative allocation of emission allowances at energy exchanges. The CO_2 mitigation costs are indicated in €/t CO_2, which are incurred by the coal and co-firing electricity production costs and saved CO_2 emissions, see Equation (4.8):

$$\mathrm{MC}_{\mathrm{CO}_2} = \frac{(\mathrm{C}_{\text{co-firing}} - \mathrm{C}_{\text{coal}}) \cdot 10 \cdot \mathrm{E}_{\text{output}}}{\mathrm{CO}_2\,\text{emissions}} \tag{4.8}$$

where $\mathrm{MC}_{\mathrm{CO}_2}$ are the mitigation costs (in €/t CO_2), $\mathrm{E}_{\text{output}}$ is the annual electricity output of the conversion plant (in MWh_{el}), and CO_2 emissions are the annually emitted emissions (cp. Equation (4.3)).

Data for co-firing subsidies

The efficiency of co-firing under the influence of the support schemes from Belgium and the UK as well as variable prices are investigated. Different cases and scenarios for co-firing support are presented for Belgium, the UK, Germany and Austria and compared with other renewable energy generation systems. The explicit findings are presented in Section 5.3.2.

In Belgium, co-firing biomass in coal plants is supported by the Green Certificate System (GCS). The GCS requires an inclusion of upstream biomass energy (i.e. direct fossil energy required to produce and transport the biofuel to the conversion plant). The number of credited green certificates for co-firing biomass in a coal plant is calculated according to Equation (4.9) [32, 33]:

$$\text{No of GC} = \frac{\mathrm{H}_{\text{u,pellets}} \cdot \eta_{\text{coal plant}} - \sum \mathrm{E}_{\text{upstream fossil}}}{\mathrm{H}_{\text{u,pellets}} \cdot \eta_{\text{coal plant}}} \cdot \mathrm{E}_{\text{pellets}} \tag{4.9}$$

where No of GC is the number of annual Green Certificates granted for the co-firing of biomass in a coal plant [in %], $\mathrm{H}_{\text{u, pellets}}$ is the net calorific value of pellets [in MWh],

$\eta_{\text{coal plant}}$ is the electric efficiency of coal plant [in %], $\sum E_{\text{upstream,fossil}}$ is the total energy consumed during upstream production and transport operations [in MWh_{el}/t pellets], and E_{pellets} is the amount of electricity produced from pellet co-firing [in MWh_{el}]. The value of one Green Certificate (GC) is at least 80 € per MWh_{el}, which corresponds to generation plants under operation prior to 2010 [112, 113]. This value is used for all considered scenarios. To summarise, the GC calculation scheme indicates that the more upstream fossil energy is consumed for pellet production and transportation to the conversion plant, the less green certificates will be granted and the lower is the profitability of co-firing pellets.

In the UK, the Renewables Obligation (RO) system provides support for the co-firing of biomass and energy crops [114]. For co-firing biomass, 0.5 Renewables Obligation Certificates (ROCs) per generated MWh_{el} are granted. For energy crops the support is 1 ROC/MWh_{el} [109]. The reference buy-out price for 2012/2013 is 40.71 £/ROC, which corresponds to 50.60 €/MWh_{el} (1 £ = 1.243 €). Starting from 2011, the RO system requires biomass power generators to provide sustainability reports for the biomass feedstock. The target maximum level of GHG lifecycle emissions from resource to electricity generation is 285 kg CO_{2eq}/MWh_{el}. From April 2013 onwards, meeting this GHG criterion should formally be linked with the eligibility for ROC support [34, 35].

The Flemish and English subsidy schemes are analysed considering possible price variability for pellets, hard coal and CO_2 prices. Thus, a base case and three scenarios for co-firing are investigated, with price assumptions presented in Table 4.3. More exactly, the four cases are:

- The base case and current policy case with actual market prices,
- Scenario 1 with low CO_2 and high pellet prices,
- Scenario 2 with moderate fuel and CO_2 prices,
- Scenario 3 with high coal and CO_2 prices.

For the base case, real market prices for industrial pellets and hard coal delivered to Rotterdam and CO_2 allowances are assumed. According to APX-ENDEX, the pellet market price in Rotterdam is assumed to be 130 €/t [19]. The prices for imported hard coal at the cross-border point is set 85 €/t for Belgium and the UK, and 90 €/t for Germany and Austria [106, 115]. The final fuel prices and underlying prices in the scenarios are listed in Table 4.3 and include inland transportation costs to the conversion plant, which are derived from Prognos (2006) [116] and Sumetzberger (2012) [117]. The inland transport distance is assumed to be 75 km for Belgium and the UK, 400 km for Germany, and 1200 km for Austria. The price for CO_2, auctioned at the European Energy Exchange, is set 15 €/t [107].

Table 4.3: *Base case and scenario price assumptions for fuels delivered at conversion plant and CO_2 allowances (in €)*

Prices ex works	**Pellets**	**Import hard coal**	**CO_2 allowances**
Base case and current policy case			
Belgium, UK	140.50	90.00	15
Germany	152.00	94.33	15
Austria	162.50	94.33	15
Scenario 1: low CO_2 and high biomass prices			
compared to base case:	+20 %	stable	low
Belgium, UK	168.60	90.00	7
Germany	182.40	94.33	7
Austria	195.00	94.33	7
Scenario 2: moderate fuel and CO_2 prices			
compared to base case:	+10 %	+25 %	moderate
Belgium, UK	154.55	112.50	15
Germany	167.20	117.91	15
Austria	178.75	117.91	15
Scenario 3: high CO_2 and coal prices			
compared to base case:	+20 %	+40 %	peak 2005 - 2012
Belgium, UK	168.60	126.00	30
Germany	182.40	132.06	30
Austria	195.00	132.06	30

Other incentives like tax reduction (BE) or market regulations (UK) are not considered.

4.4.3 Costs for torrefaction-based supply chains

Investment costs for the biomass pretreatment, with either typical pelletisation technology or combined torrefaction and pelletisation plant, are derived from plant engineering expertise, literature data and technology component costs. Above all, the

described data are based on the experience in concept development, engineering and set-up of a pyrolysis plant in Austria [47, 92].
For the 40,000 t/a torrefaction unit, investment costs are derived from typical engineering and commissioning costs and the technology component costs, consisting of belt dryer, torrefaction rotating drum reactor, heat generator for torrefaction and drying, conveyor system, storage, cooling and grinding [92]. The combination with a 40,000 t/a pelletising plant allows several cost and energetic synergies. Total investment costs are evaluated and presented in Sections 5.5.1 and 5.5.4. The basic technology and cost data for the pelletising technology are based on detailed analyses of pelletising costs [47] (see 4.4.1). Adjustments in terms of costs and energy balance are derived from grinding tests in a 1.5 kW_{el} mill and pelletising tests in a 3 kW_{el} laboratory pellet press from Amandus Kahl, documented in [66] (cp. Section 4.2.2). The operation and maintenance, costs for energy consumption and other costs are estimated due to average operation costs for production and energy conversion plants, the capacities of technology components and based on the recommendations of the VDI 2067 [102].

The combined torrefaction and pelletising plant was up-scaled to 120,000 t/a production capacity using the same, branch typical factors as for pellet plants [47].

Methods and data used for the raw material and fuel costs in the exporting country, transportation routes and logistical means as well as investment costs for the pelletising equipment and coal conversion plants are the same as described for the conventional pellet production, supply and end-use phases for a conversion plant 75 km from EU import harbour, see Section 4.4.1.
Coal and CO_2 costs at the EU end-user correspond to 2012 levels with 97 €/t hard coal and 7 €/t EU emission allowances. Fuel specific properties like increased net calorific value, specific energy and mass balances and operating costs for pretreatment and end-use (cp. Section 4.2.2) are translated into respective costs and energy inputs of the torrefaction-based supply chains.

4.5 Price risk evaluation

4.5.1 Definition of price risks along pellet supply chains

The risk analysis in this thesis starts with the definition and characterisation of most relevant price risks along international supply chains. This is based on a comprehensive literature review and individual interviews with biomass market actors.

As a result, significant risks along the supply chain pattern are characterised and correspondent price indices and their recent development – as starting point for the subsequent risk assessment – are discussed. As for the policy analysis, the assessment of price risks is investigated for the conventional wood pellet supply chains only. For torrefied pellets no market exists yet, which makes it impossible to conduct a reliable and credible analysis.

4.5.2 Evaluation of 10-year price variations

Methods

The defined supply costs for wood pellets are basis for evaluating market risks in the supply chain. Thus, for most vulnerable, market-related cost items, the imputed risk is evaluated as effect of underlying price changes. This is a common approach during cost accounting for entrepreneurial activities. That means, based on historical price variations within one contractual period, the expected losses or revenues for the future period can be extrapolated [118]. Certain attempts of this approach have been performed for individual price effects [41] or in connection with sensitivity analyses [40]. Sikkema et al. (2011) [87] further explored the general market and trade conditions and prospects of the European pellets market. Anyway, so far there has been no comprehensive price risk analysis for pellet supply chains. So in this thesis, most relevant price variations within the recent 10 years are identified and determined. The 10-year period covers the time frame the pellet market has just evolved. Hence, a straightforward and unambiguous statistical analysis is applied by assessing the range of price variations as factors of total supply chain costs.
Based on the obtained supply costs for Canadian, Australian and Russian pellets exported to the EU, the total supply costs for pellets delivered at the conversion plant are assumed to be arithmetic mean. With that, the relevant price variation – in terms of their standard variation or range – is charged as multiplier of the respective cost share in the supply chain (see Equation 4.10 and 4.11). In that way, the price effect of each factor on total costs can be revealed.
The total supply costs subject to standard deviations of price indices are defined as:

$$\mathrm{C}_{\mathrm{Total}(x,\sigma_{xp}^{\pm})} = C_x \cdot (1 + \sigma_{xp}^{\pm}) + \sum_{i=1,i\neq x}^{n} C_i \tag{4.10}$$

where $\mathrm{C}_{\mathrm{Total}(x,\sigma_{xp}^{\pm})}$ are the total supply costs, which are subject to the standard deviation of price index xp in cost item C_x [€/t], $\sigma_{xp}^{\pm}$ is the negative (-) or positive

(+) standard deviation of index xp, described as percentage of arithmetic mean of index xp [%] and C_i are the cost components 1 to n in the supply chain [€/t]. The total supply costs subject to lower and higher ranges of price indices are defined as:

$$C_{\mathrm{Total}(x,R^{\pm}_{xp})} = C_x \cdot R^{\pm}_{xp} + \sum_{i=1, i \neq x}^{n} C_i \tag{4.11}$$

where $C_{\mathrm{Total}(x,R^{\pm}_{xp})}$ are the total supply costs, which are subject to the lower (R^{-}_{xp}) or higher (R^{+}_{xp}) range of price index xp in cost component x.

Data

As shown in Figure 4.3 and listed in Table 4.4, different price indices along the supply chain are identified. The selection is based on available data, which match best the respective cost items in the supply chain. Thus for some aspects, only approaching indices are recorded and available, e.g. the wood product index in Russia, which is used here. Another example is that no EU transport index is available. Therefore, the German freight index is applied, which is representative for West and Central Europe. The stated data series for a 10-year period are inflation-adjusted using the relevant consumer price indices [119].

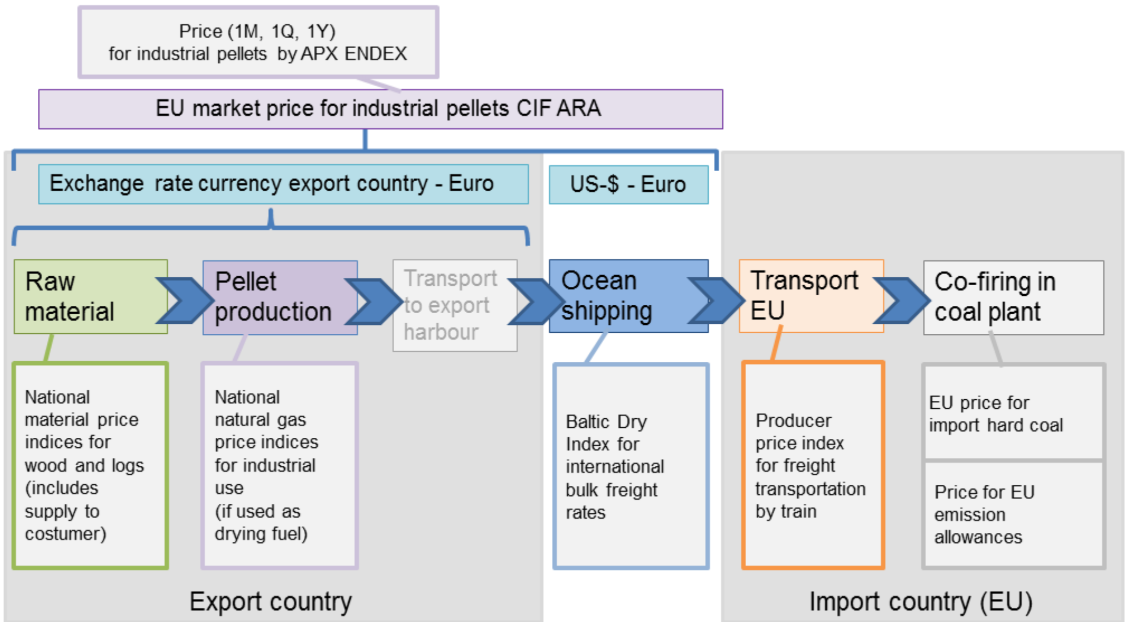

Figure 4.3: Price indices for modelling 10-year price fluctuations along pellet supply chains destined for EU co-firing

Table 4.4: List of considered price indices and their influence on the supply chain

Price aspect	**Considered price index**	**Data sources**
Raw material (and biomass process fuel) price for pellet production	Wood chipping index Australia	[120]
	Raw material index, logs and bolts, softwood, Canada	[121]
	Wood product and manufacturing index Russia	[122]
Process fuel price for pellet production	Natural gas wholesale prices Australia	[123]
	Natural gas consumer price index Canada	[124]
	Natural gas consumer prices industry Russia	[125]
Influence on costs in exporting country	Exchange rate AUS-$ – €	[108]
	Exchange rate CAN-$ – €	
	Exchange rate RUS rouble–€	
	Exchange rate US-$ – €	
Worldwide index for dry bulk freight rates	Baltic Dry Shipping index (adjusted to €-equivalents)	[126, 127]
Import market price for industrial pellets at ARA ports	EU pellet market price	[19]
Index for rail freight rates in the EU	Freight rate index Germany	[128]
Price for fossil fuel to be substituted	Hard coal EU	[106, 115]
CO_2 prices on fossil fuels	CO_2 emission allowances	[129]

4.5.3 Simulation of recent 3-year variations on supply costs

Methods

After the observation of long-term price variations, actual supply cost changes in the 3-year period from 2008 to 2011 are investigated. A period of 3 years complies with the typical (long-term) planning and contracting horizon of pellet producers and end-users [86, 87]. So the simulation of the recent 3-year variations reflects the cumulative annual price changes due to raw material prices, exchange rates, and ocean shipping rates as crucial price factors (see Figure 4.4). Apart from that, all other costs (the "base costs") are assumed to be constant as defined for 2011 (see Section 5.3). The EU pellet market price for imported pellets reported by APX-ENDEX [19] serves as reference.

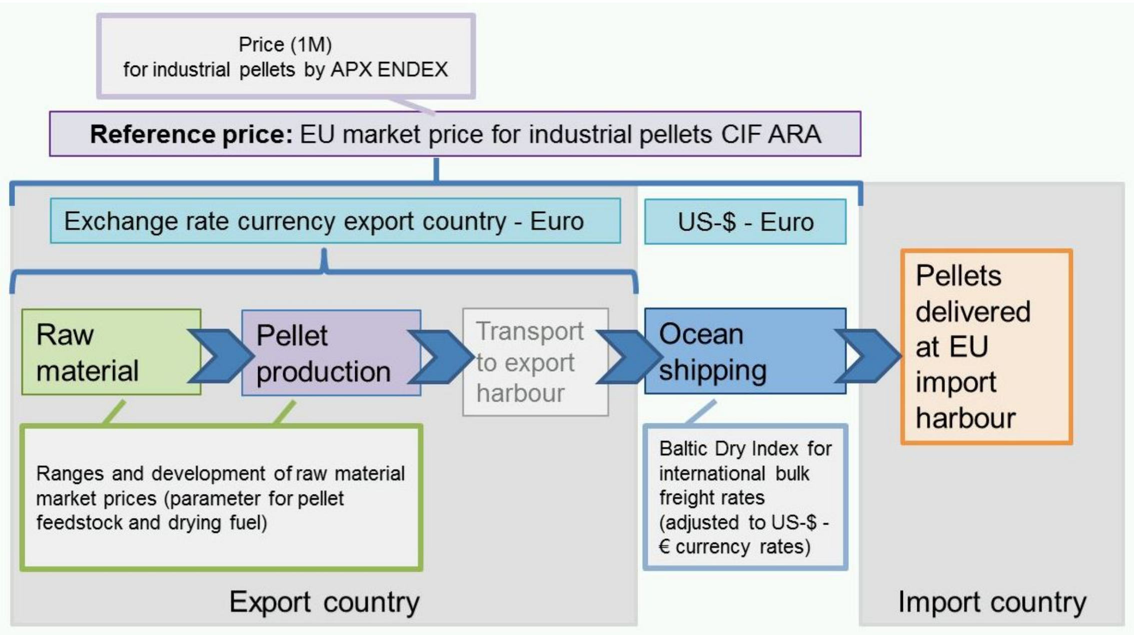

Figure 4.4: *Indices and prices for simulating 3-year price fluctuations*

As fossil reference, the composition of hard coal supply costs from Australia and Russia to Europe is demonstrated. The projected changes of the supply costs due to exchange rates are displayed. Due to scarce data on coal supply costs, here 2007 serves as reference year with a projection to 2011. For comparison, the achievable market prices CIF Northwest (NW) Europe are presented. This comparison provides a rough reference to the corresponding fossil supply system. As data are available just rudimentarily and thus cannot be investigated in detail, it gives some indication for reference, but cannot meet the challenge to comprehensively compare the fossil and biomass supply systems.

Data

For actual pellet feedstock price variations the use of alternative assortments is considered. Due to higher quality and the delivery over long distances or demand from other industries, this feedstock is associated with higher purchase prices, see Table 4.5. For Australia, the case of cheaper alternative sawdust at minor costs is investigated as well [130]. The variation of exchange rates and ocean shipping rates is derived from data sources described in Table 4.4. Reference supply costs for hard coal and their specific freight rates are based on the market report from Ritschel and Schiffer (2007) [89], detailed supply data from Baruya (2007) [131] and summarised market prices from Euracoal association [132].

Table 4.5: *Price variation of raw material in the case study countries*

Country	**Price changes** (base price)	**Unit & biomass assortment**	**Sources**
Canada	65 (32)	€/t_{dry} harvest residues	[17,133]
Russia	40 (22)	€/t_{dry} sawmill residues purchased	[10]
Australia (price increase)	70 (39)	€/t_{dry} plantation whole tree chips	[134,135]
Australia (price decrease)	11	€/t_{dry} sawdust	[130,134]

4.5.4 Sensitivity analysis for pellet production, raw material prices and exchange rate fluctuations

In another step, the effect of variating operational parameters during pretreatment is examined in economic terms. Based on experience of pellet production plants, often part time operation is applied rather than 8000 h year-round operation. That means, instead of 7 days/ week operation pelletising is running only 5 days/ week and many pellet producers have an annual 2 week revision phase with shut-down of all machines. Resulting effects on the pellet production economies are calculated, with the electricity and heat costs, operating efforts (personnel), product input and output as variable, linearly adapted parameters. Thus, the economic impact of operating hours on total supply costs (free EU import harbour) are described. Furthermore, the impact raw material prices on total supply costs are investigated. The prices are considered as delivered at the pellet plant, variating in the same range (-35 %

to +35 %). The characteristics of raw materials are assumed to be constant for the respective production country and correspond to the standard cases. In addition to the investigations on empirically based exchange rate fluctuations, their theoretical impact in full range on production and supply costs in the exporting country are examined. Therefore, a range between -35 % to +35 % of the 2011 exchange rate between export country currency and Euro is considered. These variations are described as factor for all costs incurred in the examined export countries Australia, Canada and Russia. For all sensitivities, the costs for pellets with natural gas as processing fuel are considered. This allows, above all for raw material prices, to understand the pure changes due to input material and to exclude the factor process fuel. All other relevant costs, which underlie variations along the supply chain, are covered in the previous investigations regarding price risks (see Section 4.5). Variations related to the environmental impact and applied policies are discussed and covered in frame of the scenario analysis (see Section 4.4.2). Variating parameters for torrefied pellets such as lower/ higher investment costs or increased raw material input are directly considered in the respective torrefaction investigations (cp. Section 4.2.2).

4.5.5 Expert interviews on supply risks and de-risk strategies

The risk analysis is complemented by personal communications with pellet market actors and related literature regarding their evaluation and hedging mechanisms against price risks in international biomass trade. The interviews were conducted face-to-face or via e-mail, following a semi-structured guideline. Not all questions have been or could be answered by all interviewed experts. For confidentiality reasons, interview results containing potential sensitive data are indicated in aggregated form in Appendix B.1. With these, insight is gained into possible hedging and contractual provisions to catch arising price gaps. Resulting findings can be found in Section 5.4. Giving the frame of questions raised to the interviewees and the different position of interviewees, neither questions nor answers fulfil a strict standard scheme, which allows or intends to compare statements. In this context, the aim is to gather insight into the dynamics and interconnections within the supply chain patterns and market activities. That is why interview citations and results do not have the claim to represent the meaning of all actors interviewed, but demonstrate a kind of collective understanding or statement of several stakeholders. Not confidential data information from interviewees like biomass or logistics prices are indicated separately and cited with the name of the interviewee. The interview results are incorporated into the price risk section, in defining most crucial price risks in Section 5.4.1, and above all in concluding hedging strategies in Sections 5.4.5 and in summarising decision making aspects in Section 5.6.4. Beyond, individual data or information and statements are used consecutively in other methods and results sections, where applicable .

Chapter 5

Results and Discussion

5.1 Supply chain case studies

5.1.1 Australia to Europe

Southern Australia offers an increasing potential of eucalyptus (blue gum) plantations from marginal farmland destined for industrial pellets production. It is expected to provide significant volumes to the global pellet market, including Europe [12,91]. Foresters expect an extension of the plantation area from 0.58 million ha in 2009 up to 2 million ha in 2014. In 2010, the first large-scale 125,000 t/a pellet plant (later upscaled to 250,000 t/a) started the production of industrial wood pellets from plantation residues in Albany (Western Australia), mainly for export to Northwest Europe. The industry and biomass representatives announced an increasing set up of pellet plant facilities from 80,000 to 850,000 t/a production capacity in near future [136–138]. The location of future plants should be in the centre of South Australia's major pine milling industry [138]. But different factors currently hinder the pellet export: The operator of the largest Australian pellet plant recently faced economic problems due to strength of Australian dollar to Euro, problems with the processing of blue gum material (contaminated with sand), and resulting switch from residues to more expensive raw material [139]. Another influencing factor for the Australian-European trade is the competition with Asia, which could lead to more exports from Australia to Japan or Korea [137]. Thus pellet exports to the EU will be favoured only if 1) the production chain is optimised, 2) ocean freight rates are cheap, and 3) the exchange rate is favourable [136]. Nevertheless, the EU is still one of the dedicated target markets for future pellet exports from Australia [9,134,140]. The present supply model is based on the evaluation of the existing pellet plant in

Western Australia replying on local eucalyptus plantation residues [137, 141]. The assumptions and results related to the environmental balance for this standard case are listed in Table 5.1.

The use of plantation logs is analysed as an alternative feedstock in terms of variating costs (see 5.4.3) and concerning the environmental balance as described in Table 5.2. Plantation logs are a much more expensive but an actually used feedstock option for pellet production in Australia [139, 142].The production phase is based on 120,000 t/a capacity, which corresponds to approximately one pelletising unit in Albany. The modelled pellet production plant includes an additional grinding unit suitable for coarse material (wood chips). The transport distance to the export harbour Albany is roughly 25 km by truck [137]. The shipment to Rotterdam via the Cape of Good Hope accounts 21,570 km [143].

The corresponding cost breakdown for all standard costs from raw material supply to delivery at conversion plant are described in Table 5.3.

Table 5.1: *Energy consumption and CO_{2eq} emissions along the supply chain Australia - Europe, standard biomass*

	Basic data	**Direct fossil energy input** [kWh/t pellets delivered]	**Primary energy input** [kWh/t pellets delivered]	**GHG emissions** [kg CO_{2eq}/t pellets delivered]	**Reference for basic data**
1) Raw material production and collection					
Raw material transport	10 km to collection point	8.40	12.17	1.07	[45, 137]
Raw material preparation	Chipping plantation logs roadside, 45 % mc, 5 l diesel/MWh biomass 3 % mass losses	29.98	9.42	9.07	[39, 45]
Raw material transport	50 km by truck (including empty return trip)	37.80	54.74	4.29	[136, 137]
2) Densification					
Handling & storage of raw material	0.25 kWh electricity & 0.02 l diesel/MWh biomass	1.89	4.78	1.55	[41]
Pellet production	120,000 t annual production, 1 % mass losses included				Adapted from [47]
Electricity consumption (for both process fuels)	26 kWh electricity/MWh pellets	125.00	474.39	158.71	
Natural gas consumption for drying	551 MJ/MWh pellets, 90 % boiler efficiency	760.68	874.72	192.51	
Biomass consumption for drying	551 MJ/MWh pellets, 90 % efficiency	0.00	775.58	2.92	
Handling & storage	assumed as negligible				
3)+4) Export to Europe					
Transport to port Albany	40 km by truck	18.12	26.23	2.03	[137]
Handling & storage	0.25 kWh electricity & 0.02 l diesel/MWh biomass	2.20	5.11	1.82	[41]
Ocean transport	40,000 t load capacity, 21,570 km, 0.0039 l heavy fuel oil/tkm 1.5 % mass losses	959.41	990.34	285.00	[99, 143]
1)-4) Subtotal pellets delivered at Rotterdam harbour	Biomass (natural gas)	1183 (1943)	2346 (2445)	466 (656)	
5) Delivery to conversion plant					
Handling & storage at import port	0.25 kWh electricity & 0.02 l diesel/MWh biomass	2.13	5.11	1.00	[41]
a) Transport to BE/UK	Train electric, 75 km	3.34	11.00	1.89	[99]
c) Transport to AT	Train electric, 1,200 km	49.65	175.95	30.29	[99]
Handling at coal plant	2.1 kWh electricity/MWh biomass, 1 % mass losses	9.38	33.24	5.72	[41]
6) Conversion in power plant					
Coal power plant	800 MW_{el} coal plant, 46 % electric efficiency	MWh/ MWh_{el}	MWh/ MWh_{el}	kg CO_{2eq}/ MWh_{el}	[103]
a) in BE/UK, pellets Bio (NG)		0.53 (0.87)	3.25	212.55 (297.38)	
c) in AT, pellets Bio (NG)		0.55 (0.90)	3.32	225.25 (310.08)	
For comparison: Conversion of hard coal in EU			4.49	900.55	
All primary energy and emission factors from [99, 100].					

Table 5.2: *Energy consumption and CO_{2eq} emissions along the supply chain Australia - Europe, considering alternative raw material plantation logs*

	Basic data	**Direct fossil energy input** [kWh/t pellets delivered]	**Primary energy input** [kWh/t pellets delivered]	**GHG emissions** [kg CO_{2eq}/t pellets delivered]	**Reference for basic data**
1) Raw material production and collection					
Alternative raw material: wood chips from eucalyptus logs	Eucalyptus plantation incl. energy use for production: 5 l diesel/MWh biomass	43.02	13.38	13.01	[45, 100]
All other processing and operational phases 1) to 4) are added as described in Table 5.1. For drying the use of biomass residues is assumed (see Table 5.1).					
1)-4) Subtotal pellets delivered at Rotterdam harbour		1226	2372	480	
5) Delivery to conversion plant as described in operational phases in Table 5.1.					
6) Conversion in power plant					
Conversion in coal power plant	800 MW_{el} coal plant, 46 % electric efficiency	MWh/ MWh_{el}	MWh/ MWh_{el}	kg CO_{2eq}/ MWh_{el}	[103]
a) in BE/UK, pellets (drying with alternative biomass)		0.56	3.26	218.37	
c) in AT, pellets (drying with alternative biomass)		0.58	3.33	231.07	
All primary energy and emission factors from [99, 100].					

Table 5.3: *Cost breakdown along the supply chain Australia - Europe, corresponding to basic costs with standard biomass*

	Basic data	**€/t pellets delivered**	**References**
1) Raw material supply			
Raw material	Sawdust and wood chips from blue gum plantation incl. delivery, 45 % mc	27.20 €/t feedstock	[120, 134, 135]
Raw material delivered to pellet plant	198,327 t/a feedstock used	44.95	Own calculation based on feedstock characteristics
2) Pellet production			
Pellet production	120,000 t/a production, additional coarse grinding unit suitable for wood chips, 1 % mass losses	11.29 million € investment costs	Own calculation based on [47], local energy prices and staff costs (see A.2); data include handling & storage of raw material and pellets
Capital costs	6 % interest rate, 17.5 a life time of equipment	8.83	
Consumption costs	excl. raw material & fuel	9.19	
Natural gas costs for drying	90 % boiler efficiency	13.83	
Biomass costs for drying	90 % boiler efficiency	8.27	
Operation & maintenance	3 shifts/day, 7 working days/week	5.25	
Other costs		2.60	
Subsum pellet production costs	Drying with natural gas Drying with biomass	84.65 79.09	
3) Transport to export port			
Loading		3.00	[47]
Transport to export port Albany	40 km (20 km with empty return trip) by truck, incl. unloading	6.17	[136, 144, 145]
4) Ocean shipping to Europe			
Handling & storage at export port	Dedicated wood pellets terminal available, 1 % mass losses	2.70	[146]
Ocean transport	handysize or panamax, Albany-Rotterdam: 21,570 km, 1.5 % mass losses	47.50	[147]
1)-4) Subtotal import costs to Rotterdam	Pellets (NG) Pellets (Bio)	144.03 138.46	
5) Delivery to conversion plant			
Handling & storage at import port	Discharge by clam buckets, conveyor system, storage & load	5.00	[41, 47, 117]
Transport to conversion plant	75 km by train	5.50	Calculation based on [116, 148] with cost adjustment based on [128]
Total costs free conversion plant	**Pellets (NG)** **Pellets (Bio)**	**154.53** **148.96**	

5.1.2 West Canada to Europe

British Columbia in Western Canada has a vast potential of 417 million ha forests representing the 3rd largest forest area in the world [149]. An area of 60 million ha is forested, with timber production on 25 million ha woodlands. In 2010, the lumber production was 27 million m^3 [150] with resulting volume of sawmill residues between 18 and 25.6 million m^3/a (6.8 to 9.7 million t_{dry}/a) [151,152]. The amount of biomass feedstock originating from forest harvest was around 9.95 million t_{dry} in 2008 [150]. The resource base should be stable within the next years with an expected decrease from 2015 to 2017 induced by reduced cut of beetle infected wood [85, 152].
The standard raw material for pellet production taken into account consists of sawdust and shavings from spruce (36 % mc), which is transported 100 km on average from sawmills or harvesting sites to the pellet plant [41, 51]. The alternative raw material for the environmental analysis are wood chip residues from timber harvesting, (36 % mc after air drying at roadside). The energy consumption for haulage and chipping of biomass at forest road (2.23 l diesel per MWh biomass) conforms to an average value for producing forest wood chips [45, 153]. A supply radius of 150 km, which is the maximum feasible distance according to Verkerk (2008) [151], is assumed (see Table 5.5). The use of forest chips implicates the need of an additional grinding unit in the pellet plant, resulting in slightly higher electricity input requirements. The assumed pellet plant capacity is 120,000 t/a. Within the production process, a rotary drum dryer with respective energy demand is considered [51, 70].
Table 5.4 presents all supply steps and respective environmental balance for the standard case from Canada to Europe. For the standard case, the raw material costs are set 23.41 €/t_{wet} feedstock delivered at pellet mill gate. This corresponds to 33.25 €/t_{wet} pellets, which is in line with the data provided by Sikkema et al. (2010), Bradley (2012), and Ferguson (2010) [41, 133, 149].
The cost related input data and results for the pellet production and delivery phases are listed in Table 5.6.

Table 5.4: *Energy consumption and CO_{2eq} emissions along the supply chain Canada - Europe, standard biomass*

	Basic data	**Direct fossil energy input** [kWh/t pellets delivered]	**Primary energy input** [kWh/t pellets delivered]	**GHG emissions** [kg CO_{2eq}/t pellets delivered]	**Reference for basic data**
1) Raw material production and collection					
Raw material at sawmill	Sawdust & shavings from spruce, 36 % mc	0	0	0	[4]
Raw material transport	100 km truck transport to sawmill, 3 % mass losses	66.66	96.52	7.57	Data from [87]
2) Densification					
Handling & storage of raw material	0.25 kWh electricity & 0.02 l diesel/MWh biomass	1.77	3.94	0.69	[41]
Pellet production	120,000 t annual production, 1 % mass losses included				Adapted from [47, 51, 70]
Electricity consumption (for both process fuels)	22 kWh electricity/MWh pellets	70.93	259.29	35.42	
Natural gas consumption for drying	299 MJ/MWh pellets, 90 % boiler efficiency	418.72	483.62	103.72	
Biomass consumption for drying	299 MJ/MWh pellets, 90 % efficiency	0.00	442.97	0.74	
Handling & storage	assumed as negligible				
3)+4) Export to Europe					
Train transport to port Vancouver	500 km, train electric	72.17	263.83	7.33	[154]
Handling & storage	0.25 kWh electricity & 0.02 l diesel/MWh biomass, 1 % mass losses	1.83	4.07	0.71	[41, 45]
Ocean transport	40,000 t load capacity, 16,500 km, 0.0039 l heavy fuel oil/tkm 1.5 % mass losses	722.93	749.99	215.83	[99, 143]
1)-4) Subtotal pellets delivered at Rotterdam harbour	Biomass (natural gas)	936 (1355)	1810 (1866)	268 (371)	
5) Delivery to conversion plant					
Handling & storage at import port	0.25 kWh electricity & 0.02 l diesel/MWh biomass	2.16	5.19	1.00	[41]
a) Transport to BE/UK	Train electric, 75 km	3.34	11.00	1.89	[99]
c) Transport to AT	Train electric, 1,200 km	49.65	175.95	30.29	[99]
Handling at coal plant	2.1 kWh electricity/MWh biomass	9.51	33.72	5.80	[41]
6) Conversion in power plant					
Conversion in coal power plant	800 MW_{el} coal plant, 46 % electric efficiency	MWh/ MWh_{el}	MWh/ MWh_{el}	kg CO_{2eq}/ MWh_{el}	[103]
a) in BE/UK, pellets Bio (NG)		0.42 (0.60)	2.99	122.00 (168.00)	
c) in AT, pellets Bio (NG)		0.44 (0.63)	3.06	135.00 (180.00)	
All primary energy and emission factors from [99, 100].					

Table 5.5: *Energy consumption and CO_{2eq} emissions along the supply chain Canada - Europe, considering alternative raw material forest residues*

	Basic data	Direct fossil energy input [kWh/t pellets delivered]	Primary energy input [kWh/t pellets delivered]	GHG emissions [kg CO_{2eq}/t pellets delivered]	Reference for basic data
1) Raw material production and collection					
Alternative raw material: forest residues from coniferous wood	Haulage, air drying incl. chipping at roadside: 2.23 l diesel/MWh biomass, 36 % mc	34.20	130.15	33.09	[45, 153]
Raw material transport	150 km truck transport, 3 % mass losses	99.98	144.78	11.36	[151]
2) Densification as described in Table 5.4 with exemption of electricity consumption:					
Electricity consumption	26 kWh electricity/MWh for wood chips	83.26	304.37	41.58	Adapted from [47]
3) + 4) Export to European import harbour as described in Table 5.4.					
1)-4) Subtotal pellets delivered at Rotterdam harbour		1016	2049	315	
5) Delivery to conversion plant as described in Table 5.4.					
6) Conversion in power plant					
Conversion in coal power plant	800 MW_{el} coal plant, 46 % electric efficiency	MWh/ MWh_{el}	MWh/ MWh_{el}	kg CO_{2eq}/ MWh_{el}	[103]
a) in BE/UK, pellets dried with alternative biomass		0.46	3.04	142.60	
c) in AT, pellets dried with alternative biomass		0.48	3.11	155.12	
All primary energy and emission factors from [99, 100].					

Table 5.6: *Cost breakdown along the supply chain Canada - Europe, corresponding to basic costs with standard biomass*

	Basic data	**€/t pellets delivered**	**References**
1) Raw material supply			
Raw material	Sawdust and wood chips from spruce incl. delivery, 36 % mc	5.00 €/t feedstock	[51,150]
Raw material transport to pellet plant	100 km on average by truck from sawmill incl. unload and handling	18.41 €/t feedstock	[51] with annual 2 % cost increase
Raw material delivered to pellet plant	170,438 t/a feedstock used	33.25	Own calculation based on feedstock characteristics
2) Pellet production			
Pellet production	120,000 t/a production, 1 % mass losses	9.18 million € investment costs	Own calculation incl. use of rotary drum dryer based on [47,51,70], local energy prices and staff costs (see A.2); data include handling & storage of raw material and pellets
Capital costs	6 % interest rate, 17.5 a life time of equipment	7.18	
Consumption costs	excl. raw material and fuel	7.52	
Natural gas costs for drying	90 % boiler efficiency	7.42	
Biomass costs for drying	90 % boiler efficiency	3.17	
Operation & maintenance	3 shifts/day, 7 working days/week	4.82	
Other costs		2.60	
Subsum pellet production costs	Drying with natural gas Drying with biomass	62.79 58.54	
3) Transport to export port			
Loading		1.50	[41]
Transport to export port Vancouver	500 km by train, 84 t (130 m^3) load per railcar, incl. unloading	24.85	[154,155]
4) Ocean shipping to Europe			
Handling & storage at export port	Wood pellets terminal, 1 % mass losses	2.38	[41]
Ocean transport	handysize, Vancouver-Rotterdam: 16,500 km, 1.5 % mass losses	36.61	[149,156]
1)-4) Subtotal import costs to Rotterdam	Pellets dried with natural gas Pellets dried with biomass	128.12 123.87	
5) Delivery to conversion plant			
Handling & storage at import port	Discharge by clam buckets, conveyor system, storage & load	5.00	[41,47,117]
Transport to conversion plant BE	75 km by train	5.50	Calculation based on [116,148] with cost adjustment [128]
Total costs free conversion plant	**Pellets (NG)** **Pellets (Bio)**	**138.62** **134.37**	

5.1.3 Northwest Russia to Europe

Russia has vast wood reserves and a strong wood industry. The region Northwest Russia is favoured by direct access to the Baltic Sea. Sawmills in the Leningrad region surrounding St.Petersburg process more than 1 million m^3 wood per year [157]. The annual forest waste composes at least 100 million m^3, reported by Cocchi et al. (2011) [10]. The number of pellet production plants is constantly growing. The 800,000 t/a production capacity reported in 2008 [158] and the recent increase by the 1 million t/a pellet plant Vyborgskaya amount to a total capacity of 1.8 million t/a in the region. Up to now, the actual production is estimated at only 1 million t/a [159]. Most pellets are exported to the EU industrial market, where the revenue is comparably high. It is assumed that no export duties are imposed to exported pellets [158]. For the Russian supply case, sawdust from soft wood with 55 % mc is considered as standard raw material. The supplying wood industry is nearby the pellet plant. As alternative feedstock for the environmental analysis, roundwood from regional coniferous forests is chosen, as described in Table 5.8. This is much more expensive than sawmill residues, and the use of primary wood resources is controversial (see Sections 5.6 and 6.1 for discussion). Nevertheless, roundwood is used at the Vyborgskaya pellet plant [10,160] and is therefore considered as well. For that case, tree harvesting is accounted with an energy consumption of 273 MJ/m^3 [70]. The roundwood is transported 200 km to the pellet plant. A special roundwood handling and pretreatment (debarking) unit is necessary. Similar technology used at Vyborgskaya plant [160] is considered. This requires around 6 kWh electricity per MWh biomass and 0.34 l diesel per MWh biomass for additional on-site transport efforts, according to Reisenbichler(2009) [161]. All assumptions and results on the environmental balance can be found in Table 5.7.

Following the market price for sawdust in Northwest Russia, the raw material price results in 28 €/t pellet product (see Table 5.9). A smaller pellet plant with 40,000 t/a capacity is taken into account, which is the case at installed sites in Northwest Russia [10]. From the pellet plant the transport distance to export harbour St. Petersburg is 400 km on average. The costs for handling and transshipment of pellets at St.Petersburg harbour is high with 12 €/t pellets. This is due to a lack of a specialised cargo handling terminal with dedicated equipment for pellet transshipment [10, 162, 163]. All economic input data and resulting costs are listed in Table 5.9. In consequence of the highly unpredictable economy and strongly fluctuating and negotiable tariffs e.g. for transportation [164], the given supply costs give a realistic point of reference, but are subject to constant variations.

Table 5.7: *Energy consumption and CO_{2eq} emissions along the supply chain Russia - Europe, standard biomass*

	Basic data	**Direct fossil energy input** [kWh/t pellets delivered]	**Primary energy input**[kWh/t pellets delivered]	**GHG emissions** [kg CO_{2eq}/t pellets delivered]	**Reference for basic data**
1) Raw material production and collection					
Raw material from wood industry	Residues from spruce, 55 % mc	0	0	0	[4]
Raw material transport	25 km truck transport, 3 % mass losses	23.58	34.14	2.68	[158]
2) Densification					
Handling & storage of raw material	0.25 kWh electricity & 0.02 l diesel/MWh biomass	1.85	3.93	1.04	[41]
Pellet production	40,000 t annual production, 1 % mass losses included				Adapted from [47]
Electricity consumption (for both process fuels)	23 kWh electricity/MWh pellets	105.99	321.49	84.17	
Natural gas consumption for drying	878 MJ/MWh pellets, 90 % boiler efficiency	1230.58	1353.64	308.68	
Biomass consumption for drying	878 MJ/MWh pellets, 90 % boiler efficiency	0.00	1241.89	1.10	
Handling & storage	assumed as negligible				
3)+4) Export to Europe					
Train transport to port St.Petersburg	400 km, train electric	81.54	247.34	13.16	[157]
Handling & storage	0.25 kWh electricity & 0.02 l diesel/MWh biomass, 1 % mass losses	1.83	4.07	0.71	[41,45]
Sea transport	4,000 t load capacity, 1,600 km, 0.004 l heavy fuel oil/tkm 1.5 % mass losses	71.89	72.73	20.93	[39,143]
1)-4) Subtotal pellets delivered at Rotterdam harbour	Biomass (natural gas)	287 (1518)	1931 (2038)	125 (433)	
5) Delivery to conversion plant					
Handling & storage at import port	0.25 kWh electricity & 0.02 l diesel/MWh biomass	2.13	5.11	1.00	[41]
a) Transport to BE/UK	Train electric, 75 km	3.34	11.00	1.89	[99]
c) Transport to AT	Train electric, 1,200 km	49.65	175.95	30.29	[99]
Handling at coal plant	2.1 kWh electricity/MWh biomass	9.38	33.24	5.72	[41]
6) Conversion in power plant					
Conversion in coal power plant	800 MW_{el} coal plant, 46 % electric efficiency	MWh/ MWh_{el}	MWh/ MWh_{el}	kg CO_{2eq}/ MWh_{el}	[103]
a) in BE/UK, pellets Bio (NG)		0.13 (0.68)	3.07	58.66 (194.32)	
c) in AT, pellets Bio (NG)		0.16 (0.70)	3.15	71.18 (206.84)	
All primary energy and emission factors from [99, 100].					

Table 5.8: *Energy consumption and CO_{2eq} emissions along the supply chain Russia - Europe, considering alternative raw material roundwood*

	Basic data	**Direct fossil energy input** [kWh/t pellets delivered]	**Primary energy input**[kWh/t pellets delivered]	**GHG emissions** [kg CO_{2eq}/t pellets delivered]	**Reference for basic data**
1) Raw material production and collection					
Alternative raw material production	Coniferous roundwood, 55 % mc; forest management, harvesting & haulage to forest road: 4.36 l diesel/MWh biomass; 3 % mass loss	183.14	205.11	55.38	[70]
Raw material transport	100 km truck transport	92.41	133.81	10.50	[158]
2) Densification					
Handling & storage of raw material	0.25 kWh electricity & 0.02 l diesel/MWh biomass	1.82	3.85	1.04	[41]
Pellet production	40,000 t annual production, 1 % mass loss				[47]
Roundwood pretreatment	Incl. debarking: 6.3 kWh electricity/MWh biomass	23.85	72.33	18.94	Data derived from [161, 165]
	On-site handling of roundwood: 0.34 l diesel/MWh biomass	14.27	15.98	4.32	
Electricity consumption	27 kWh electricity/MWh pellets	124.43	377.43	84.17	Adapted from [47]
Biomass consumption for drying	878 MJ/MWh pellets (biomass residues), 90 % boiler efficiency	0.00	1358.62	26.78	
Handling & storage	assumed as negligible				
3)+4) Export to Europe see Table 5.7					
1)-4) Subtotal pellets delivered at Rotterdam harbour		596	2497	251	
5) Delivery to conversion plant as described in Table 5.7					
6) Conversion in power plant					
Conversion in coal power plant	800 MW_{el} coal plant, 46 % electric efficiency	MWh/ MWh_{el}	MWh/ MWh_{el}	kg CO_{2eq}/ MWh_{el}	[103]
a) in BE/UK, pellets dried with biomass		0.27	3.31	114.56	
c) in AT, pellets dried with biomass		0.29	3.39	127.09	
All primary energy and emission factors from [99, 100].					

Table 5.9: *Cost breakdown along the supply chain Russia - Europe, corresponding to basic costs with standard biomass*

	Basic data	**€/t pellets delivered**	**References**
1) Raw material supply			
Raw material	Sawdust incl. delivery, 55 % mc	13.89 €/t feedstock	[10]
Raw material delivered to pellet plant	80,800 t/a feedstock used	28.06	Own calculation based on feedstock characteristics
2) Pellet production			
Pellet production	40,000 t/a production, 1 % mass losses	3.74 million € investment costs	Own calculation based on [47], local energy prices and staff costs (see Appendix A.2); data include handling & storage of raw material and pellets
Capital costs	6 % interest rate, 17.5 a life time of equipment	8.78	
Consumption costs	excl. raw material and fuel	8.44	
Natural gas costs for drying	90 % boiler efficiency	8.80	
Biomass costs for drying	90 % boiler efficiency	8.33	
Operation & maintenance	3 shifts/day, 7 working days/week	6.22	
Other costs		2.60	
Subsum pellet production costs	Drying with natural gas Drying with biomass	62.89 62.43	
3) Transport to export port			
Loading		1.50	[41]
Transport to export port Vancouver	400 km by train, incl. unloading	10.03	[157,163]
4) Ocean shipping to Europe			
Handling & storage at export port	Standard terminal, 1 % mass losses	12.00	[10,162]
Sea transport	small vessel (4,000 t capacity), St.Petersburg - Rotterdam: 1,600 km, 1.5 % mass losses	20.30	[117]
1)-4) Subtotal import costs to Rotterdam	Pellets dried with natural gas Pellets dried with biomass	106.72 106.26	
5) Delivery to conversion plant			
Handling & storage at import port	Discharge by clam buckets, conveyor system, storage & load	5.00	[41,47,117]
Transport to conversion plant BE	75 km by train	5.50	Calculation based on [116,148] with cost adjustment based on [128]
Total costs free conversion plant	**Pellets (NG)** **Pellets (Bio)**	**117.22** **116.76**	

5.2 Environmental balance along the three supply chains

5.2.1 Base data from biomass to end-use

Based on the previous assessments (Sections 5.1.1 to 5.1.3), the direct energy consumption up to delivery at the conversion plant is shown for the three cases Australia, Canada, Russia in Figure 5.1. Most direct fossil energy is used in the Australian case considering natural gas for drying (almost 2 MWh/t pellets), followed by the Russian and Canadian cases (natural gas) with a consumption between 1.6 and 1.4 MWh/t. All biomass cases are less extensive in fossil energy consumption, with the Russian biomass case at the minimum of only 0.3 MWh/t. Heavy fuel oil use during ocean transports has a strong impact in the Canadian and Australian cases. Production of plantation logs has a minor effect on the overall balance for Australian pellets, but using roundwood doubles the fossil fuel input for Russian pellets compared to the standard case. The energy balance for delivery of pellets either to Belgium or to Austria is similar, as train transport is very energy-efficient.

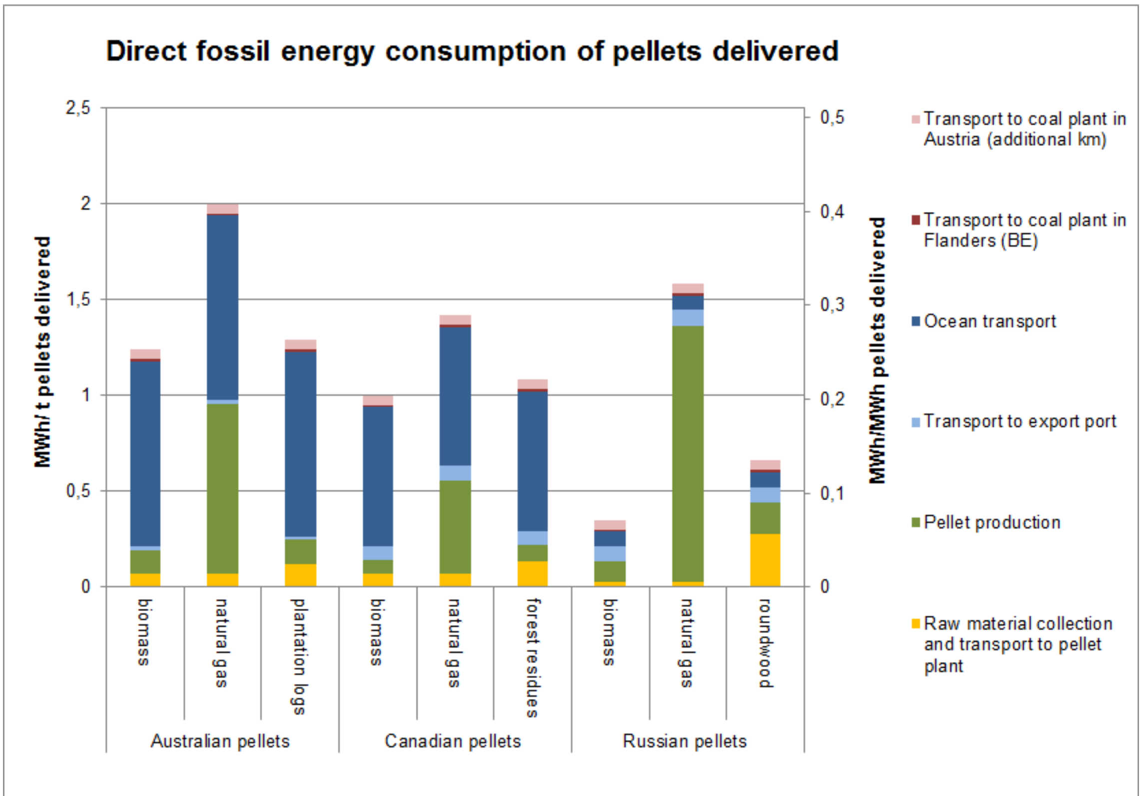

Figure 5.1: *Direct fossil energy consumption along the supply chain of exported pellets from Australia, Canada, and Russia to Europe*
For electricity, the share of fossil energy included in the national electricity mix is considered. Handling, storage and loading activities are included in the preceding supply step.

Concerning primary energy, the difference between the use of natural gas and biomass is marginal only. Figure 5.2 demonstrates that due to the Russian electricity mix and drying of wet fuel, all Russian pellets cases have a higher primary energy consumption than Canadian pellets. Russian pellets from roundwood have an extremely high primary energy use due to raw material production and 60 % increased energy input for pellet production.

The results (2.51 MWh/t for pellets from Australia, 1.95 MWh/t from Canada and 2.05 MWh/t from Russia when biomass is used for drying) comply with the assessments by Sikkema et al.(2010), who reported 1.94 MWh/t for the Canadian chain to the Netherlands, and with Uasuf (2010) for Argentinian pellets from sawdust (53 % mc) with 1.79 MWh/t pellets, which are shipped 12,000 km to the Netherlands. Hamelinck et al.(2005) [39] reported slightly lower values for pellets from Latin America to the Netherlands.

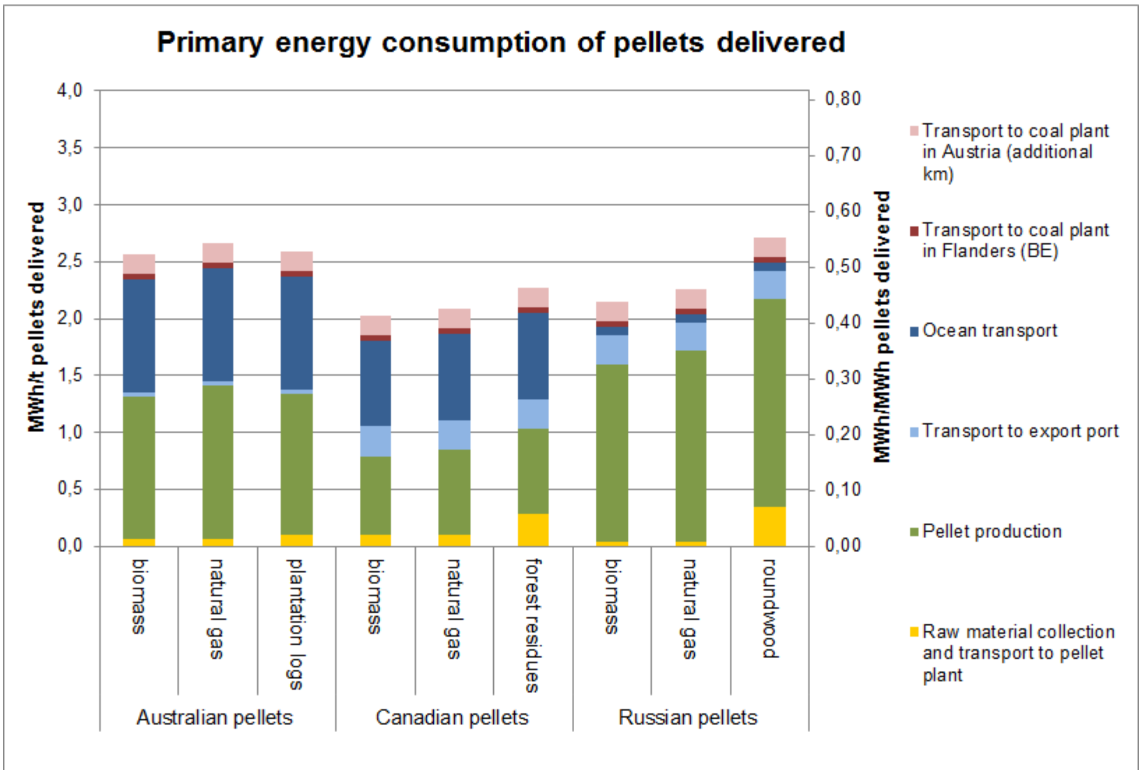

Figure 5.2: *Primary energy consumed along the supply chains of exported pellets from Australia, Canada, and Russia to Europe*

Calculation of primary energy consumption is based on the direct energy consumption and the primary energy factor for the respective source of energy

The greenhouse gas emissions along the supply chain are particularly high for cases with long ocean transports and natural gas use, as shown in Figure 5.3. The resulting emissions are in agreement with Uasuf(2010) and Magelli et al.(2009) [40,70]. For the Australian supply case, the resulting CO_2 emissions from plantation to pellet plant gate are in agreement with those estimated for eucalyptus plantations by Jawjit et al. (2006) [166].

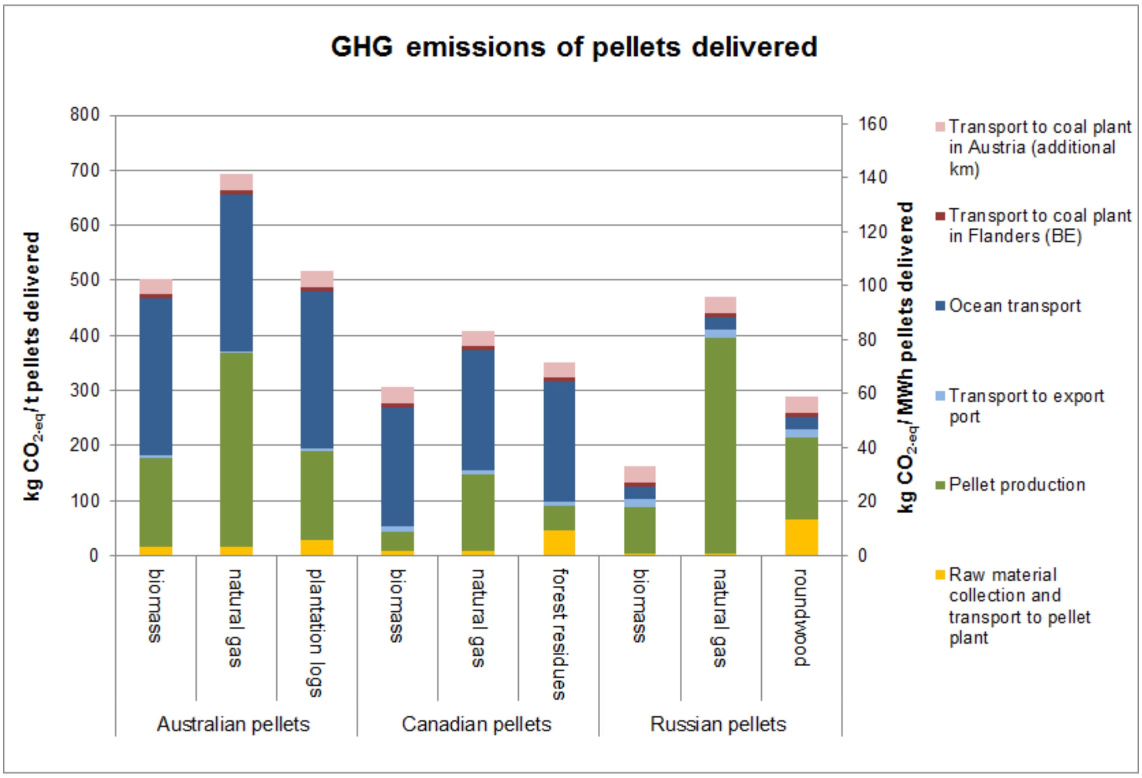

Figure 5.3: *Greenhouse gas emissions calculated along the supply chains of exported pellets from Australia, Canada, and Russia to Europe*
GHG calculation is based on the direct energy consumption and the GHG emission factor for the respective source of energy.

The CO_2 emissions for ocean transport and the energy demand for drying raw material for the Canadian case study conform to the values assessed by Magelli et al. (2009) [70].

Figure 5.4 illustrates the GHG emissions of generated electricity from pellets imported from the three countries. The CO_2 savings related to the EU-average electricity mix are marked. All supply chains meet the 60 % standard target of 285 kg CO_{2eq}/ MWh_{el}, as well as the 66 % emission savings (UK target for 2020), except Australian pellets with process fuel natural gas.

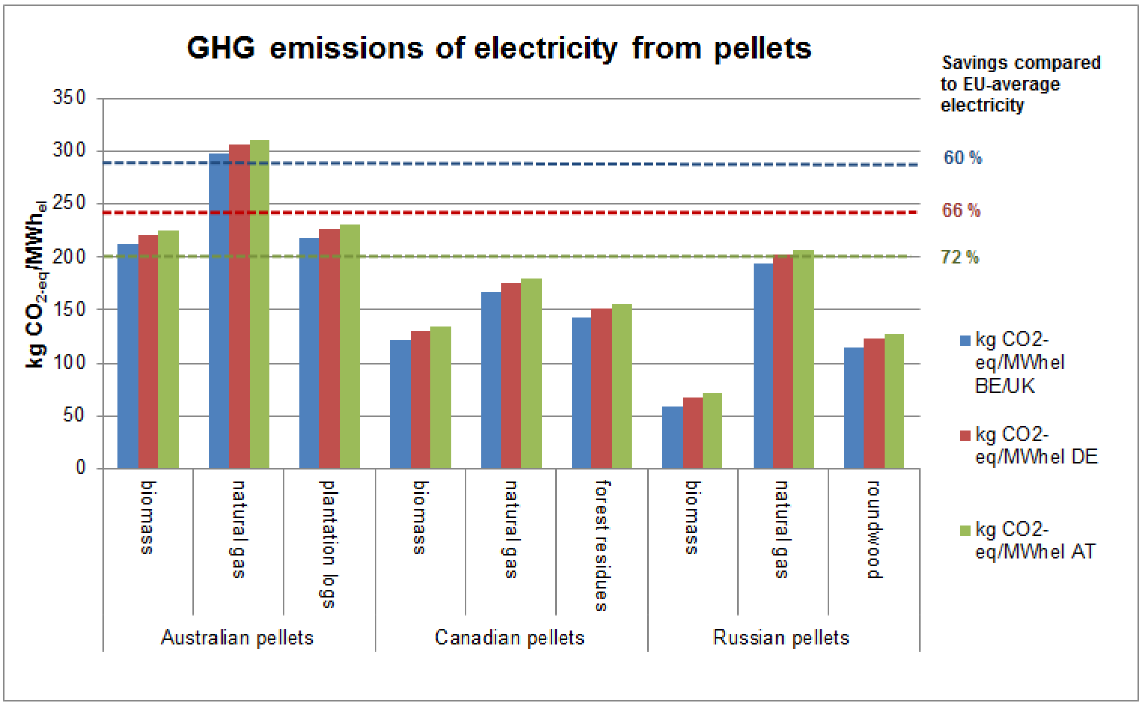

Figure 5.4: *GHG emissions per generated MWh_{el} from pellets exported from Australia, Canada, and Russia to Europe, and svaings compared to EU average electricity mix*
Sources: own results with UK's saving targets from [167]

5.3 Supply costs along the supply chains

5.3.1 Base data from biomass to end-use

The overall pellet supply costs for supply chains from Canada, Australia and Russia to EU import harbour are summarised in Figure 5.5. The raw material costs amount to about one third of the total costs. Transport costs from pellet plant to EU import harbour amounts to another 30 to 50 % of total supply costs. The cases with natural gas (NG) as drying fuel are slightly more costly than those with biomass (Bio), which is due to the quite low raw material costs required for international pellet trade. The resulting total supply costs from Australia to Europe are in line with the estimations by Smith (2010) [136], taking into account the 2009 framework assumed in his study.

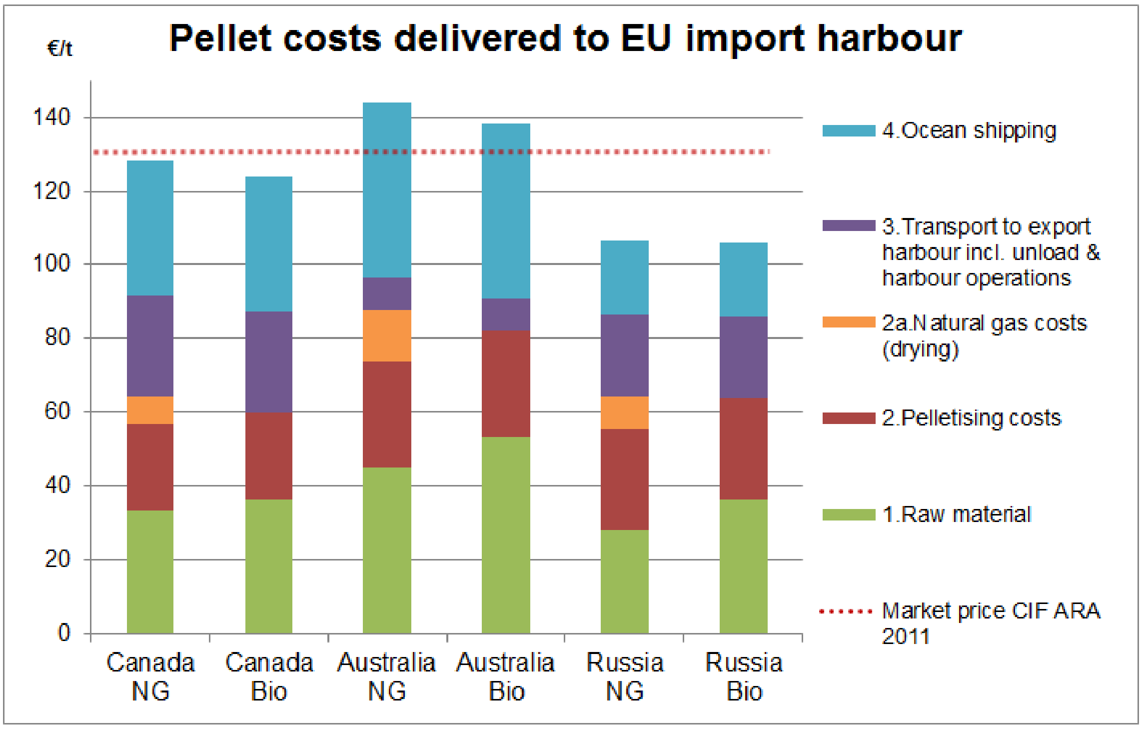

Figure 5.5: *Supply costs of defined pellet chains from origin to EU import harbour Rotterdam and average market price for pellets.*
Source for pellets market price: [19]

As seen in Figure 5.5, the total costs for Canadian pellets delivered to Rotterdam are 124 to 128 €/t, or 134 to 139 €/t pellets delivered to the conversion plant 75 km from EU import harbour. The composition of costs is similar to those estimated by Ferguson(2010) and Sikkema et al.(2010) [41, 149]. Compared to Sikkema et al.(2010) [41] less freight costs are spent on shipping, which is result of increased freight capacity and return trips on the Vancouver – Rotterdam route that could be realised within the last few years (interviews according to Appendix B.1).

The CIF ARA market price (price including cost, insurance, freight set at the ports Amsterdam, Rotterdam, Antwerp) indicated in Figure 5.5 is 131 €/t pellets on average for the year 2011 [19]. Apparently, the Australian supply costs exceed the achievable market price in the EU. Thus, for the present input data and exchange rate, the Australian supply chain is not profitable. Supply costs for Canadian pellets are below the market price, but without much scope for profit or guarantee margins. Against, the supply costs for Russian pellets are very low with sufficient scope for both pellet producer and trader margins, which usually amount to between 8 and 10 % each (interviews according to Appendix B.1).

5.3.2 Effect of co-firing policies on electricity generation costs

Co-firing under current policies

In Figure 5.6, the electricity production costs for coal combustion and co-firing of pellets are illustrated according to the current policy frame. As shown, the production costs with or without co-firing pellets do not differ substantially, but in most cases are still higher for co-firing. This particularly applies to Germany and Austria, where no co-firing support scheme exists. Here, the difference in production costs is around 0.40 to 0.45 €-Cent/kWh_{el} and the financial gap is between 3.64 €-Cent/kWh_{el} (Germany) and 4.06 €-Cent/kWh_{el} (Austria).

For comparison, the Belgium and UK's situations are included in Figure 5.6. For Belgium, the electricity production costs for co-firing are much closer or even below those from coal only. The effect of offsetting the number of green certificates against the upstream energy balance results in a clear favouring of low energy biomass chains. In the UK, ROCs are constant for each case. Thus, the financial gap and CO_2 mitigation costs are equal for each case with forest biomass or with energy crops. Opposite to the Flemish system, in the UK the relatively energy intensive Australian chains are credited with full certificates because energy crops are used. Co-firing Canadian and/or Russian pellets in the UK is still more expensive than electricity from coal.

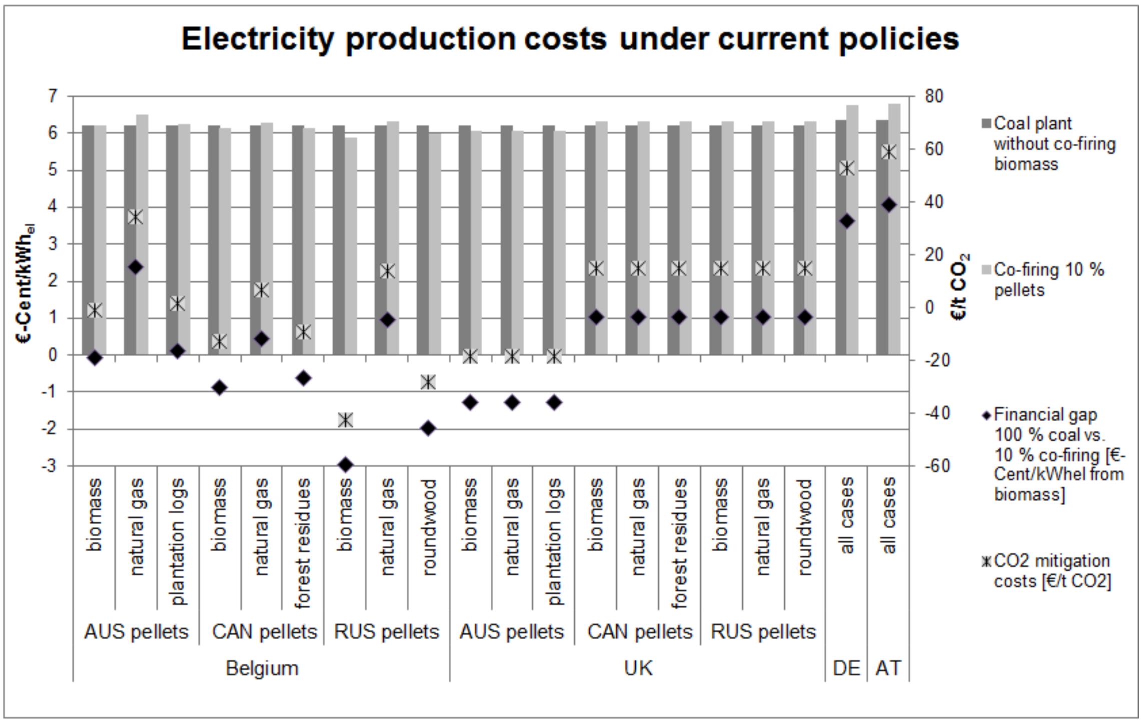

Figure 5.6: *Electricity production costs under current national policies*

Base case: Applying the Flemish und UK's co-firing subsidies to Germany and Austria

Assuming that the Flemish or UK's co-firing subsidies are applied, the electricity production costs for co-firing pellets are adapted for Germany and Austria. Figure 5.7 illustrates the situation with Belgium and the UK as comparative factors. The result is that cost levels approach those of Belgium and the UK with financial gaps mostly between 0 and 2 €-Cent/kWh$_{\mathrm{el}}$.

Scenario analysis for variable fuel price development

Next, the co-firing support schemes are evaluated for different price scenarios (see 4.4.2). Scenario 1 (Figure 5.8) demonstrates low CO_2 and high pellet prices. The impact of unfavourable pellet price conditions becomes very obvious. Financial gaps are much higher, thus co-firing pellets becomes less attractive, especially for pellets dried with natural gas under the Flemish subsidy system. Australian pellets lose their cost advantage in the UK's system and reach a financial gap of 0.4 to 1.4 €-Cent/kWh$_{el}$. The Russian case (biomass) still achieves favourable values for Germany and Austria. The CO_2 mitigation costs mainly exceed the set market price for CO_2 with 7 €/t, except for the Russian cases with biomass as drying fuel and partially for Canadian pellets. In scenario 2 (Figure 5.9), moderate fuel and CO_2

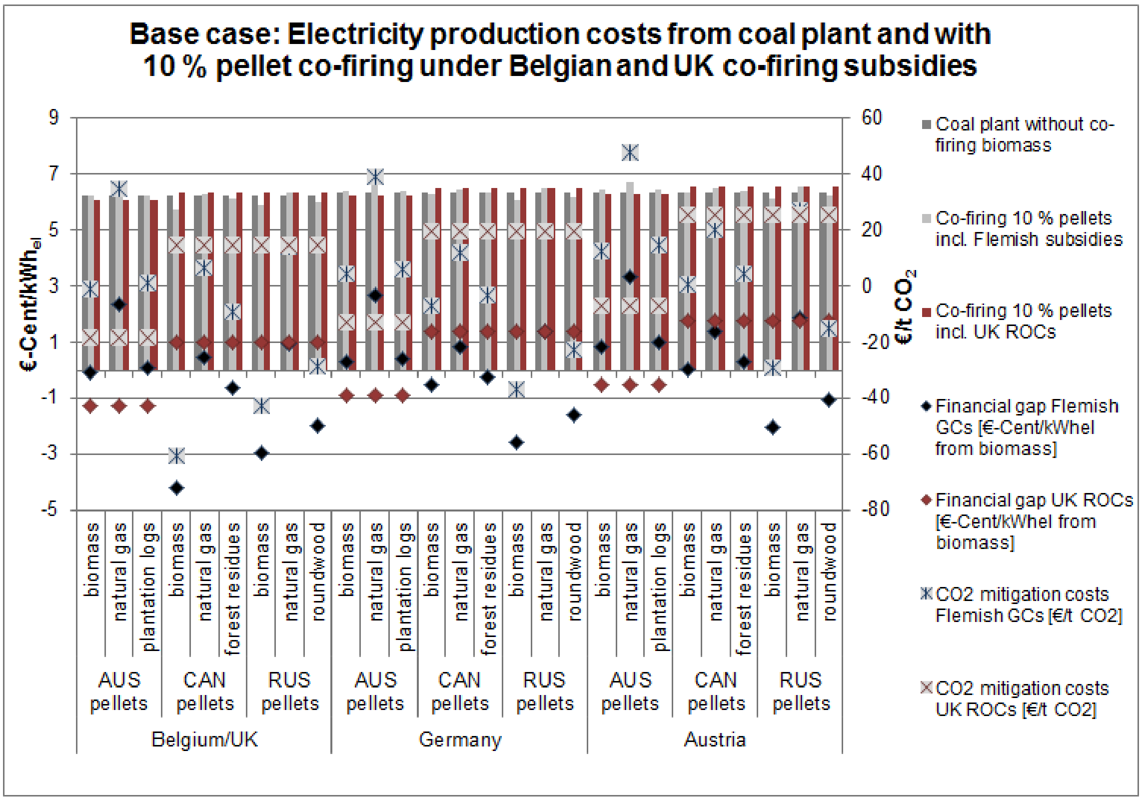

Figure 5.7: Base Case: Electricity production costs applying the Flemish and UK's subsidies to locations in Germany and Austria

prices are considered. Under this scenario, the production costs for co-fired Russian pellets (biomass) are very low under the Flemish support system, resulting in a financial gap of up to -2.95 €-Cent/kWh$_{el}$. Favourable CO_2 mitigation costs are also reached by Canadian pellets in Germany (biomass and forest residues). Australian pellets reach negative CO_2 mitigation costs under the RO system. The remaining cases have much lower CO_2 mitigation costs than in the base case, mostly between 0 and 30 €/t CO_2. Scenario 3 (Figure 5.10) represents high coal and CO_2 prices. It shows that in the Flemish Green Certificate System pellets from all origin countries are favoured against coal, except for pellets with natural gas as process fuel. Once more, the UK's system represents an advantage for Australian pellets solely falling below coal costs.

For Germany, all pellets dried with biomass are cost-competitive under the Flemish system and have favourable CO_2 mitigation costs between -48 €/t and -4 €/t CO_2, under the English system between -24.4 and 8.5 €/t CO_2, and with -17 and 16 €/t CO_2 in Austria. All pellets dried with natural gas achieve a much lower financial gap with a maximum of 2 €-Cent/kWh$_{el}$ under the Flemish system. In turn, the RO system results in financial gaps between -2 and 1 €-Cent/kWh$_{el}$ with the most advantageous values for Australian 'energy crop' pellets.

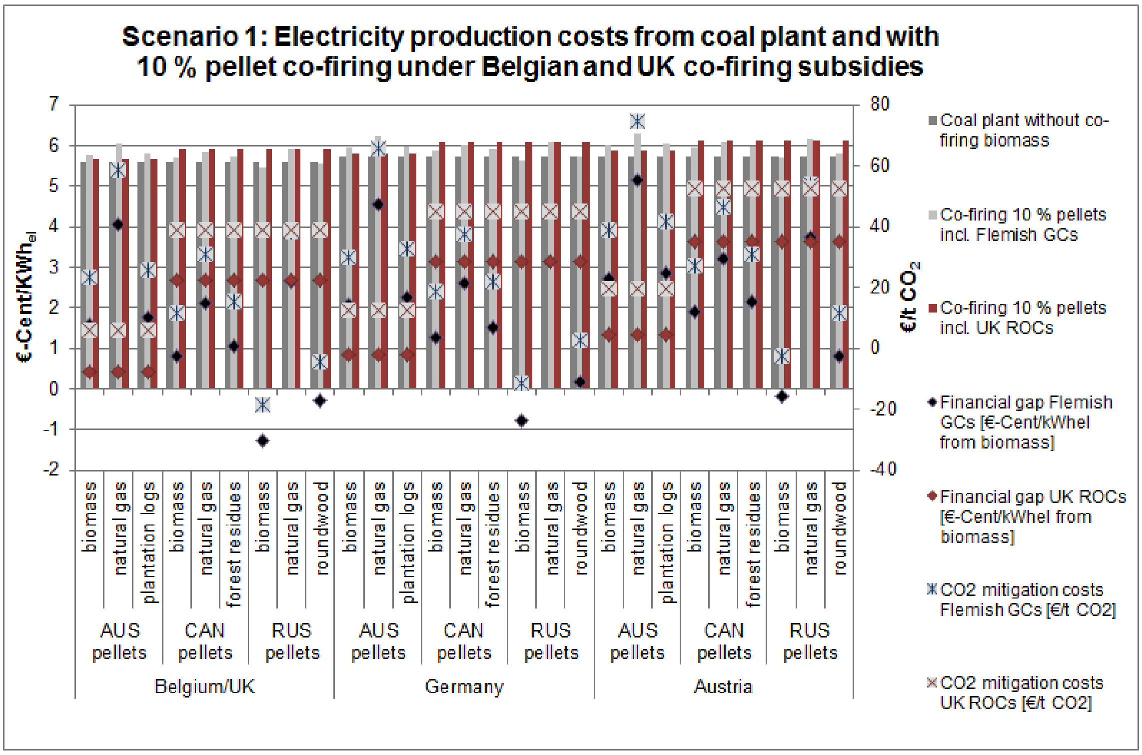

Figure 5.8: Electricity production costs under scenario 1 (low CO_2 and high pellets prices)

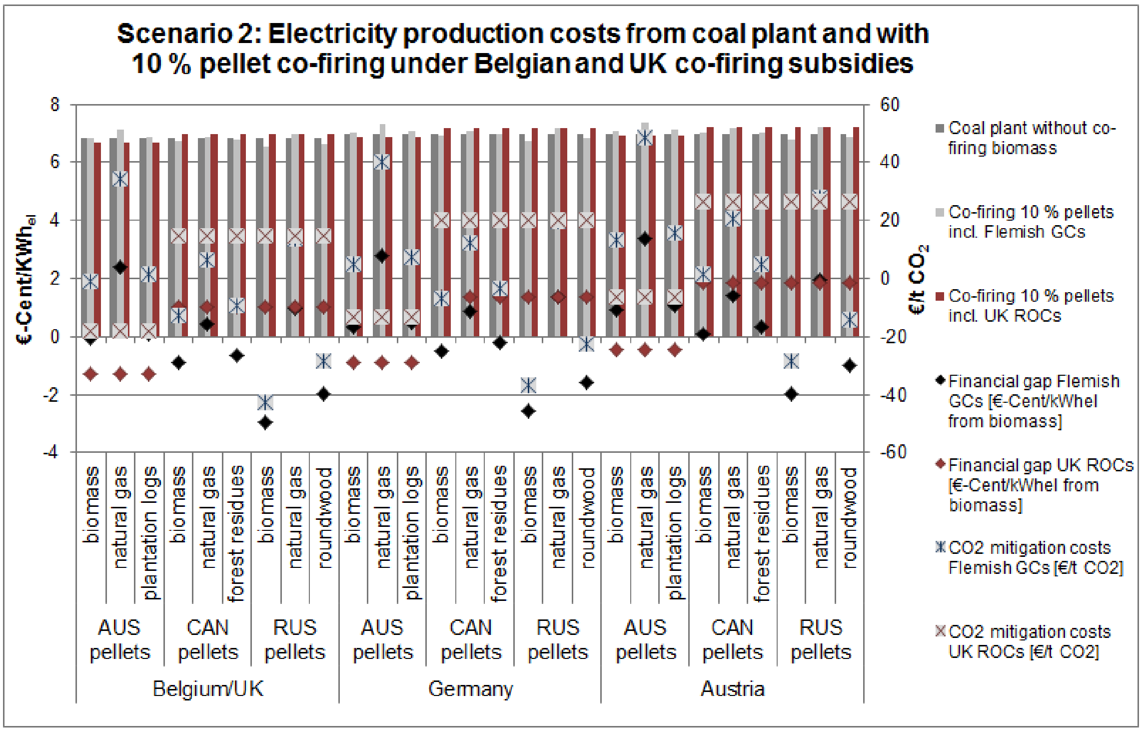

Figure 5.9: Electricity production costs under scenario 2 (moderate fuel and CO_2 prices)

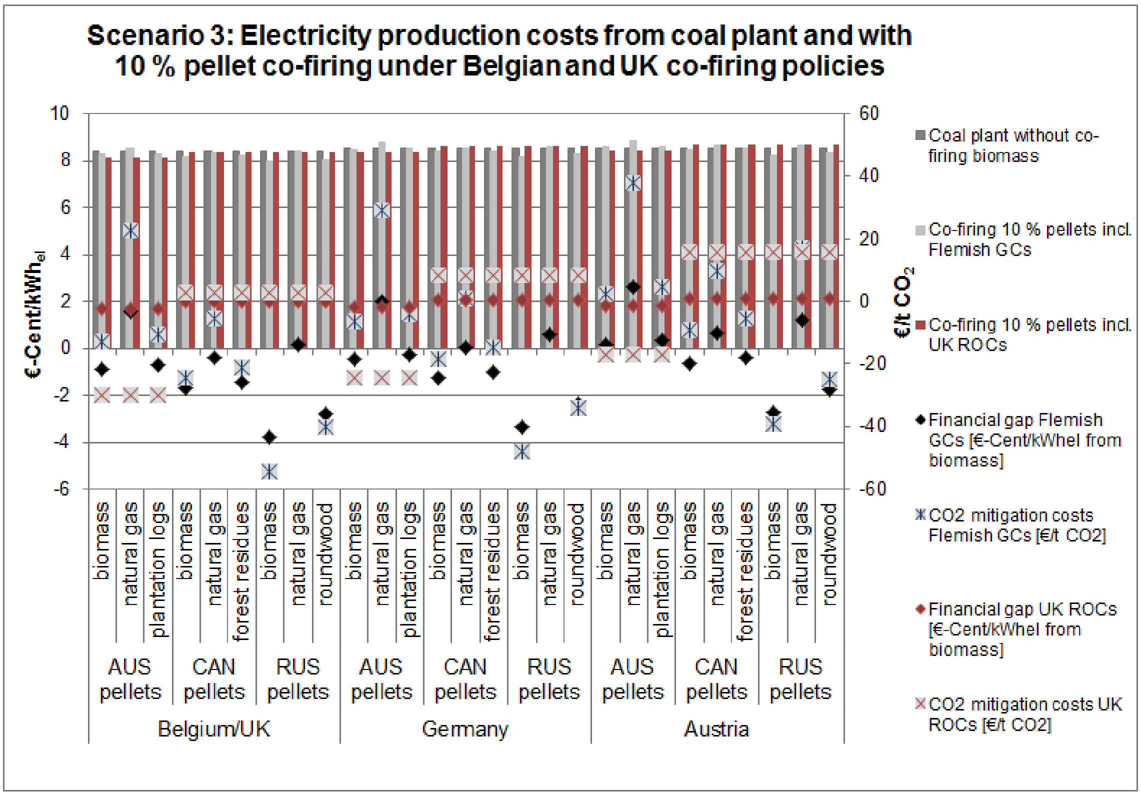

Figure 5.10: *Electricity production costs under scenario 3 (high coal and CO_2 prices)*

Comparison of co-firing with other expenditures on renewable electricity

Figure 5.11 gives an outline of cost ranges for different renewable electricity (RE) technologies referenced by the International Panel on Climate Change (IPCC, 2012) [31]. For comparison, the results from the base case analysis (without funding) are included. With a cost range between 1.7 and 6.8 €-Cent/kWh$_{el}$ [168], co-firing is one of the cheapest renewable energy technologies available. Only hydropower, onshore wind or geothermal energy can demonstrate cheaper alternatives when considering the minimum production costs, starting from 1.4 €-Cent/kWh$_{el}$ (hydro), 2.9 (geothermal) and 3.4 €-Cent/kWh$_{el}$ (onshore wind). In contrast, electricity from photovoltaic (PV) is the most expensive technology with costs between 13 and 53 €-Cent/kWh$_{el}$.

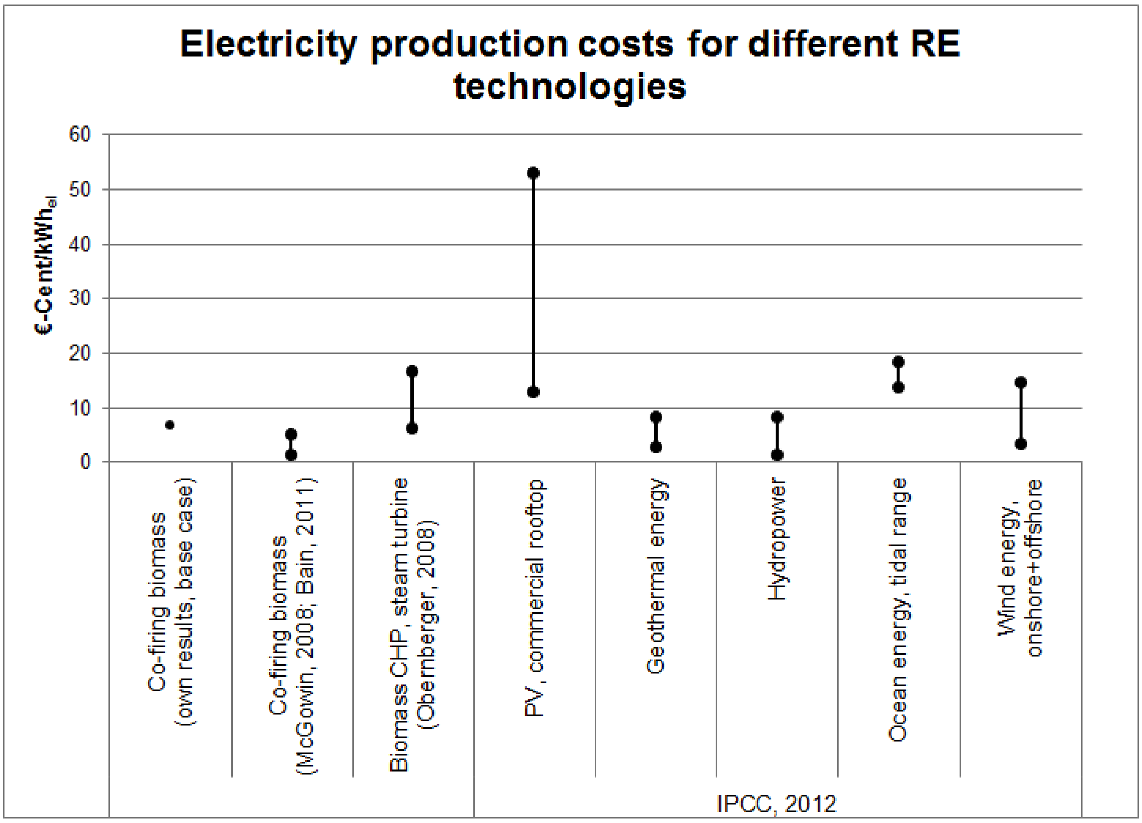

Figure 5.11: *Electricity production costs for different renewable energy (RE) technologies Sources: own results, [31, 168–170]*

In terms of CO_2 mitigation, co-firing implicates costs between -43 and 59 €/t CO_2 (Figure 5.12). Most other state-of-the-art renewables (compared to a reference electricity generation mix) are more expensive with 50 to 166 €/t CO_2 for biomass power [110, 171], for wind power with 60 to 100 €/t CO_2 and for PV with 300 to 950 €/t CO_2 ([36, 171]. Only small hydropower in Austria [171] and the current price for EU emission allowances [107] allow for comparably low mitigation costs.

As evaluated in Section 5.3.2, the financial gap for co-firing (see Figure 5.13)

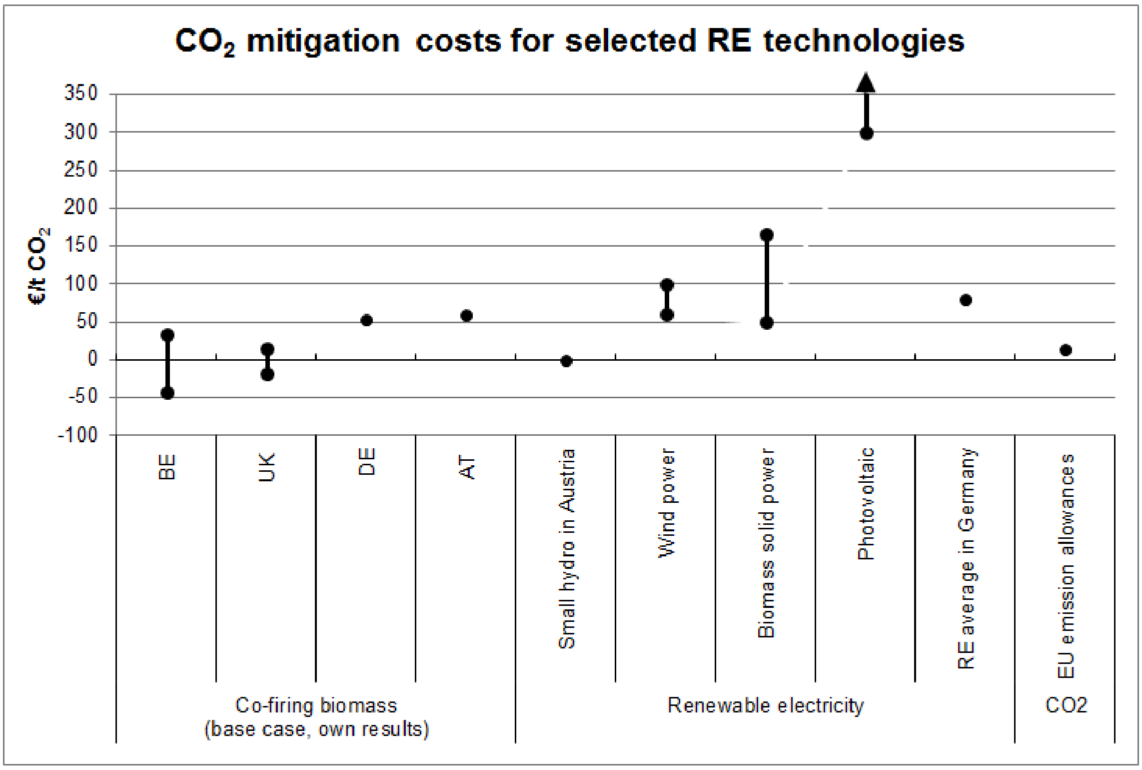

Figure 5.12: *CO_2 mitigation costs for co-firing biomass (reference coal plant) and selected renewable energy (RE) technologies for power generation (compared to natural gas or respective expenditure on support payments)*
Sources: own results, [36, 107, 110, 111, 171]

is between -3 €-Cent/kWh$_{el}$ (Flanders) and 4 €-Cent/kWh$_{el}$ (Austria). Compared with the current electricity support for renewables [103, 113, 172, 173], highest grants are spent on PV with 6 to 24 €-Cent in Germany, 8 to 26 €-Cent in the UK (supplementary to ROCs) and 50 €-Cent/kWh$_{el}$ in Austria, 5 to 13 €-Cent/kWh$_{el}$ for hydropower and 22 €-Cent/kWh$_{el}$ for geothermal power in Germany. When considering the relatively low biomass subsidies with 8 €-Cent/kWh$_{el}$ in Belgium and 2.5 to 5 €-Cent/kWh$_{el}$ plus 4 €-Cent for feed-in, co-firing biomass demonstrates a cost-attractive and low subsidised technology.

Therefore, the present study might serve as a supporting tool for policy makers in order to decide which sort of renewable energy technology should be promoted (via incentives or similar supports) from CO_2 emission reduction, economic constraints and sustainability point of view.

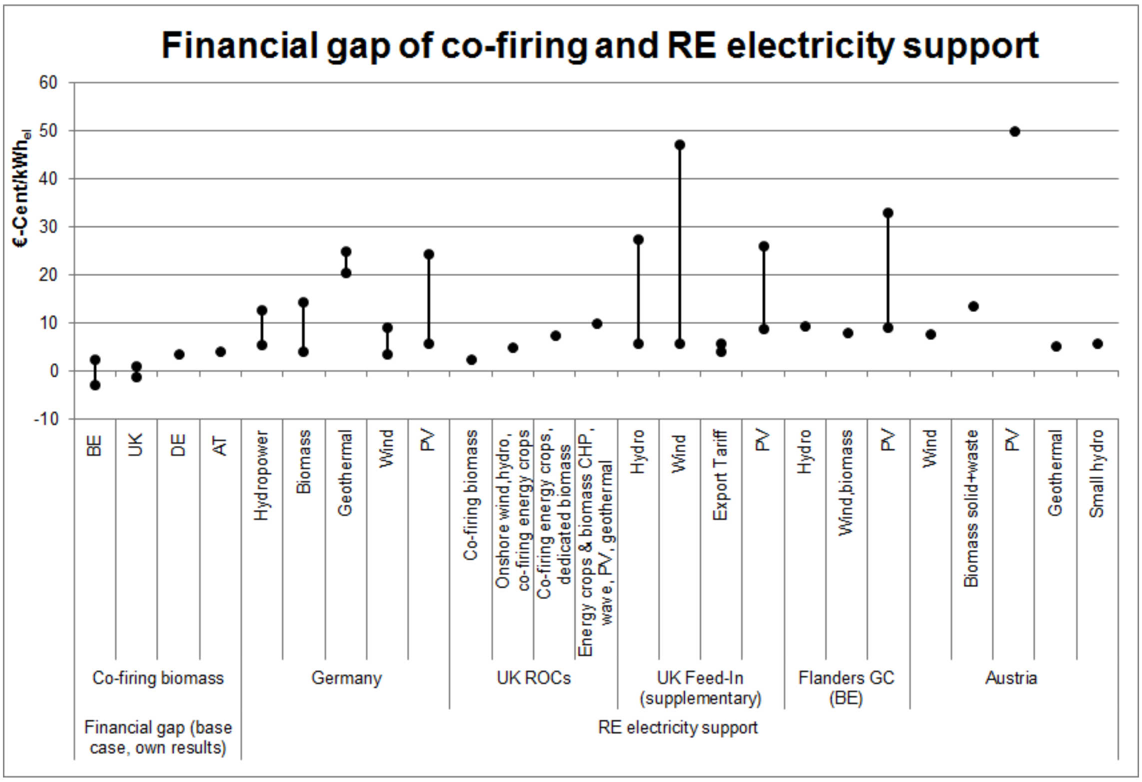

Figure 5.13: *Financial gap of electricity production costs from co-fired pellets against coal firing only (base case) and reference subsidies for electricity generation from renewable energy (RE) in Germany, UK, Flanders (BE) and Austria*
Sources: own results, [103, 109, 113, 173]

5.4 Price risks along the supply chains

5.4.1 Identification of most crucial price risks and related indices

Raw material

Availability of feedstock is directly dependent on (regional) forests, on supplying sawmills as well as the regional demand for the specific feedstock. Hence, pellet producers compete not only among themselves, but also against the wood industry (panel and paper) for the same wood assortments [20],(interviews according to Appendix B.1). Also, when not supplying sawmill residues to other industries, sawmills can convert it to heat and power for own utilisation. Bradley et al.(2010) [150] argue that the economic recession led to worldwide closure of sawmills, which resulted in drastically reduced supply of low-cost sawdust, and in transition to more costly harvest residues as pellet feedstock. Actually, pellet feedstock is increasingly getting scarce while brokers enter this market to capture supply. One approach of pellet producers must therefore be to purchase feedstock from multiple sources and providers [20,174]. Another approach is investing in energy crop plantations in warm climatic zones [10, 91].
Scarce data is available about biomass prices, because residues – the main feedstock for pellets – are not traded as commodity yet, and so market prices are not monitored. In the countries considered in this thesis, currently biomass residues from forests and industry are often available for free or at minor costs, so harvesting and delivery are main cost factors (interviews according to Appendix B.1). Nevertheless, for a statistical indication, national raw material indices for wood logs or the wood industry [120–122] (see Figures C.1, C.5, C.3 as appendices) are chosen as indicator for the price development for respective feedstock delivered to the consumer. That means any kinds of transportation efforts to the recipient are included here.

Pellet production

For the pellet production process the main risks are the raise of new capital, the technology investment at a certain location and in time, as well as the cost-effective operation [150], (interviews according to Appendix B.1). These technical and entrepreneurial issues should not be considered here. As a measurable price risk, natural gas as drying fuel in pellet production might have a considerable effect. Thus national price indices for natural gas are selected for investigation (see Figures C.2, C.6 and C.4 as appendices) [121–123].

Transportation and logistics

Transportation and logistics highly depend on the load volumes shipped, the frequency, utilised capacity of transportation routes and on the storage duration at transshipment sites, as discussed by Bradley et al.(2009) [42], Senechal et al.(2009) [175] and Sikkema et al.(2011) [87]. Mostly, the transportation over long distances is only economic when large volumes are shipped and return trips with the same means of transportation can be realised [158], (interviews according to Appendix B.1). As already mentioned in Section 5.1, the infrastructure for logistic operations is a crucial aspect with significant cost differences, depending on the availability of suitable port handling and loading equipment. Ocean shipping of pellets is operated by dry bulk transportation companies and generally underlies extremely fluctuating freight rates on a global scale. These variations influence operating costs for vessels, fuel, crews as well as the degree of matching supply and demand of transported goods, frequency of transport routes and available ship capacity [42, 48]. For maritime shipping, the Baltic Dry Index (BDI) is the common price indicator. It records current ocean shipping rates (including heavy fuel oil) for transporting dry bulk good on main and most frequented trade routes, reported from various market actors [126, 127].

Figure 5.14 shows the inflation adjusted annual rates, peaks and lows of the BDI and heavy fuel oil prices from 2000 to 2011. Within this period, the index shows remarkable fluctuations with the total peak (11,793 points) and total low (663 points), both in 2008. These are a result of the increasing global trade with goods, due to the enormous economic growth and trade in Asian countries and the lack of new shipping capacity to meet this demand. In particular, the strong fluctuation is also reflected by a variation of pellet shipping rates from Vancouver to Rotterdam between 35 and 100 US-$/t in 2009 [42, 150].

The actual freight rate for shipping pellets is usually fixed bilaterally in US dollar for every individual route, depending on volumes, utilised capacities and the contract period [147, 150], (interviews according to Appendix B.1). For the EU inland transport by train, no official indicator for price changes is available. Instead, the German transportation index for rail freight rates, starting from 2006, serves as a reference for the further analysis [128](see Figure C.8 as appendix).

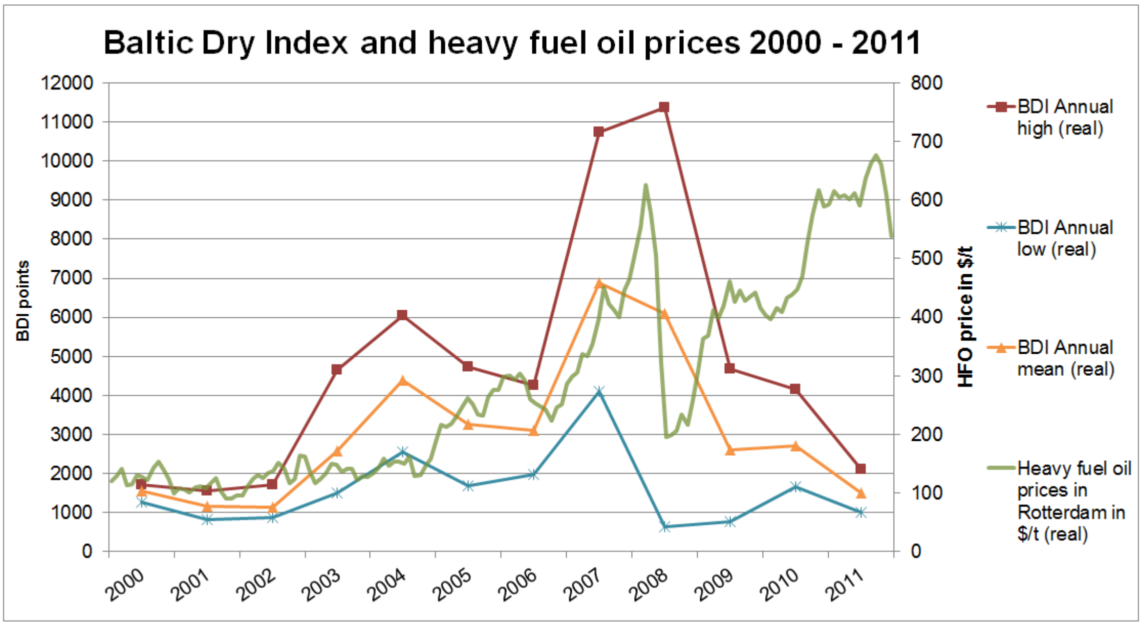

Figure 5.14: *Annual rates of Baltic Dry Index representing bulk shipping freight rates and heavy fuel oil prices between 2000 and 2011*
Sources: [126, 127]

Conversion in power plants

Industrial pellets in Europe are currently destined for power production, above all for co-firing in coal power units. Dedicated funding opportunities are the crucial economic aspect for co-firing as investigated by Ehrig and Behrendt (2013) [1]. Other competing factors are the price for fossil fuel to be substituted by use of pellets and the charged EU emission allowances (interviews according to Appendix B.1). The following analysis is based on the price developments for EU emission allowances and import hard coal (CIF ARA) reported by the energy exchanges EEX and bluenext from 2006 to 2012 [106,107,129]. As illustrated in Figure 5.15 and Figure 5.16, some correlation between coal prices and US-$/€ exchange rate as well as between prices of coal and EU emission allowances exists.

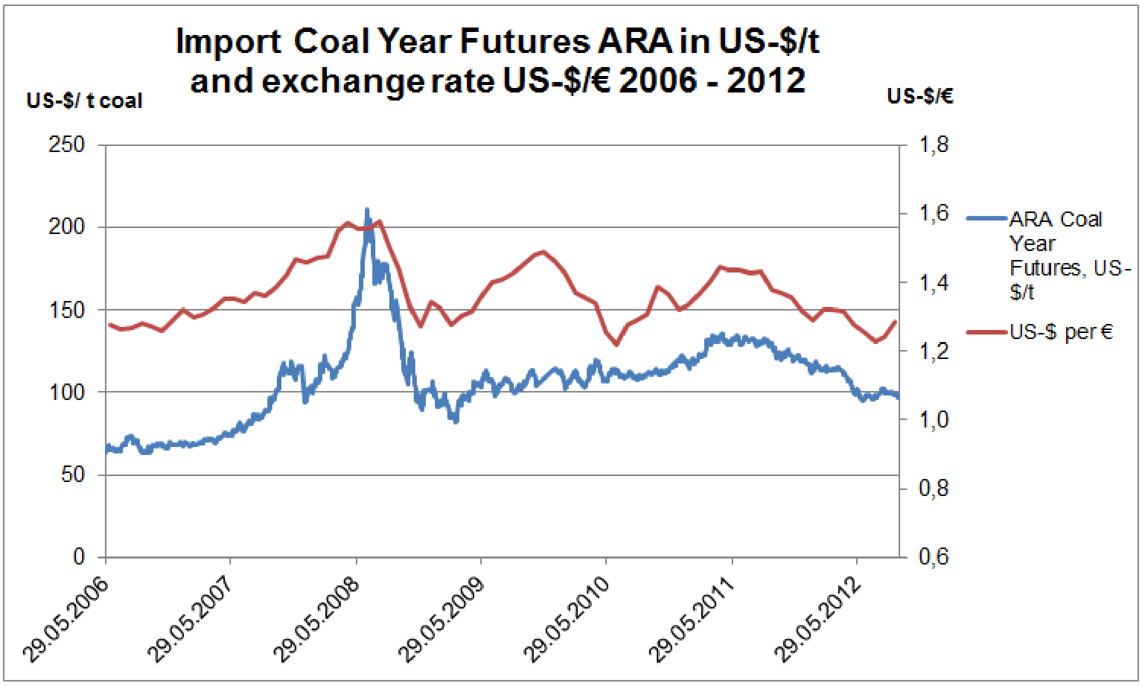

Figure 5.15: *Prices of coal year futures (1 year forward prices) traded at ARA ports in US-$/t and exchange rate US-$/€ 2006 to 2012*
Sources: [107, 108]

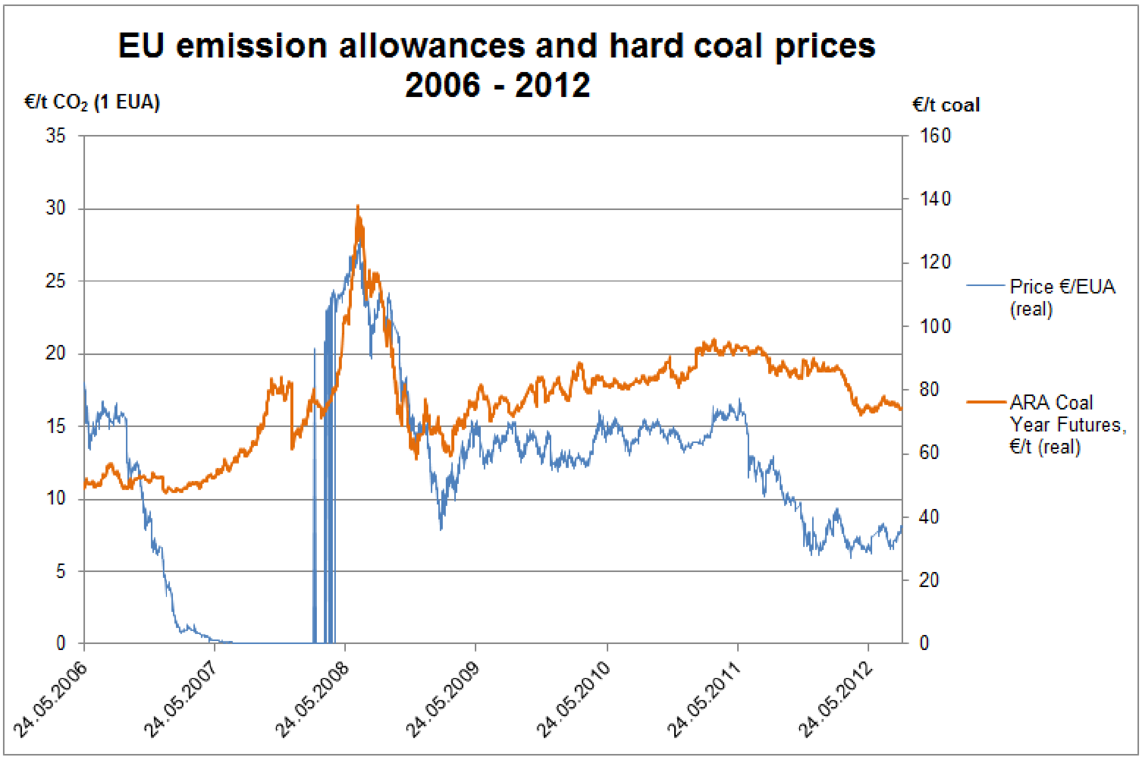

Figure 5.16: *EU emission allowances and German import price for hard coal 2006 to 2012*
Sources: [106, 129]

Prices affecting the whole supply chain

The upstream supply chain to export harbour is subject to varying exchange rates of the origin country's currency to Euro. The exchange rate data of AUS-$, CAN-$, US-$ and Russian rouble per € from the European Central Bank [108] are visualised in Figure 5.17 and Figure 5.18. For CAN-$ and AUS-$, a significant decline per € (or strong dollars to Euro) can be determined from 2009 to 2012. Based on average annual rates, the Australian dollar changed from 1.77 AUS-$/€ in 2009 to 1.35 AUS-$/€in 2011, which amounts to 31 % variation. That means, within this period Australian exporters have faced a crucial disadvantage for trades to the EU when contracts were set in €. The effect of exporters' impaired profit margins due to strongly variating exchange rates is well known from the trade with hard coal [89]. With a similar effect, the Canadian dollar per € declined 15 % in the same period with remarkable disadvantages for pellet exporters. As a result, even North American export prices in CAN-$/t have fallen since 2010 due to the weak Euro [10]. For the Russian rouble the opposite trend can be observed, with a 12 % increase of rouble per €, which means that purchase prices tied to € became more profitable.

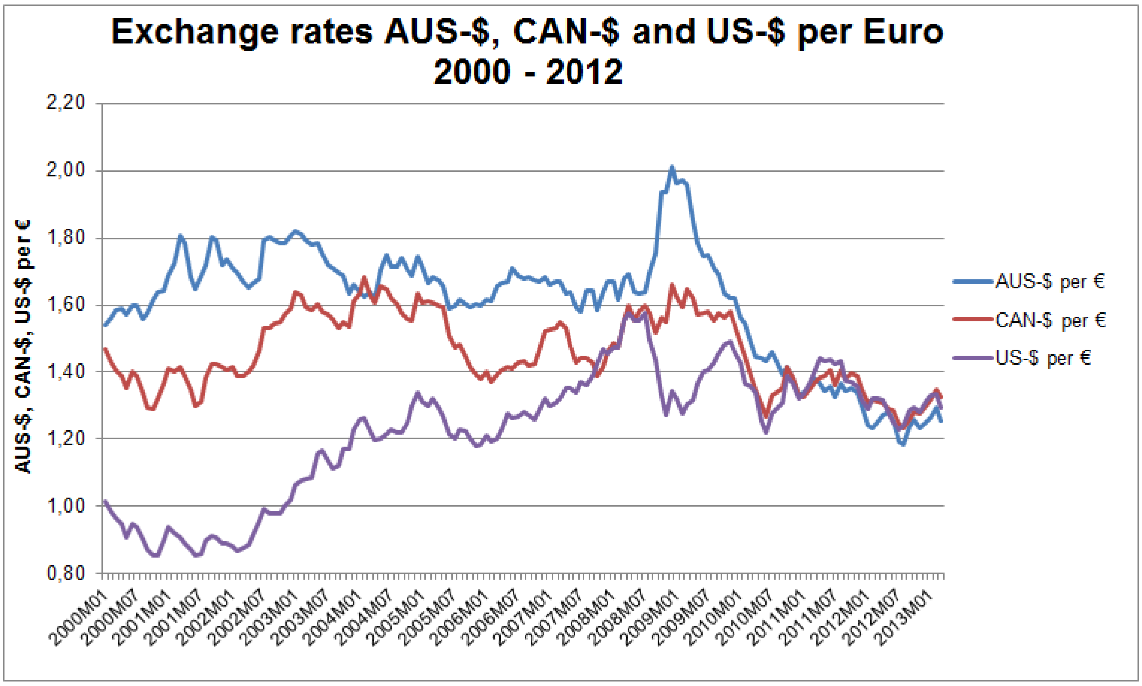

Figure 5.17: *Exchange rates AUS-$, CAN-$ and US-$ per € from 2000 to 2012, monthly data Source: [108]*

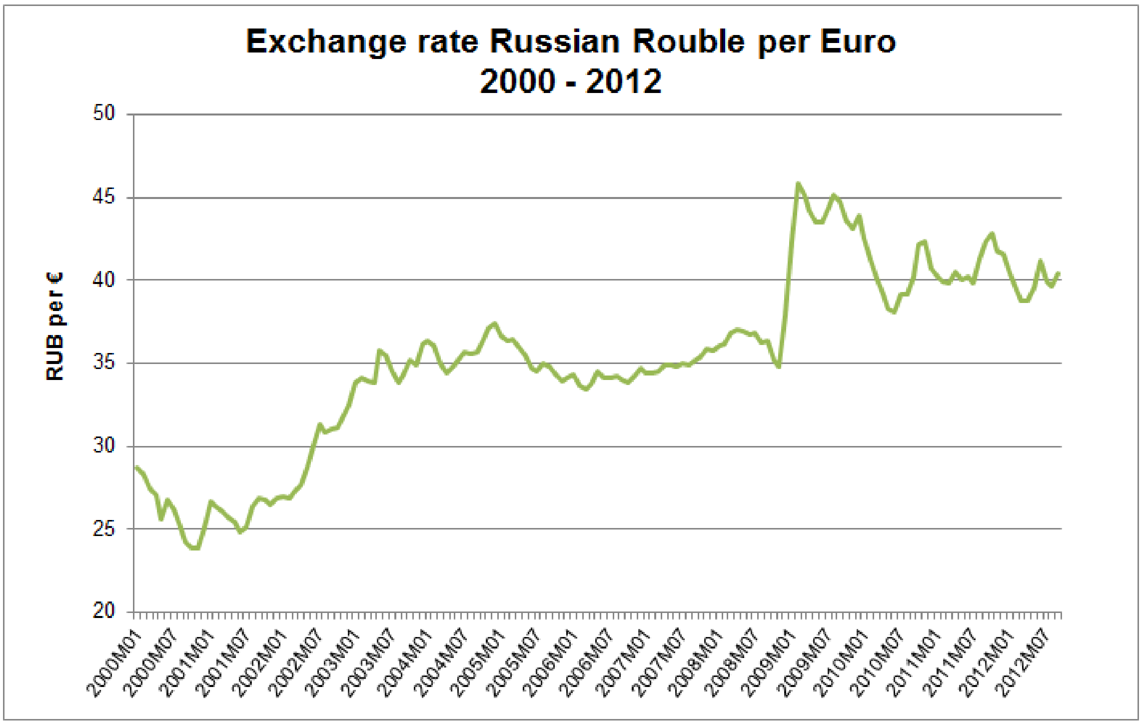

Figure 5.18: *Exchange rates of Russian rouble per € from 2000 to 2012, monthly data*
Source: [108]

Concerning the situation at the EU import harbour, the pellet supply price is determined by exchanges like APX Endex, which reports the actually set forward market prices in trades and orders for industrial pellets since beginning of 2008 at the ARA ports [19](see also Figure C.7 as appendix). The CIF ARA price development is presented in Figure 5.19 and compared with exchange rates € per US-$ and per CAN-$. There is correlation between pellet prices and US- and CAN-$, which might result from Canada and the USA as main pellet exporting countries to the EU. Besides, a general correlation exists among EU import energy prices traded in US-$, and among exchange rates in $ to € [176], which are also used as reference for pellet trade (interviews according to Appendix B.1). A slight shift between reported and actual pellet market prices results from the forward trade terms, which means the price is fixed one month ahead from supply (month+1).

Price data as for CIF ARA or at other pellet market places serve as reference within price negotiation between pellet exporters, traders and buyers (interviews according to Appendix B.1). These data are significant market indicators, even if the exchanges as market places have a limited amount of actors [87] due to few large power companies dominating the EU market. Besides, bilateral trade contracts and supply agreements between these actors predominate. Furthermore, it should be no-

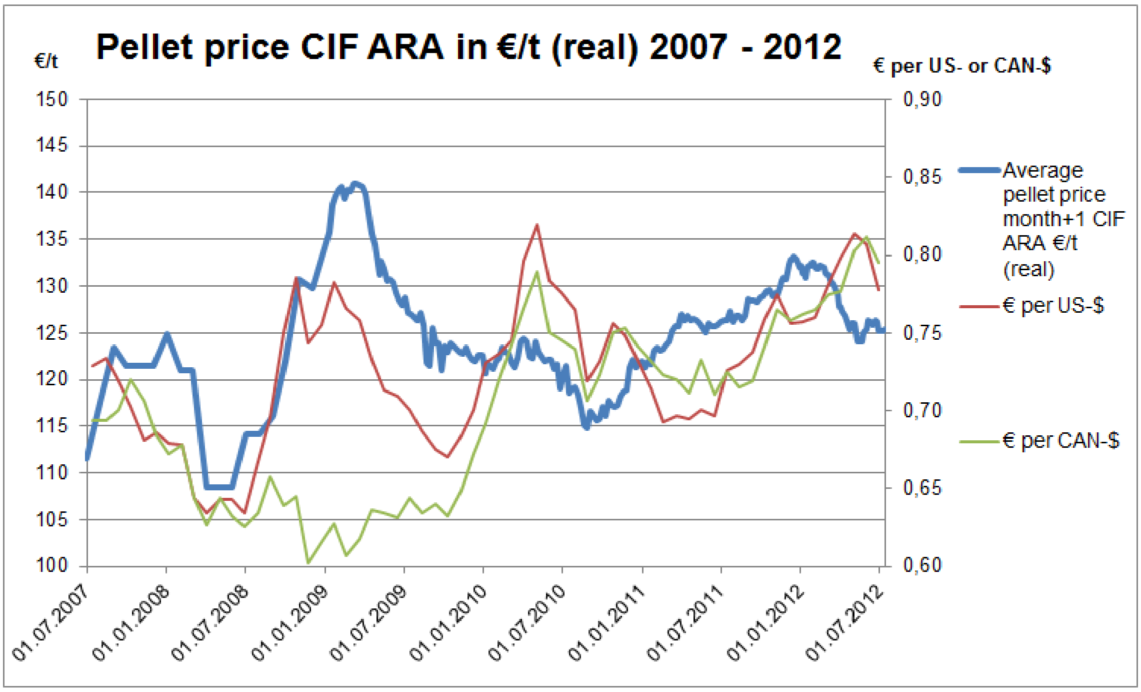

Figure 5.19: *Pellet price CIF ARA in €/t and exchange rates US-$ and CAN-$ to €*
Sources: [19] (pellet prices 2008 to 2012), [108], [177] (pellet data in 2007 are for the Netherlands)

ticed that the CIF ARA price does not reflect price determination within longer-term contracts [87]. As shown in Figure 5.20, there is a certain upward trend for both coal and pellet prices from 2010 to 2011. As found by Alakangas et al.(2012) [86] and visible here, often a time lag of a year or more occurs between fossil fuel price hikes and increases in pellet prices because of long-term decisions to switch from fossil fuel to bioenergy.

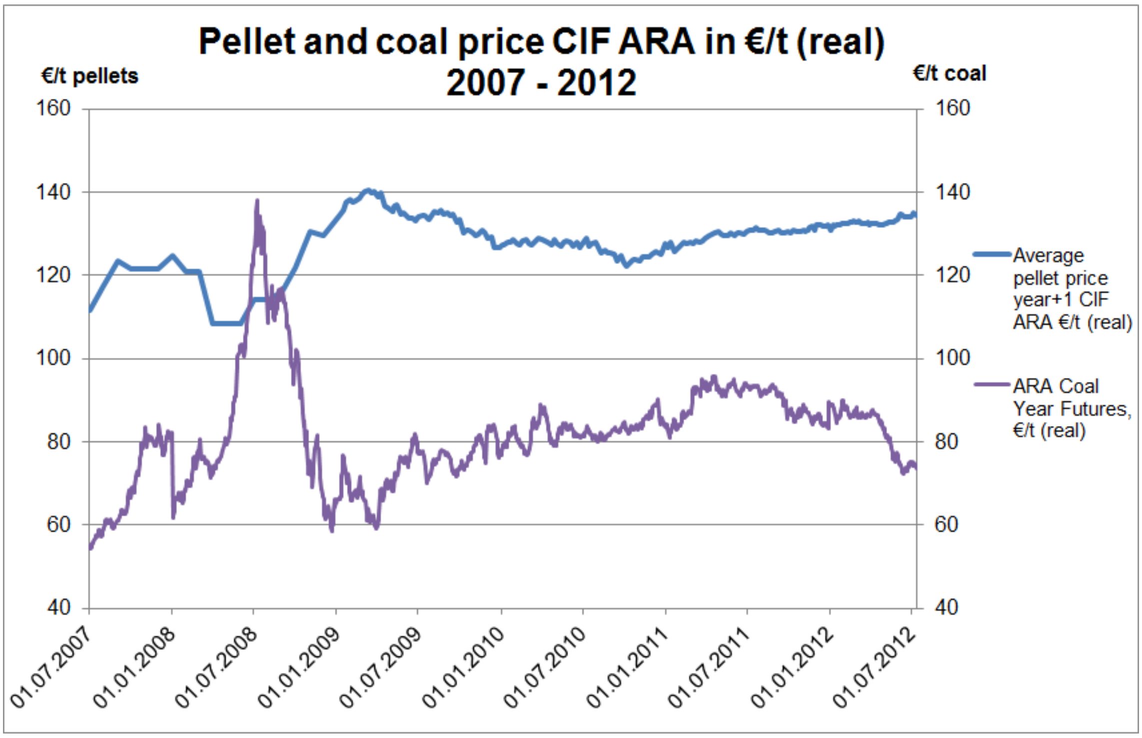

Figure 5.20: *Pellet and coal prices CIF ARA in €/t from 2007 to 2012*
Sources: [19, 106]

5.4.2 Modelling 10-year price variations

The price indices discussed in Section 5.4.1 serve as indicator for modelling latent 10-year price variations along the three pellet supply chains from Section 3. For all indices the standard deviation as well as the upward and downward ranges are calculated and described as percentage of the arithmetic mean, see Table 5.10.

Table 5.10: *Standard deviation, lower and higher range limits of 10-year historic index values*

Index	**Standard deviation** (σ)	**Lower range limit** (R_-)	**Upper range limit** (R_+)	**Data source**
Wood chipping index Australia	8 %	88 %	113 %	[120]
Raw material index, logs and bolts, softwood, Canada	6 %	86 %	112 %	[121]
Wood product and manufacturing index Russia	9 %	94 %	105 %	[122]
Natural gas wholesale prices Australia	20 %	75 %	135 %	[123]
Natural gas consumer price index Canada	6 %	87 %	110 %	[124]
Natural gas consumer prices industry Russia	3 %	94 %	105 %	[125]
Exchange rate AUS-$ – €	8 %	82 %	108 %	[108]
Exchange rate CAN-$ – €	6 %	92 %	109 %	[108]
Exchange rate RUS rouble –€	13 %	73 %	124 %	[108]
Exchange rate US-$ – €	6 %	92 %	109 %	[108]
Baltic Dry Shipping index (adjusted to €-equivalents)	48 %	43 %	201 %	[126, 127]
EU pellet market price	5 %	86 %	112 %	[19]
Freight rate index EU	0.9 %	99 %	102 %	[128]
Hard coal EU	32 %	57 %	159 %	[106, 115]
CO_2 emission allowances	30 %	0.1 %	211 %	[129]
Basis: 10-year time series of indices based on their annual average values (5 years Russian data, EU pellet market price and transport EU, 7 years CO_2 emission allowances). Inflation adjusted with national consumer price indices from Eurostat [119] values are indicated in % of arithmetic mean of historic values				

As defined in the methodology (Section 4.5.2), these price variations are integrated into the respective cost components of the supply costs from assessed case studies (cp. Section 5.3.1). As a result, the varying supply costs from Canada, Australia, and Russia (free EU conversion plant) are illustrated in Figure 5.21, Figure 5.22 and

Figure 5.23 for all chains with natural gas for drying (NG). As shown, the imputed variations based on the raw material indices are minor. On the one hand, this is due to the quite low share of raw material costs on total supply costs. On the other hand, these results show that the existing raw material indicators allow only little conclusion about the real cost variations for pellet feedstock (cp. Section 5.4.1). Thus, the issue of actual feedstock market prices will be further discussed in Section 5.4.3. Also minor influence results from the natural gas prices as marginal costs within the whole supply chain.

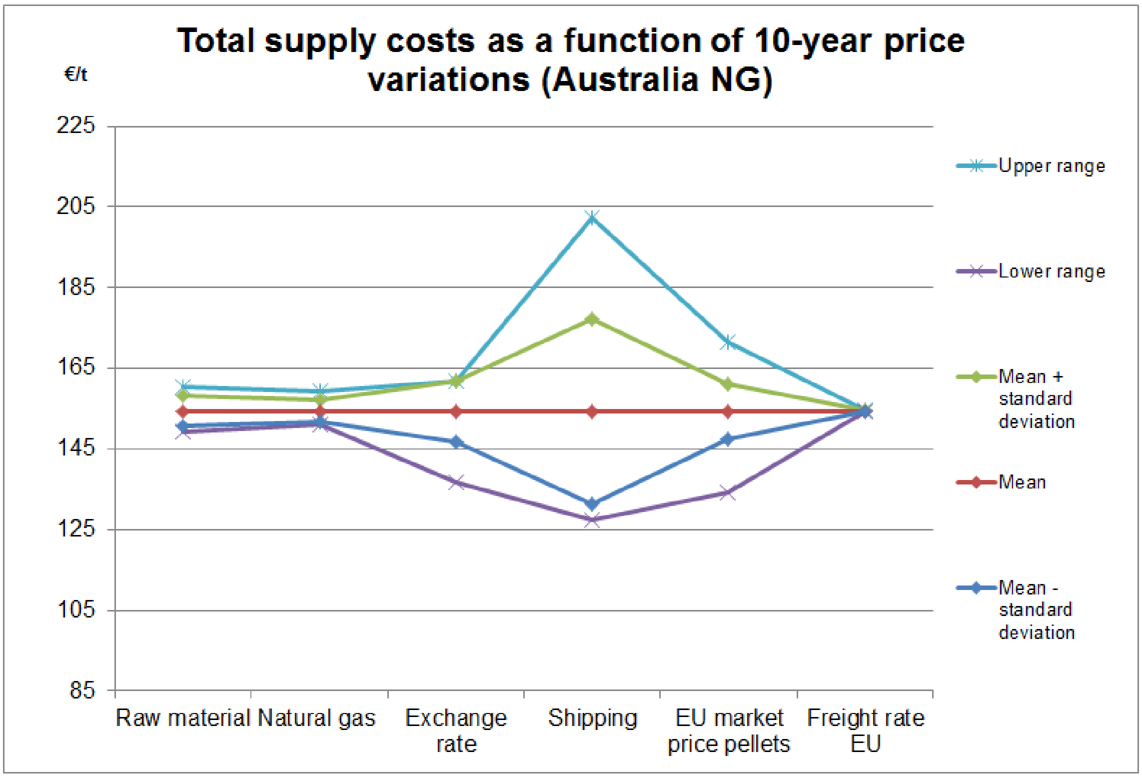

Figure 5.21: *Supply costs for Australian pellets to the EU, subject to 10-year price variations*

The exchange rate indicates only slight variations between 4 % (σ) and 6 % ($R_{\pm}$) for the Canadian pellet supply to the EU. For the other cases a more significant effect from 5 % (σ) to 12 % (R_{-}) for Australian supply and between 10 % (σ) and 20 % (R_{-}) for the Russian supply chain can be determined.

Varying shipping freight rates turn out to have the strongest influence on prices. Depending on the share of freight costs for the total supply costs, they cause a price range of between 17 % (σ) and 36 % (R_{+}) for the total Australian and Canadian supply chain or, due to minor share of freight costs, between 9 % and 18 % for the total Russian supply chain.

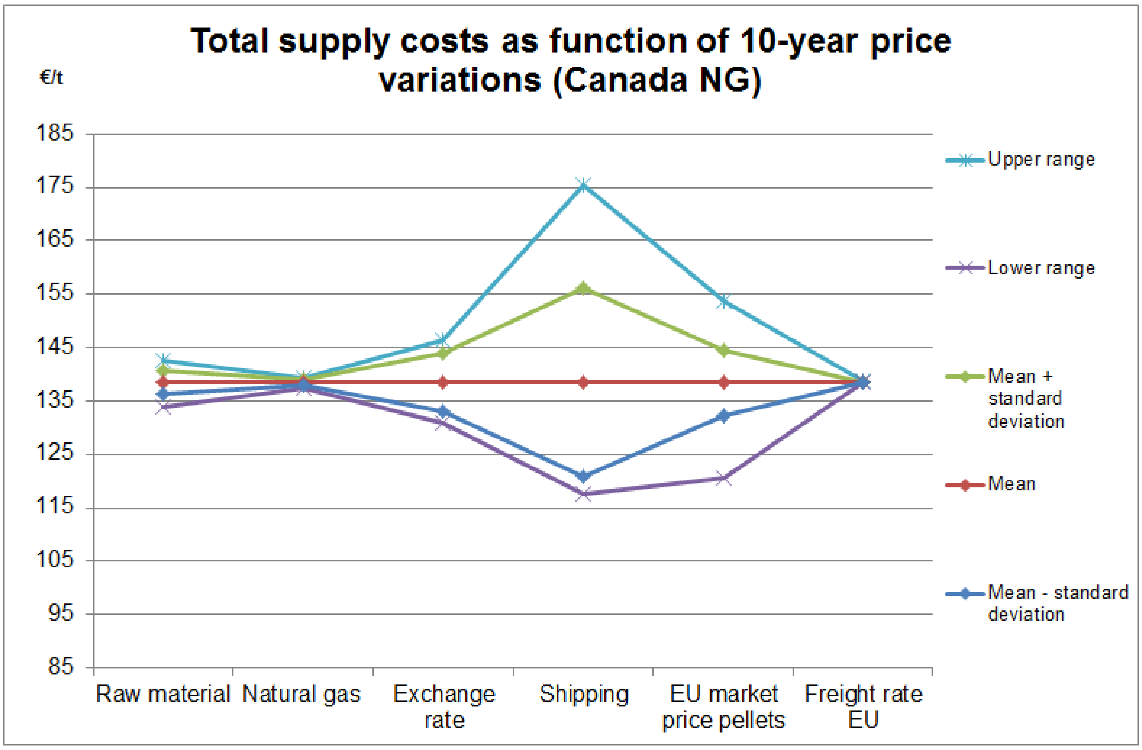

Figure 5.22: *Supply costs for Canadian pellets to the EU, subject to 10-year price variations*

The EU market price for industrial pellets causes 5 % (σ) to 14 % (R_-) variations in supply costs. With that, it shows only little variation compared to the preceding price risks, which are integral part of the EU market price. Inland EU freight rates turn out to have minor impact on supply costs.

The influence of fuel price variations on electricity costs is shown in Figure 5.24. For the pellet supply prices three different kinds of upstream prices are distinguished:

- Raw material and shipping index,
- Exchange rate fluctuations and shipping index,
- EU market price.

The standard deviation of electricity generation costs for burning 10 % pellets and 90 % coal is between 15 and 17 % of the mean costs. As for the pellet supply costs, the lower and upper ranges of co-firing costs are significantly more pronounced with 30 (R_-) to 140 % (R_+) of mean values. 100 % coal firing (subject to coal and CO_2 price fluctuations) can cause higher fluctuations with 22 to 143 % range in the given period. Consequently, even when only 10 % of fuel input are represented by pellets,

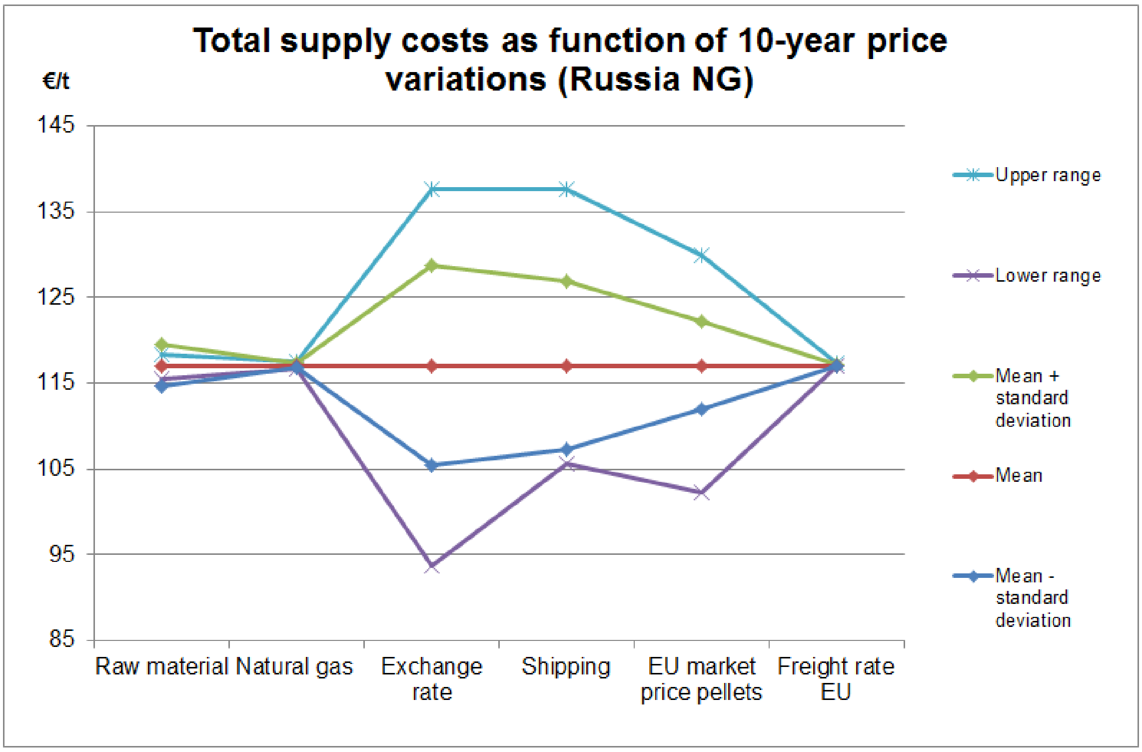

Figure 5.23: *Supply costs for Russian pellets to the EU, subject to 10-year price variations*

the fuel price risk can be reduced by co-firing. Beyond, the three kinds of pellet price composition differ only slightly from each other.

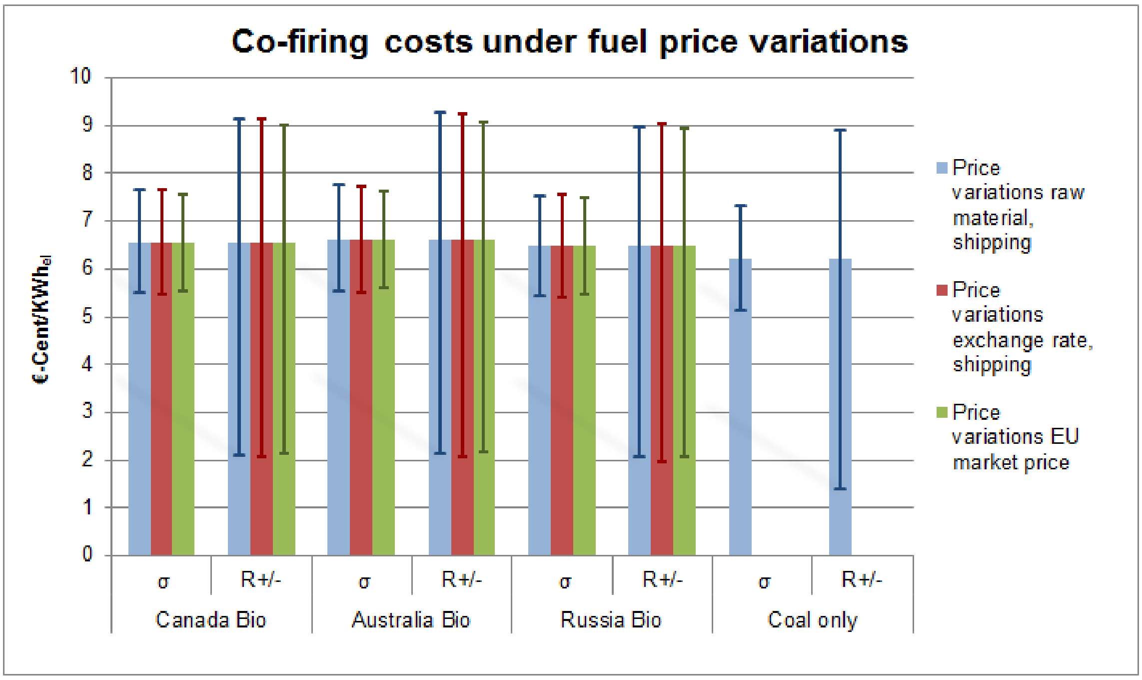

Figure 5.24: *Co-firing costs in EU coal power plant (90 % coal, 10 % pellets) under fuel price variations (raw material and shipping, exchange rate and shipping, CIF ARA price)*

5.4.3 Simulation of recent 3-year price fluctuations on supply costs

Besides purchases on the spot or forward market, long-term supply contracts over 3 years (or longer) are very common in the industrial pellets market [87], (interviews B.1). Moreover, in the very young pellet sector, recent market developments have shown extreme fluctuations within a relatively short time. Therefore, the following analysis simulates relevant price changes within a 3-year supply period, i.e. the situation between 2008 and 2011. As the use of natural gas for drying turned out to have minor influence (cp. Section 5.4.2), only cases with biomass for drying (Bio) are considered here. For the same reason, EU transport costs are excluded here, i.e. the supply price at EU import harbour is the reference.
First, the influence of exchange rates on supply costs is described. From 2008 to 2011, the annual increases of Canadian and Australian dollar against Euro caused a 12 % (Canada) to 21 % (Australia) increase of export supply costs. This results in 8 % to 15 % increased total pellet supply costs to Europe by 2011 compared to 2008, see Figure 5.25 and Figure 5.26. In contrast, the Russian rouble was devalued against the Euro, which resulted in 10 % reduced supply costs for Russian pellets in 2011, see Figure 5.27, column B. By knowing that the Australian and North American pellets export to the EU was strongly affected by exchange rate fluctuations [139, 149], one can approve the evidence by Auboin and Ruta (2011) [178] that exchange rate volatility has a significant (negative) effect on trade, especially for differentiated products like pellets. This aspect is supported by the fact that general imports from these countries to the EU dropped in the strong dollar years while Russian imports rose [11].

A negative situation as mentioned above can have extreme effects when regarding the case of simultaneously occurring, positive or negative annual changes: Within the 2008 to 2011 period, exchange and shipping rates together resulted in a range of 66 to 157 % of the 2011 base price, with most pronounced ranges for Australian pellets, see columns B and C in Figures 5.25, 5.26, 5.27. Thus, freight rates alone can easily turn supply costs to uneconomic, but also to more profitable values. Increased raw material costs (D) can effect a 16 to 30 % increase of total supply costs, whereas this rise is reduced in Canadian or completely compensated in Australian supply, when the exchange rate falls back to 2008 values (columns E). For Australia, the use of low cost sawdust could even turn the 2011 supply costs into positive values. In contrast to these huge variations, the EU pellet import price CIF ARA reflects just

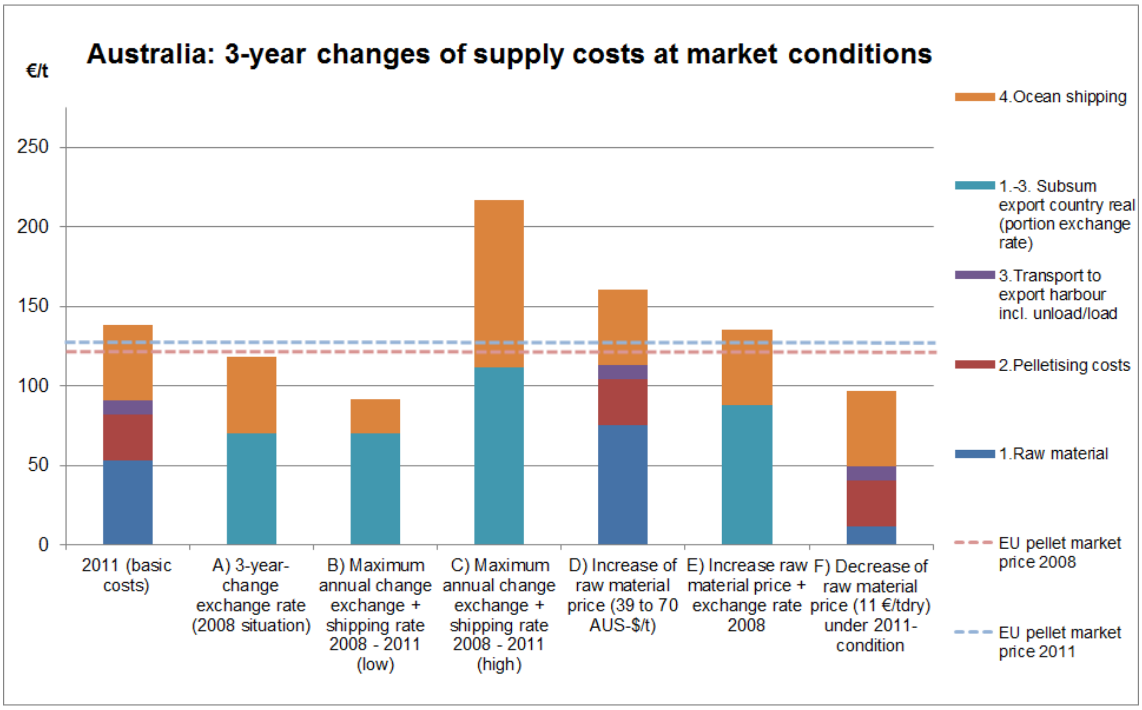

Figure 5.25: *Projection of 3-year changes on supply costs for Australian pellets exported to the EU*

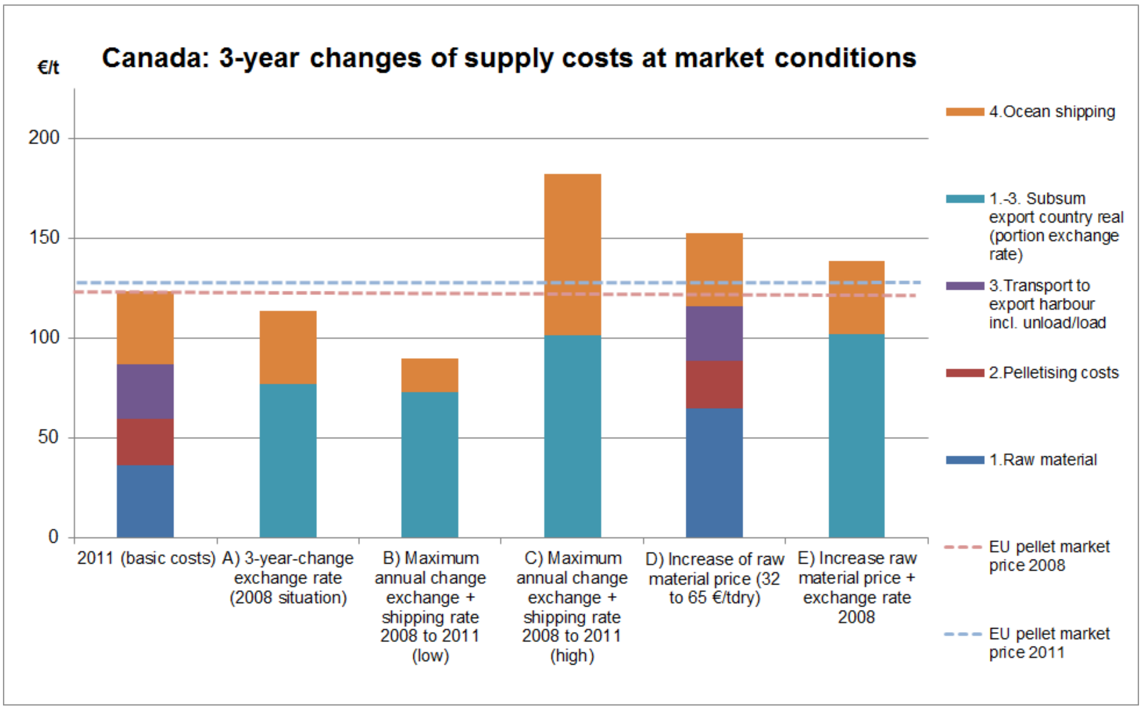

Figure 5.26: *Projection of 3-year changes of supply costs for Canadian pellets exported to the EU*

minor volatility with $\sigma = 5\,\%$ and $R_{\pm}$ between 86 and 112 % of total costs within these 3 years.

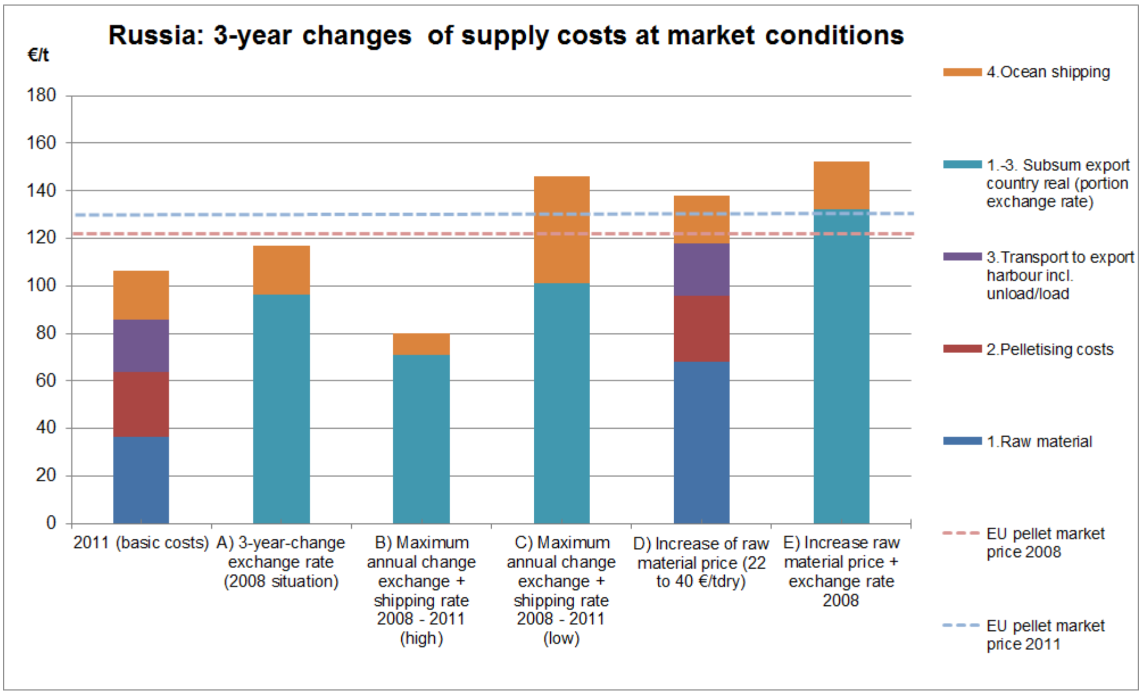

Figure 5.27: *Simulation of 3-year changes of supply costs for Russian pellets exported to the EU*

A rough comparison of average hard coal supply costs imported to Europe in 2006/ 2007 with these in 2011 is given in Figure 5.28. For approaching the costs for the year 2011, the variation of exchange rates from 2006 to 2011 is included in projected 2011 costs. As for pellet supply costs, hard coal supply from Australia has become more costly in €-equivalents, which means less profit margins for exporters. In the same time, actual freight rates for hard coal shipped from Australia to Europe [132] have decreased from 41 €/t in 2007 to 14 €/t in 2011, which corresponds to the trend of the Baltic Dry Index and related shipping rate variations demonstrated for pellet supply chains. As for pellets, supply costs for hard coal from Russia to Europe are reduced by the exchange rate difference, meaning less costs for Russian exporters. The achievable hard coal import costs CIF Northwest Europe for 2007 as well as 2011 show that there is a much higher profit margin than for pellets. Furthermore, the gap between US-$ as trading currency and export currencies like AUS-$ and CAN-$, as stated by Ritschel and Schiffer (2007) [89], was narrowed within the recent years (cp. Section 5.4.1 and Figure 5.17). That means, for the trading currency US-$, profit margins of exporters in these countries were less affected by exchange rates.

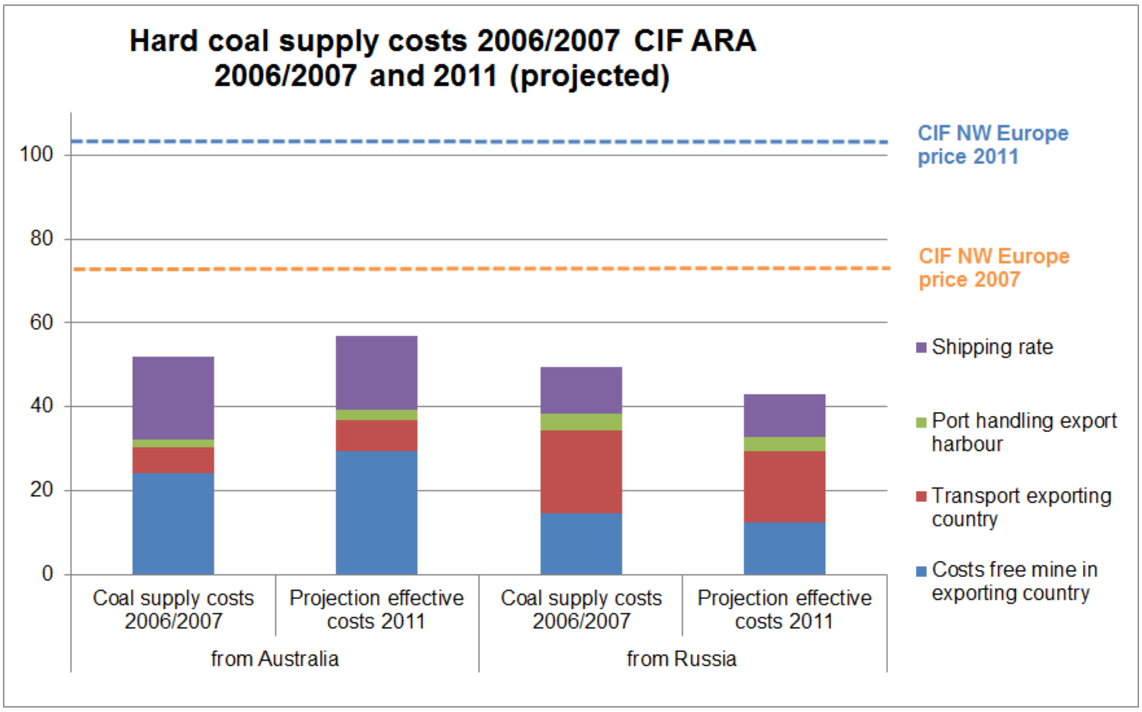

Figure 5.28: *Supply costs for imported hard coal from Australia and Russia to Europe for 2006/2007 and projected changes to 2011*
Sources: [89, 132]

5.4.4 Sensitivity against pellet plant operation, raw material prices and exchange rate fluctuations

As discussed in the methodology (Section 4.5.4), the operating hours of a pellet plant is a sensitive issue affecting the economics during the production phase. In Figure 5.29 the total supply costs for all three pellet origins, subject to variating operating hours of pellet production, are presented. For all three pellet origins, a similar rise in production costs is taking place when less annual operating hours can be reached. Pellet production costs alone are rising by 6 to 7 % when 6000 h/a instead of 8000 h/a are realised. When the capacity even drops to 4000 h/a, production costs increase by 12 to 15 %. That means, an insufficient utilisation of capacity has immense economic impacts for the plant operator. These presented relations correspond to the findings by Obernberger and Thek (2010) [47], who examined the influence of operating hours on specific pellet production costs in Austria. They state 8000 h as maximum applicable operating hours per year. According to the increase of pellet production costs, total pellet supply costs to EU import harbour are influenced and increase with less capacity used. For 6000 h/a instead of 8000 h/a, supply costs are 3 to 4 % higher. 4000 h/a effect a 6 to 9 % increase of total supply costs.

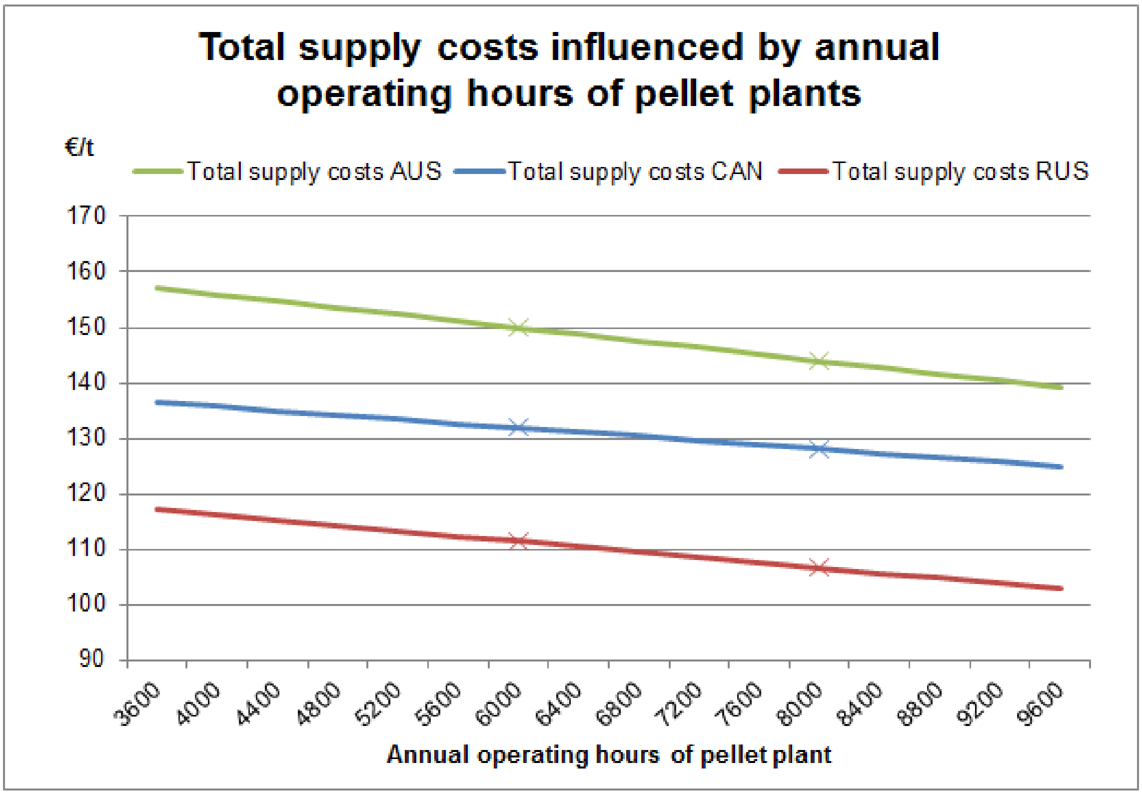

Figure 5.29: *Total supply costs influenced by operating hours of pellet production, base value for calculations = 8000 h/a, value often applied in Europe: 6000 h/a*

As analysed before in this Section, raw material prices have a crucial effect on the total pellet economics. The detailed variations in a -40 % to +40 % range of base prices are illustrated in Figure 5.30. When raw material can be purchased to a 20 % less (higher) price, 5 to 6 % less (higher) total supply costs are effected, while a 40 % increase (decline) means 10 to 12 % higher (less) supply costs to Europe. For the pellet producer, 20 % variation means 6 to 10 % higher or less production costs, while 13 to 15 % higher (less) product costs result from a 40 % increase (decrease) of raw material prices. Comparing the sensitivity results for pellet production costs assessed by Uasuf (2010) [40] and Obernberger and Thek (2010) [47], similar variations and trends can be determined.

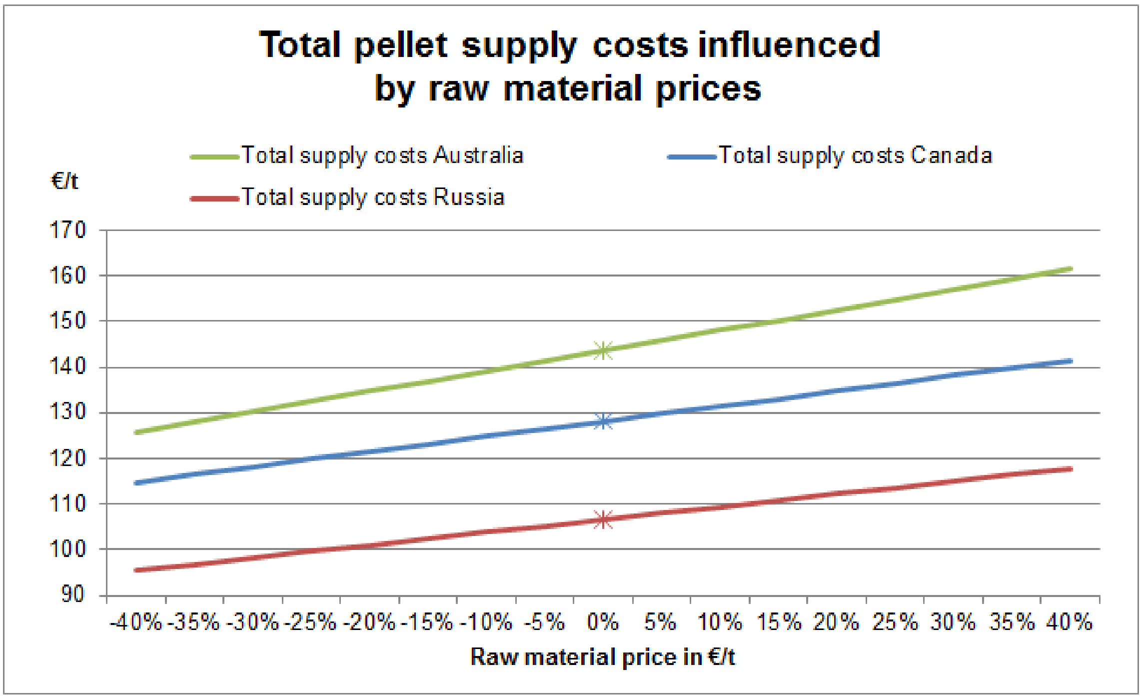

Figure 5.30: *Total supply costs influenced by raw material price changes in percentage of base prices*

The influence of exchange rate variations on total supply costs is presented in detail in Figure 5.31. While a 5 % variation of export country currency to Euro has a 3 to 4 % effect on total supply costs to Europe, 20 % exchange rate fluctuation results in 13 to 16 % change and 40 % fluctuations in up to 32 % changed supply costs. For the respective exporting countries, these effects are of course even more pronounced and cruicial for the trade economics, when the trade currency or achievable EU import prices are set in Euro.

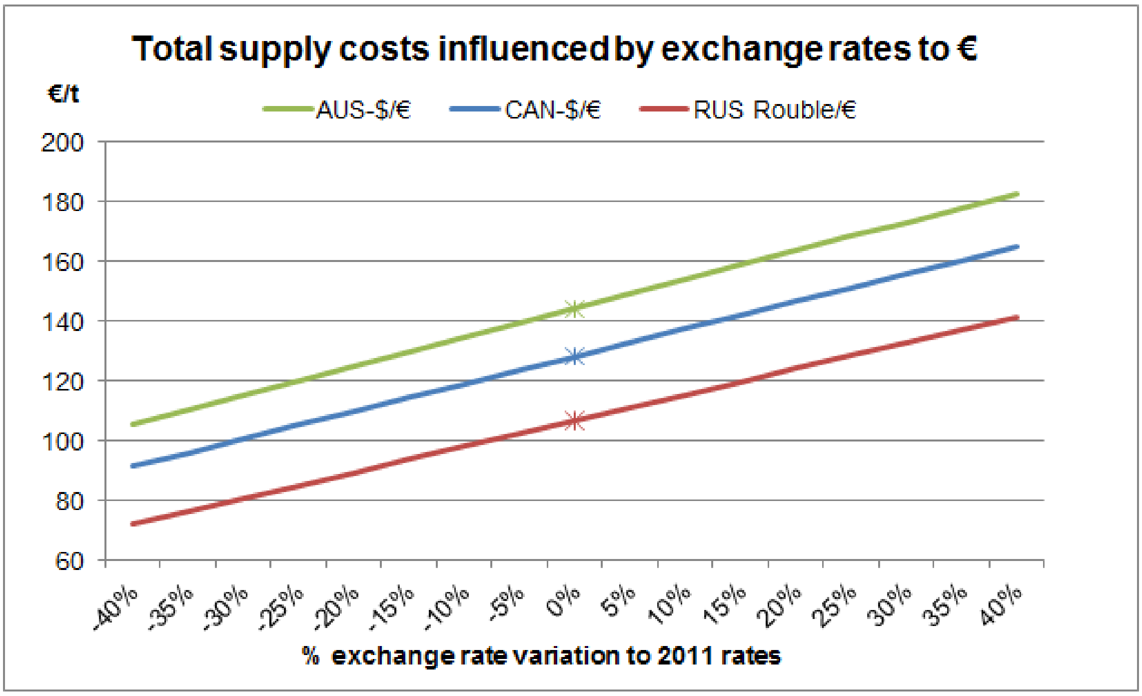

Figure 5.31: *Total supply costs influenced by exchange rate flucations in percentage of 2011 rates*

5.4.5 Concluding risks and related hedging strategies

In this Section, most significant price risks, relevant aspects and respective hedging strategies – based on the previous discussion (Sections 5.4.1 to 5.4.3) and interviews with market players – are summarised in Table 5.11. The categories follow the previously applied supply chain pattern from raw material to conversion and cross-cutting aspects. Listed aspects and de-risk measures comprise both issues already implemented and those proposed or in planning.

Table 5.11: *Price risks and related hedging strategies along international pellet supply chains Sources: own results from previous sections, supplemented with literature results [1, 20, 85, 87, 88, 150, 174, 178], interviews according to Appendix B.1*

Supply chain pattern	**Price risks**	**Relevant aspects and indicators**	**Hedging and de-risk strategies**
Raw material	• Availability of feedstock in suitable quality, (just-in-)time, to certain amount, and to reasonable price • Price setting among feedstock suppliers	• Supply and demand for feedstock in competing industries • Resource potentials • Regulatory framework • Monitoring of raw material prices and indexes, if available	• Long-term indexed contracts with feedstock suppliers • Multiple feedstock sources • Involvement in resource production • Agreement on price collars • Controlling volumes and quality of feedstock
Pellet production	• Fuel price fluctuations • Investment risk • Delays in operation start • Operation and maintenance performance	• Raw material and fossil fuel prices • Financial security (equity) • Experienced operation staff and sector networks	• Preferring long-term and upfront supply contracts • Reduction of production costs • Build aggregation network of producers and buyers for optimised pellet allocation • Domestic purchase of pellets as back-up solution
Transport and logistics	• Freight rate volatility • Expensive transportation • Suitability of transport, handling and storage equipment and facilities • Sufficiency of storage capacities • Quality loss in the logistics trajectory	• Global economic development • Use of highly frequented routes • Logistical capacities • Seasonal access of inland waterways • Logistical access to producer site & end-user • Standards on durability and fines of pellets	• Freight rates concluded with freight operators, fixed over supply period • Extend storage capacities at export and import harbours • Upstream investments (storage capacity, port equipment, biomass specific transportation means) • Implementation of standards on biofuel handling, logistics and storage

continued on next page

Supply chain pattern	Price risks	Relevant aspects and indicators	Hedging and de-risk strategies
Conversion/ End-use	• Prices of fossil fuel (coal) to be substituted • CO_2 prices • Storage capacities at conversion plant • Price setting among few large consumers	• Fuel and CO_2 price development • Just-in-time delivery of fuel in certain quality and volumes • EU energy and emission policy	• Minor retrofit costs allow for flexible fuelling of co-firing plants, thus low investment risk • Access to regional biofuel as back-up • Approved monitoring of market prices
Cross-cutting aspects affecting the whole supply chain	• Economic stability of export country • Market price of pellets and fossil fuels • Regulatory framework • Evolving sustainability requirements • Exchange rate fluctuations • Shortfall of supplies • Geopolitical risks (export taxes) • Environmental risks (extreme weather events, rise or fall of water level)	• Country related economic indicators • Sustainability regulations, public acceptance • Exchange rates • Professionalising of pellet industry: experience, number, size and in time realisation of production projects and shipping activities • Quality standards	• Mix of long-term contracts, and of forward and spot market transactions for fuel supply • Producer–buyer agreements on price collars (high-low) • Vertical integration of supply chain for better control over volumes, quality and price • Supply contracts and trading in US-$ (partly minor fluctuation and no currency converting) • Establishing networks of producers and buyers • Financial hedging of exchange rates, fuel, freight rates (forward transactions) • Taking account of risk margins • Standardisation of contract terms, fuel quality, sustainability

5.5 Economic and environmental performance of torrefaction-based supply chains

5.5.1 Parameters of the torrefaction and pelletisation process

Based on the methods described in Section 4.2.2 and 4.4.3, the investment, capital and operational costs for a combined torrefaction and pelletisation plant are derived with basic technology, energy consumption and cost data summarised in Table 5.12. For the combination of a torrefaction and pelletisation plant, investment costs and efforts for operation and maintenance can be remarkably reduced, as the components belt dryer, grinding, coolers, storage, peripheral equipment and general investments arise only once. Also, a combined torrefaction and pelletisation plant is assumed to be operated by the staff, which is required for the torrefaction unit only. Though, the torrefaction process requires a much higher raw material input (1.25 t_{dry} input for 1.0 t_{dry} output) for producing the torrefaction gas. The investment costs are 11.4 million € for a 40,000 t/a torrefaction and pelletisation plant, excluding guaranties, liability and profit margin of the plant manufacturer, but including contingency costs for the development, set-up and the commissioning phase. They may vary between ± 20 % depending on legal or operational requirements, the kind of procurement and the capacities of plant manufacturers and technology providers [92]. Drying the raw material is mainly fuelled by the torrefaction gas, but requires additional process heat. The internal recovery of heat by using the torrefaction gas is assumed to provide 2.7 MW capacity for a 40,000 t/a plant. This value depends on the torrefaction degree for the product and the moisture content of the input material. By using the torrefaction gas, the additional heat demand is significantly reduced compared to pelletising plants only. Though, for raw material with high moisture content (e.g. 55 %), a much higher share of extra process heat is required. Besides the basic assumption of an input-output material ratio of 1.25:1, varying ratios with 1.5:1 and 2:1 are considered in all calculations.

The electricity consumption during fuel production can be reduced as grinding is less energy intensive for torrefied material. Though, during the pelletising tests it has been found that much more energy is necessary to densify torrefied material. This is mainly due to higher temperatures required to activate bonding mechanisms and due to increased residence time resulting from that. Nevertheless, it has been proven that pelletising in the laboratory pellet press is technically feasible for the provided raw material sample A. The pelletising is possible without bonding agents and can be realised by higher temperatures to activate the lignin and increased moistening of the input material. Nevertheless, for industrial pelletisation the required high temperatures and dust emissions are critical factors [66]. These results comply with the results published by Wojcik and Englisch (2013) [95] as well as Larsson (2013) [179] and are taken into account in the cost estimations.

Table 5.12: *Comparative technology and cost data for a pelletising and combined torrefaction & pelletising plant.*
Sources: Adapted from [47, 92]

	Pelletising plant	**Combined torrefaction & pelletising plant**
Production capacity	40,000 t/a (upscaled to 120,000 t/a)	
Investment costs	3.74 million € (9.18 million €)	11.4 million € (27.9 million €) ± 20 %
Technology	Belt dryer, hammermill, pellet ring die	Belt dryer, rotating drum reactor, heat generator, hammermill, pellet ring die
Operation & maintenance	1.8 % of investment costs	4 % of investment costs
Other costs (insurance)	3 % of investment costs	
Required staff	1.25 persons/shift 3 shifts per day	1.5 persons/shift 5 shifts per day
Internal heat recovery due to torrefaction gas		2.7 MW (8.1 MW upscaled) depending on torrefaction degree
Input-output mass ratio	1.01:1	1.25:1 (1.5:1, 2:1 considered as possible variations)
Final product	Wood pellets	Torrefied pellets
NCV (based on defined moisture content)	4.9 MWh/t (17.7 GJ/t)	10 % increase: 5.5 MWh/t (19.9 GJ/t)
Bulk density	650 kg/m^3	705 kg/m^3
Moisture content	≤ 6 % mc	≤ 4 % mc

5.5.2 Logistics and transportation in torrefaction-based supply chains

The storage tests with 4 t torrefied pellets [97] allow first findings on the handling of the material currently available on the European market. After a 4 month storage period, a layer of about 50 cm material from the surface of the pile was completely decomposed and wet. The consistency of the material was loose, crumbly and very similar to flower pot soil. In contrast, samples from inside the pile shows torrefied pellets in their original condition. The transition area between wet and dry material was characterised by a 10 cm layer of pellets contaminated by molds [3, 97]. Very similar storage results have been reported by an anonymous operator of a torrefaction and densification pilot plant.
As a result of these existing storage tests with available pellet samples purchased from the European market (see [3, 97]), it is concluded that these torrefied pellets have limited hydrophobic properties. Thus their suitability for uncovered outdoor storage is limited, and they are assumed to require the same means for transportation and logistics as conventional wood pellets up to conversion plant. This corresponds to the statement of two interviewed biomass traders and actors (interviews according to Appendix B.1). This assumption is based on the fact that in the market development phase no specific logistic means are available for torrefied pellets, and the volumes, capacities and frequency of transport routes will be the same as for conventional pellets. Possibly, the inner part of a big storage pile might still be used for combustion purposes. Analyses by Wielen et al. (2013) [53] have shown that the mechanical durability of the torrefied pellets was on average lower than those of corresponding reference fuels. Both of these latter aspects should be subject to further storage and fuel characteristic analyses and cannot be further issued in the present study.

5.5.3 End-use of torrefied pellets

As defined in the Methods Section 4.2.2, the torrefied pellets are considered for a 10 % co-firing in a 800 MW_{el} coal power plant without major adjustments. That means, storage site, hammermill, fuel input and combustion unit of the coal plant are assumed as suitable for handling, feed-in and firing the torrefied biofuel without any major changes in equipment or any losses in capacity and utilisation of the power plant.

5.5.4 Costs along torrefaction-based supply chains

Production costs for torrefied pellets

The torrefaction relevant findings from the technical process and cost assumptions are transferred to the conventional pellet supply cases as described in Section 5.3.1 and displayed in economic terms in Figure 5.32. As shown, the production process for combined torrefaction and pelletisation is 25 % to 94 % more cost-intensive than this for pelletisation only, when considering input-output ratios between 1.25:1 and 2:1. Most costs are associated with the cases with high biomass input, as raw material is a major cost component. Another relevant cost component are the higher capital costs for the torrefaction process. Instead, heat costs can be reduced when the torrefaction gas is recovered and used for drying. When the investment costs are variated (see error bars in Figure 5.32), a 5 % reduction or increase of production costs can be achieved. Nevertheless, these cannot outweigh the general higher specific production costs for torrefied pellets.
The estimated investment costs and share of operational costs comply with the costs estimated for the Dutch Ministry [180] and those estimated by Uslu et al. (2008) [24], taking into account a risen value due to average inflation rate. Estimations for the International Energy Agency Bioenergy Task 32 for a 100,000 t/a [23] and by Svanberg et al. (2013) [69] for a 200,000 t/a torrefaction & pelletisation plant result in similar costs, considering an upscaling of technology capacities.

Costs for logistics and transportation

As a result of existing storage tests (see Section 5.5.2), for the cost estimations it is assumed that torrefied pellets should be handled, transported and stored similar to wood pellets. Concerning the increased net calorific value of torrefied pellets compared to conventional ones, two main conclusions are made. First, due to higher bulk density, the supply costs during train and ship transportation can be decreased (-9 % for torrefied pellets with 5.52 MWh/t NCV). For truck transport (relevant for delivery of premium pellets in specific pellet silo tank trucks), no advantage in terms of bulk density is expected as the transportation capacity is limited by weight (as designed for conventional pellets). Second, the supply costs per energy unit are reduced as the energy density of torrefied pellets is 10 % higher. Furthermore, other logistic processes such as (un)loading are operated as for conventional wood pellets in the corresponding quality.

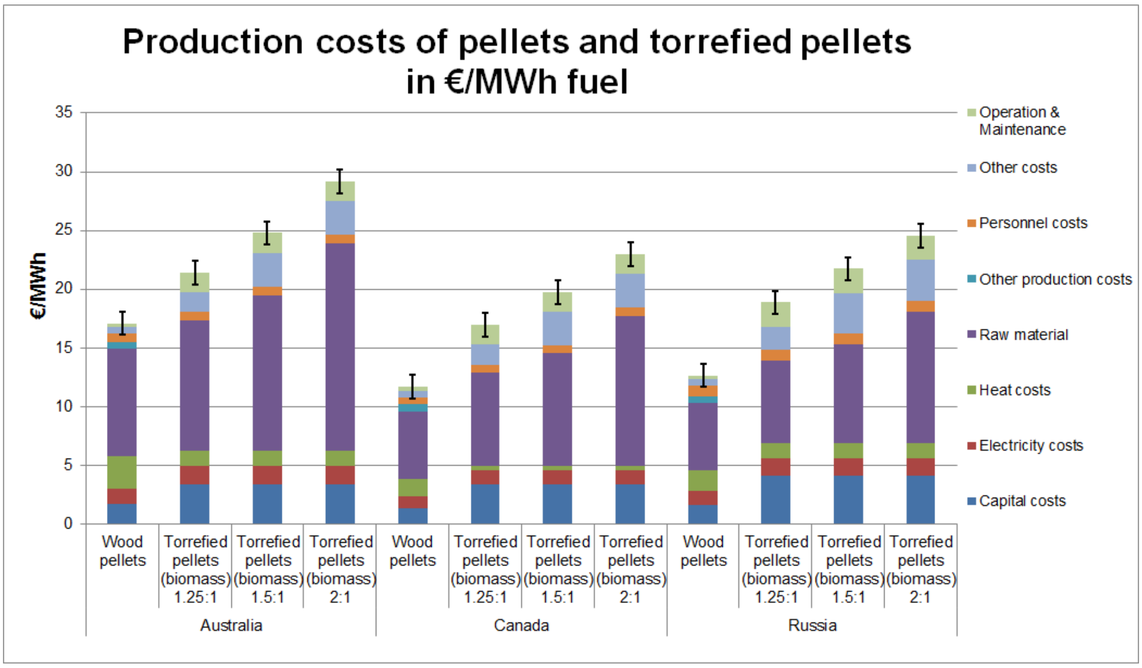

Figure 5.32: *Costs for producing torrefied pellets vs. conventional pellets for the considered origin countries; error bars indicate the impact of 20 % higher or less production costs on total costs*

The resulting transport and logistic costs are shown in Figure 5.33. Corresponding costs are reduced up to -15 % for most torrefied pellet chains. Supply chains with longer distance from pellet production to end-user have relevant cost advantages. For long-distance transport from Australia or Canada to Northwest Europe most cost reduction can be realised with torrefied pellets.

When summarising (torrefied) pellet production and transport & logistics, torrefied pellets turn out to be still more expensive than conventional pellets, as shown in Figure 5.34. When supplied to an end-user in Europe, the considered torrefied pellet chains are not competitive to conventional ones in terms of energy density and when assuming the same utilisation option of both biofuels. These findings are in line with economics assumed by Koppejan (2012) [23], but are in contrast with early publications on torrefaction economics by Bergman (2005), Uslu et al. (2008) or partly Svanberg et al. (2013) [22, 24, 48], which assume much more favourable fuel characteristics and thus advantages in processing, logistics and end-use.

End-use costs

When 10 % pellets fuel is co-fired in a coal power plant, the use of torrefied pellets results in slightly lower electricity production costs compared to wood pellets, which is due to less capital and operation costs during conversion. The respective cost

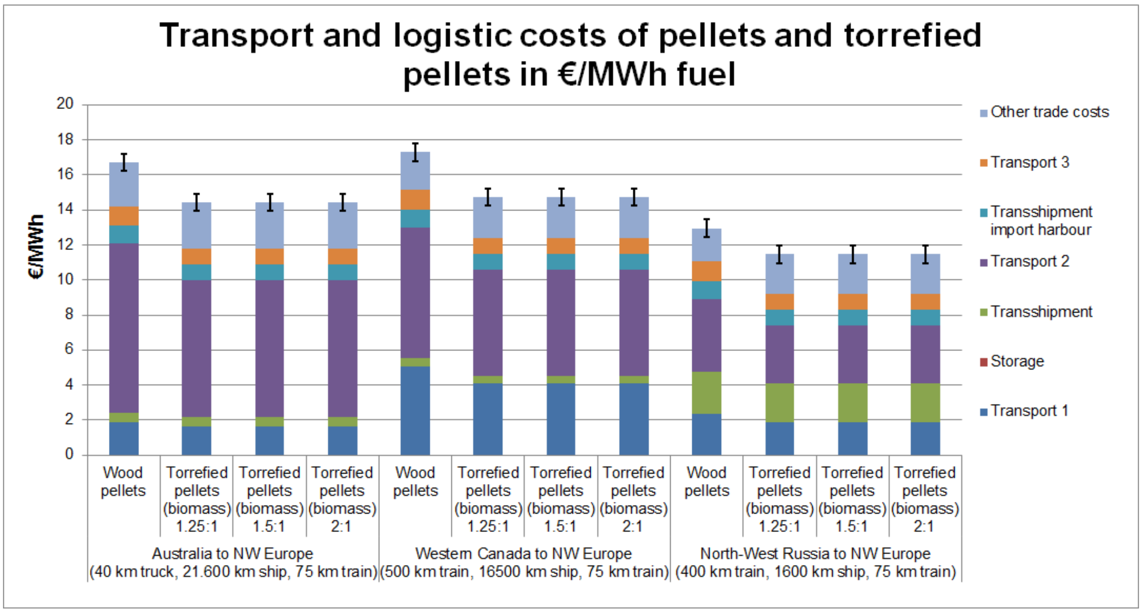

Figure 5.33: *Costs for transport and logistics of torrefied pellets vs. conventional pellets for the considered origin countries; error bars indicate the impact of 20 % higher or less production costs on total costs*

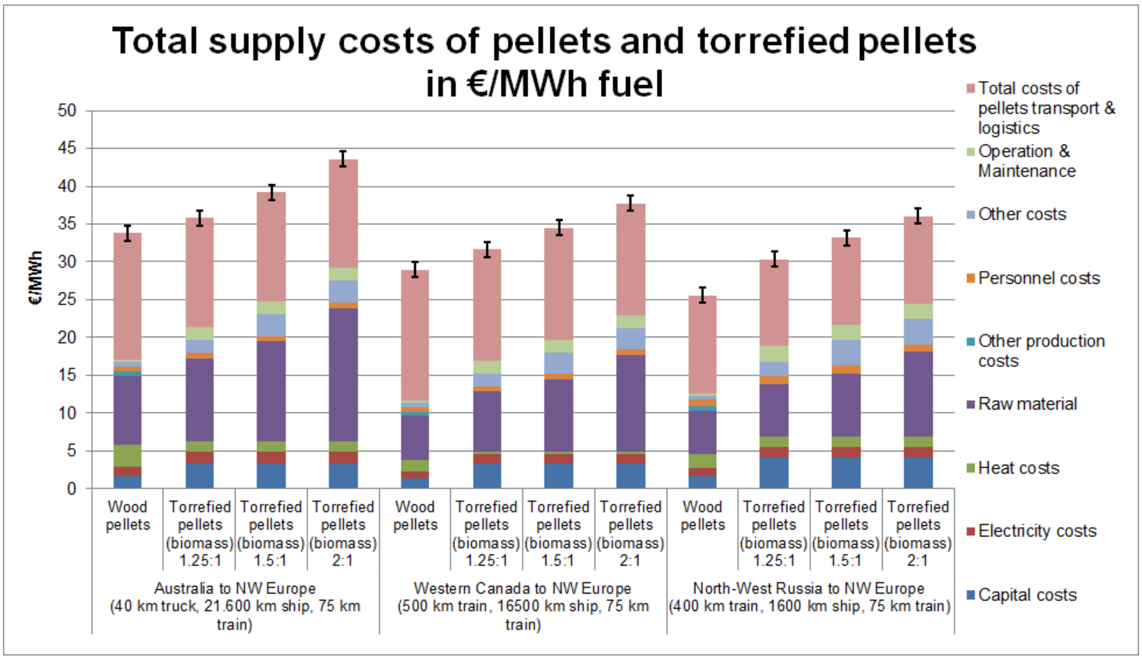

Figure 5.34: *Costs for both production and supply (transport and logistics) of torrefied pellets vs. conventional pellets delivered at end-user; error bars indicate the impact of 20 % higher or less production costs on total costs*

composition is illustrated in Figure 5.35. Here, even torrefied pellets with high input-output ratio (2:1) can be advantageous compared to conventional ones, as shown for Australian pellets.

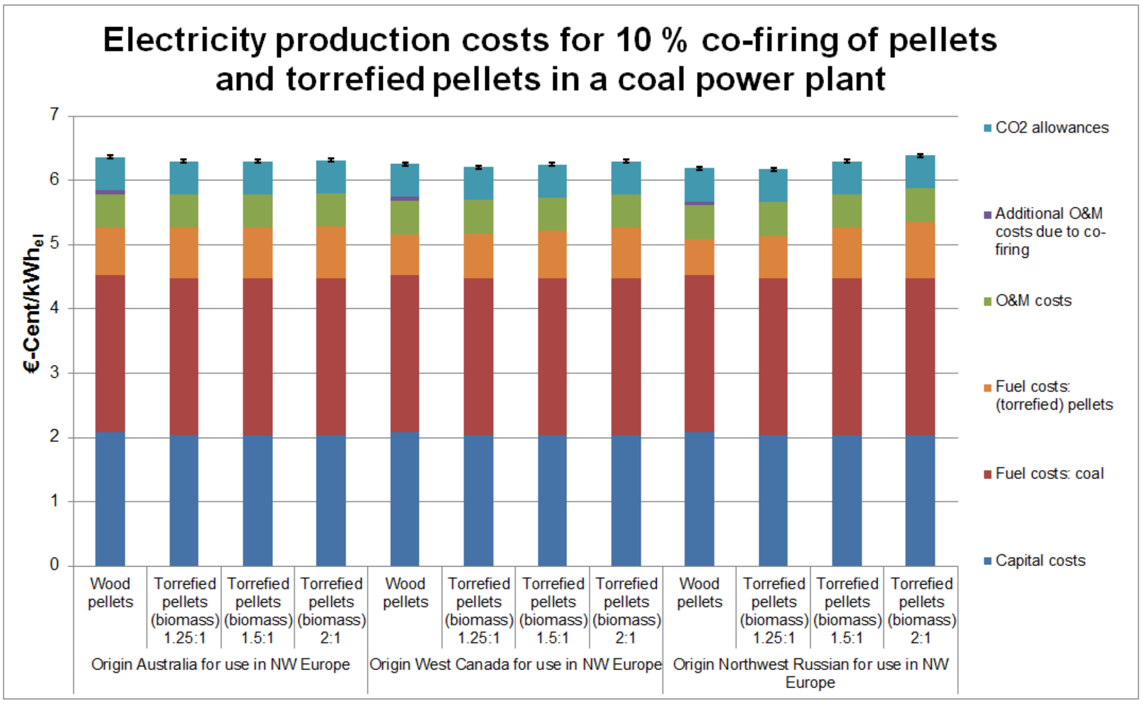

Figure 5.35: *Electricity production costs for co-firing torrefied and conventional pellets in a coal power plant; error bars indicate the impact of 20 % higher or less production costs on total costs*

5.5.5 Environmental balance for torrefaction-based supply chains

The environmental balance for supply chains with torrefied pellets is based on the input parameter as described for the process parameters of torrefaction-based supply chains (see Sections 5.5.1 to 5.5.3). It is described for the use of biomass residues as input material only, which is the most common resource for pellets. For direct comparison of the performance of torrefaction-based chains, they are directly opposed to the corresponding cases for conventional pellets.

As presented in Figure 5.36, the direct fossil energy consumption is less for most torrefaction-based chains compared to conventional pellet chains. This is mainly due to biomass as input material and process fuel, which is not associated with more fossil energy demand. In total, up to 6 % fossil energy can be saved, especially in those chains with less moisture content of the raw material (Australian and Canadian torrefied pellets to Europe). Due to higher raw material supply efforts and increased electricity requirements during the production of torrefied pellets, the share of fossil fuel consumption is higher in these phases. In contrast, the fossil energy consumed during shipping is reduced, because of the higher energy density and therefore higher capacity utilisation of vessels. This advantage makes Australian as well as Canadian torrefied pellets shipped to Europe slightly advantageous against conventional ones. In contrast, Russian torrefied pellets benefit less from this advantage and have a slightly higher fossil energy balance than conventional pellets. For Australian and Canadian pellets, an input-output ratio of 2:1 means that approximately same levels as for conventional pellets are reached. The fossil energy balance can be much worse for torrefied pellets, when natural gas use is increased or raw material supply is associated with higher biomass production or longer transportation efforts.

The primary energy consumption of torrefaction-based supply chains is at least 10 % higher than this from conventional pellet supply. This balance results from the higher biomass input ratios during the production of torrefied pellets compared to those of conventional ones. The associated primary energy demand cannot be outweighed by the heat recovery of torrefaction gas for drying, the higher energy density of the produced biofuel, or higher efficiency during transports. In those chains with higher input ratios (1.5:1 and 2:1), the production processes are characterised by even higher primary energy uses. When considering 2 t input material for 1 t produced torrefied pellets, the primary energy demand is around 200 % higher than for conventional pellets. Comparable energy balances for torrefaction-based supply chains are not available.

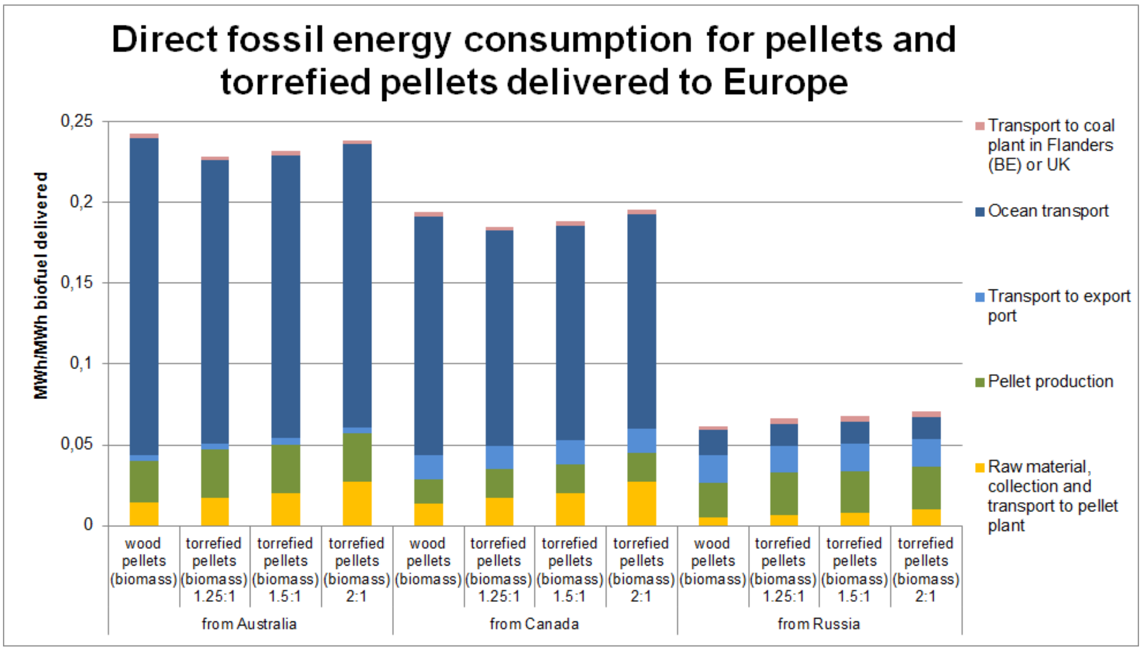

Figure 5.36: Direct fossil energy consumption of torrefaction-based and conventional pellet supply chains

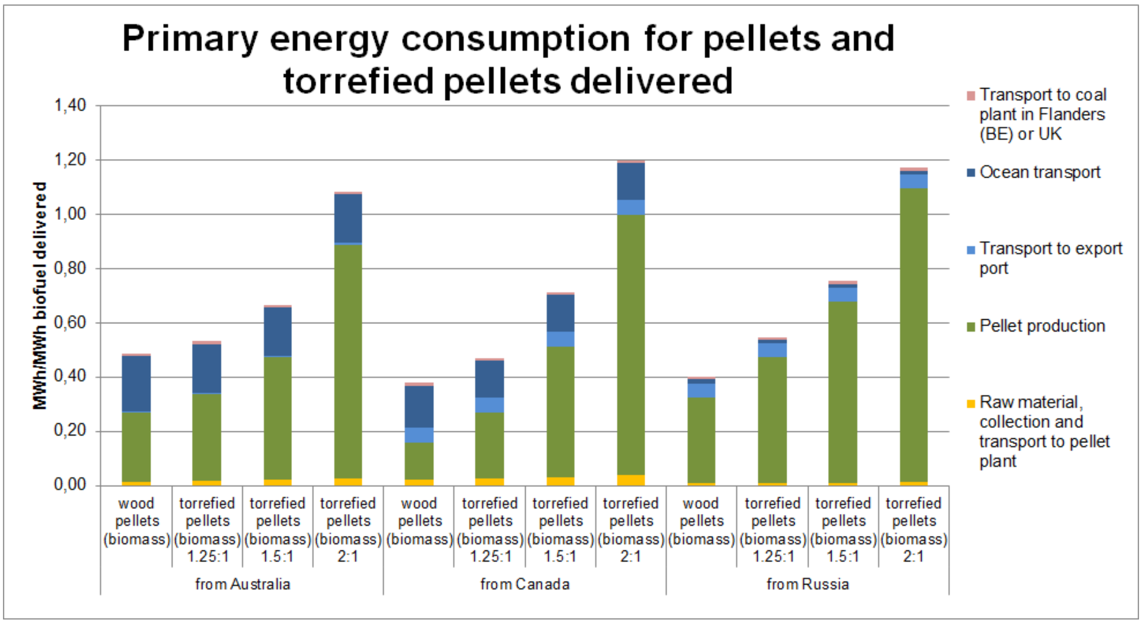

Figure 5.37: Primary energy consumption of torrefaction-based and conventional pellet supply chains

The greenhouse gas emissions along torrefaction-based supply chains are approximately on the same levels as conventional pellet chains, see Figure 5.38. During the production process, more biomass input is required. This results in slightly higher GHG emissions. These emissions can be compensated by higher transport efficiencies during long-distance shipping (as described for fossil energy consumption). The transportation advantage is less for Russian torrefied pellets to Europe. Here, the higher production efforts cannot outweigh the benefits during transport. The emission balance approximately corresponds to the results by Chiueh et al. (2012) [68], when considering the different framework conditions of assumed biomass supply cases.

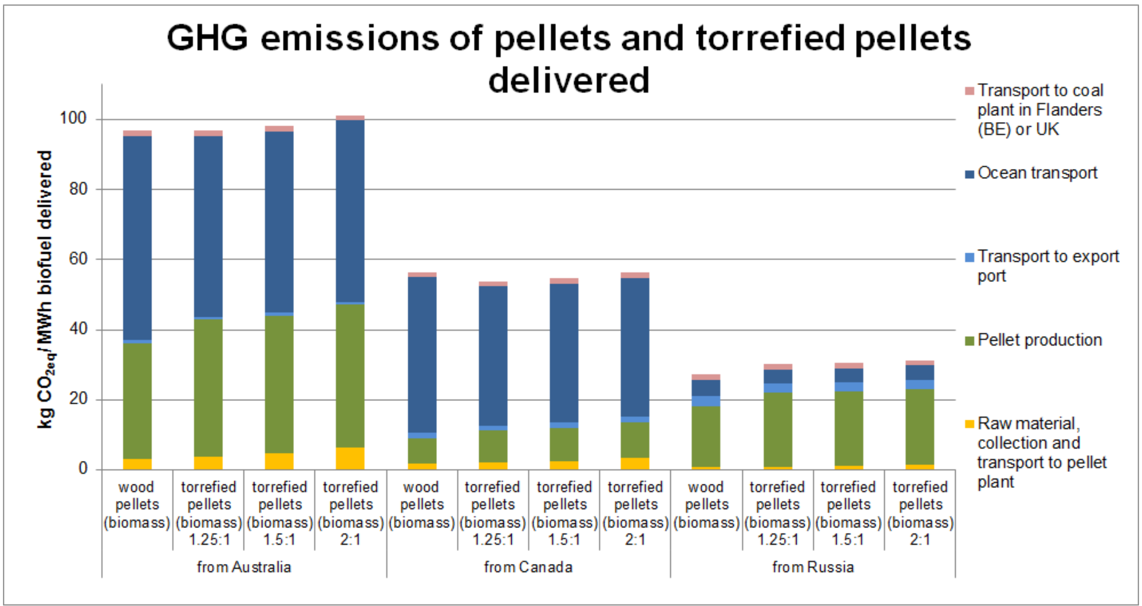

Figure 5.38: *Greenhouse gas emissions of torrefaction-based and conventional pellet supply chains*

When converted in a coal co-firing plant (see Figure 5.39),Canadian torrefied pellets emit 1 to 5 % less upstream GHG emissions than conventional pellets. Russian torrefied pellets are associated with up to 16 % higher emissions and achieve no advantage compared to emissions in the corresponding conventional pellet chains.

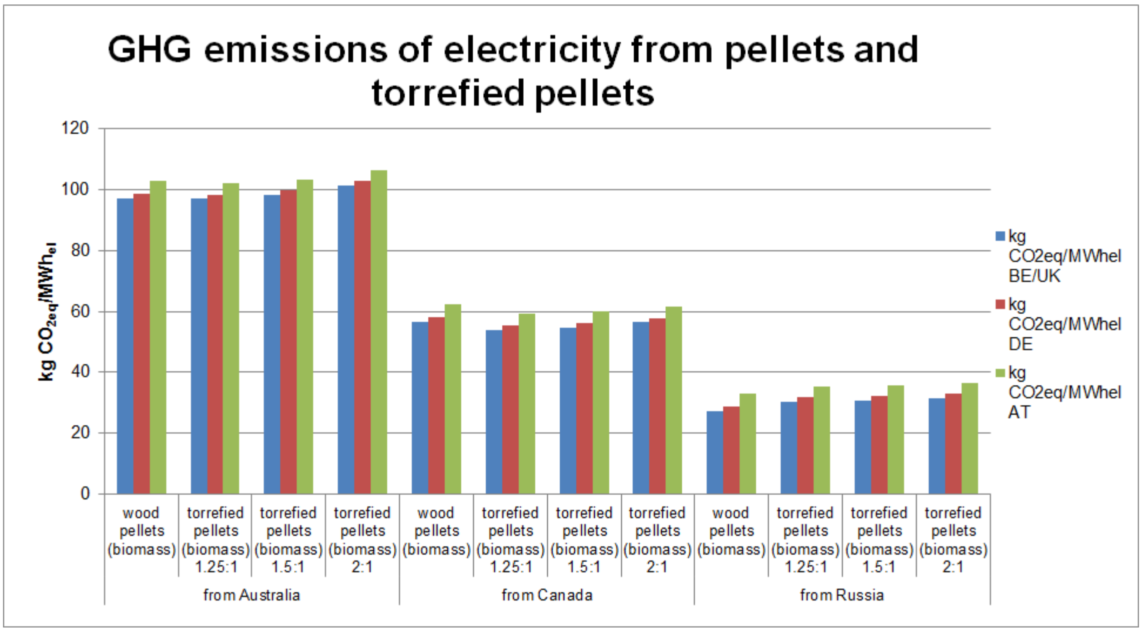

Figure 5.39: *GHG emissions from electricity of torrefied and conventional pellets*

5.6 Summary of market and policy impacts on international pellet supply chains

5.6.1 Co-firing subsidies for imported pellets

The present analysis demonstrates that energy balance and CO_2 emissions strongly depend on the individual supply chain design. This is clearly demonstrated by assessing the supply chains from Australia, Canada, and Russia in Section 5.1. When using renewable energy for the operations and choosing low emission transportation modes, imported pellets can have a very favourable energy and CO_2 footprint, even with long distance trading. Less favourable chains with high fossil fuel consumption can cause an upstream energy consumption up to half of the pellets energy content. The use of primary biomass like plantation logs has a minor effect on the fossil energy and GHG balance, but choosing roundwood for pellet production leads to doubled emissions. When applying the Flemish co-firing support model as available in Flanders, the financial gap in Germany could be reduced from 3.6 (without funding) to between -2.6 and 2.7 €-Cent/kWh$_{el}$. For Austria, the financial gap could be reduced from 4.1 to between 3.3 and -2 €-Cent/kWh$_{el}$, with Russian (biomass) pellets the most advantageous. Under the UK's RO system, the financial gap would be between -0.9 to 1.8 €-Cent/kWh$_{el}$ in Austria and Germany. This system has a contrary effect when pellets are made of energy crops, which obtain the most advantageous revenues. As a result of the subsidy analysis in Section 5.3.2, pellets transported from Australia to Europe and dried with natural gas are not profitable under the Flemish co-firing support. Under the UK's RO support, long distance is still financially viable when biomass is used for drying the pellets. It can be even more a cost-effective option when biomass comes from higher granted energy crops. This is already adopted in biomass power plants fed by overseas plantation wood like power stations in the UK [181]. In turn, relatively low energy consuming chains like from Russia and those with high renewable energy input become more profitable when applying the Flemish subsidy scheme. Though, the supply from Russia has no advantage against longer distance supply with energy crops in the UK. The results show explicitly that the design of co-firing support effectively influences supply chain decisions. So, the available biomass sourcing options will be allocated to the best suitable support systems.

Furthermore it is shown that, in comparison to different renewable production costs and subsidies as well as CO_2 mitigation costs, co-firing is a cost-effective option to

produce renewable electricity even without or relatively low incentives.
Thus, co-firing is one of the cost-attractive solutions to reach the EU 2020 targets and can be even attractive for countries with no or less co-firing support.
Finally, it should be noted that the current EU emission accounting does not consider changes in the carbon stock or (in)direct land use during biomass production, which is a general weakness of the existing system. Comprising these effects, researchers like Zanchi et al. (2010) [182] found that, in the long run, specific biomass feedstock can effect even higher greenhouse gas emissions than coal, e.g. when dedicated tree fellings occur or land is converted for bioenergy purposes. Also, the combustion of biomass is only CO_2-neutral, if the same amount of biomass regrows in the same period on global scale. In this regard, sourcing options as well as the present EU emission accounting system have to be treated carefully. However, Zanchi et al.(2010) [182] did not consider positive effects from fellings or good land management practices. A comprehensive evidence of carbon balances for wood production can be found in publications by EEA (2011) [104], Mitchell et al.(2012) [183] and Nabuurs et al.(2008) [184]. One approach might be to give priority to energy production from biomass residues (as analysed under the 'standard' biomass cases), except if those are needed to sustain soil fertility. Also, acknowledged certification systems as accredited by the Forest Stewardship Council require forest management practices, which should maintain or restore carbon stocks. Being aware of the need for certification, electric utilities are already used to purchase certified biomass, which should origin from integrative forest management practices.
However, a desirable future approach should end up in a common accounting and certification policy, which should consider these aspects thoroughly. Finally, a certification scheme should avoid a discrimination in bioenergy use as discussed by Pelkmans et al. (2012) [185], but enhance sustainable sourcing and utilisation options.

5.6.2 Price risks in the pellet supply chain

The price risk analysis demonstrates how highly volatile market prices influence pellet supply costs. When considering a 10-year period and individual price effects, ocean freight rates affect fluctuations between -17 to +36 % of total supply costs. Regarding exchange rates of the export country's currency to Euro, Canadian pellets costs can vary up to ± 6 %, Australian pellets up to -12 % and Russian pellets up to -20 %. By now, these fluctuations are not fully represented by the EU import market price of pellets, which varies between -14 and +5 %. Other impacts as from

natural gas as drying fuel during pellet production or the EU transport price indices are negligible.
Simulating a 3-year supply period between 2008 and 2011, the strongly increased dollars to Euro resulted in 12 % (Canada) to 21 % (Australia) higher export costs in € and up to 15 % higher total supply costs to the EU, whereas Russia has faced a 10 % reduction of supply costs due to stronger Euro to rouble. When annual exchange and shipping rate extremes occur simultaneously, supply costs can vary from -34 % to +57 %. Also, prices for more expensive feedstock assortments can easily lead to a 16 to 30 % rise of total supply costs. Contradictorily, these actual market fluctuations are not yet reflected by the final EU pellet market price. It has to be considered that the period under observation overlaps with the recent global economic recession with strong market fluctuations in many sectors. Nevertheless, or exactly because of this, great importance should be attached to possible strong fluctuations in these global market activities.
In respect of the high, individual price fluctuations in the pellet supply chain, both pellet buyers and producers have to de-risk financial exposure and must take a set of contractual provisions. Besides obligatory hedging of prices by large utilities, de-risk strategies are mainly based on personal branch knowledge and individual agreements between biomass producers, traders and buyers. A mix of longer-term and short-term contracts – agreed with several producers (buyers) from different countries – is one of the key measures to de-risk international pellet supply (see Sections 5.4.5). Anyway, some market actors guess that extreme fluctuations, as occurred in the Australian dollar - Euro exchange rates, can hardly be hedged (interviews according to Appendix B.1). Even when long-term contracts exist, the risk remains that counterparties - especially smaller producers - cannot compete the new market situation after the contract has expired. Also in terms of occuring fast policy changes, a diversification of both various sourcing options and allocation of pellets to different end-use alternatives and locations has proven to be a wise strategy for pellet market actors.

5.6.3 Advantages of torrefied pellet supply chains

According to the present state of knowledge and present results, there is evidence that torrefied biomass has suitable properties to be processed and used as biofuel in existing conversion technologies, especially in large-scale robust combustion plants (see Sections 4.2.2 and 5.5). The economic comparison has shown that the production phase for torrefied pellets is much more expensive than for conventional ones, even for larger-scale plants and minimised investment costs. However, when combusting the fuel without major retrofit efforts on the plant, resulting electricity costs can be slightly less than those for co-firing conventional pellets. The production costs for the pretreatment phase are much higher for torrefied pellets, but these can be partly compensated by reduced transport and logistics costs. At the end-user, the delivered torrefied fuel is still more expensive than conventional pellets. Economic investigations for Sweden have shown that upscaling torrefaction plants (to more than 120,000 t/a) could result in cost-effective production [69]. Though the present findings indicate that the conversion costs for industrial torrefied pellets are on the same cost level as of industrial wood pellets. The environmental balance for torrefied pellet chains is generally less favourable than for conventional pellet chains, because of higher energy inputs during the production phase. Nevertheless, the GHG upstream emissions and the fossil fuel demand can be more advantageous than for conventional ones. This advantage requires the use of biomass residues as input material and fuel, a favourable energy balance during fuel production, and higher transport efficiency due to increased energy density of the fuel. Final technical evidence of these favourable aspects have to be proved yet in demonstration and industrial-scale applications.

As a result of the economic and environmental assessments, it can be stated that torrefaction offers certain opportunities to replace or complement conventional wood pellet production and supply. With that, torrefied pellets turn out to be a certain alternative particularly for industrial wood pellets. However, compliance between the certain fuel quality and the requirements of the conversion plant has to be ensured. First steps therefore are made in frame of the draft ISO 17225 standard for graded torrefied pellets [54]. But still results for large-scale test series and standardisation are required for safety issues, hydrophobicity, processing, handling and the combustion behaviour of torrefied biomass.

A key factor for the success of torrefied biofuels is a continuous operation of industrial-scale torrefaction plants and thus their still pending market introduction with relevant tradable amounts on the market. Only then, evidence can be given on the real operating conditions during fuel production, on related energy balances and consequences for their processing and logistics in the supply chain. These technical aspects and respective business models will be crucial to define their position on the biofuel market.

5.6.4 Decision making aspects for international pellet supply options

In summary of the handled topics, crucial decision making aspects can be determined for international pellet supply options. The perspective is different for the various stakeholders involved in the supply chain. That is why these aspects are focussed on the view by European biomass consumers (energy utilities, end-users, importers, policy makers), who are searching for suitable international sourcing options. Concluding results are summarised in Table 5.13. The findings are demonstrated in a generalised form and can be applied as support to mobilise different biomass assortments, chosing suitable sourcing countries and trade routes.

Table 5.13: *Decision making aspects for international pellet supply options with emphasis on economic viability and supply security from a European consumer's point of view*

Supply chain pattern	**Beneficial features and targeted steering of biomass supply chains**
Exporting country	• Plenty of low-cost biomass available, preferably from residues not in competition with food, feed and fibre industry • High future biomass potential from various sources and from different producers • Low domestic demand for biomass • Low specific production costs for biomass and pretreatment options • Implementation of sustainability certification for biomass production valid in the importing country • Standardisation and quality assurance for biofuels (starting from production to end-use) • Economic stability of the country • Experienced, skilled and linked biomass actors (biomass producers, harvesting contractors, technology providers, pellet plant operators, logistic experts, biomass associations)
Transport and logistics	• Well developed infrastructure specialised on pellet handling and storage • Relevant volumes to be handled and shipped between biomass producer and end-user (economies of scale) • Long-term shipping contracts
Importing country	• High prices for fossil and CO_2 certificates to be substituted • Subsidies available for biomass use, stable over given period • High domestic demand for biomass • Available market places/ exchanges/ data monitoring for biomass • Low availability of local biomass (though certain regional biomass quantities should be secured as back-up solution) • Storage capacities for biomass • Social and political acceptance of bioenergy
End-use	• Allocation of various biomass qualities and volumes to suitable end-utilisation options with highest added value • Efficient conversion of biomass to high quality and high value product
Contractual terms between supplier & consumer	• Long-term supply contracts • Bilateral contracts or consortium agreements between supply chain actors • Indexing and price collars for sensible cost items • One trading currency for the whole supply chain • Vertical integration of supply chains • Biofuel quality, handling and fuel properties for end-use meets European standards

Chapter 6

Conclusions and Outlook

6.1 Environmental impacts of long-distance pellet trade and policy driven sourcing options

Imported and co-fired pellets are an attractive fuel for producing cost-effective renewable electricity and mitigating CO_2 emissions even when sourced over long distances. They offer an effective opportunity to quickly raise the share of renewables in the EU energy system. Nevertheless, in terms of effective sustainability, the assessment for biomass should follow a more integrated approach, as indicated in Section 5.6.1, taking into account aspects like carbon stock change and good land management practices. The assessment of the three supply chains has shown that a sustainable supply chain is characterised by a high share of renewable energy, high efficiencies and reduced carbon intensive fuels (using biomass for drying, train or vessel transportation in large volumes instead of truck, electricity generation mix). The distance itself is not a crucial factor (see Sections 5.1 and 5.2).

The preceding analyses show that the co-firing subsidy systems in Belgium and the UK have a high significance when only supporting the less energy or carbon intensive supply chains. They could set the direction towards subsidy schemes for imported biomass in other inland countries like Austria and Germany, and not for industrial use only. Besides, the requirements of subsidies have a relevant effect on the actual sourcing options allocated to the countries. In this way, even import chains with higher emissions can be favoured in the UK when energy crops are used. In turn, the Flemish system has no biomass preference and grants most green certificates to the lowest fossil upstream energy use.

Co-firing subsidies are definitely a driver for use of imported biomass, which might be one of the few possibilities for countries with few land area to reach their renewable energy targets. Nevertheless, considering the current European energy consumption still characterised by heat demand, for the overall energy system a more sustainable option remains locally sourced biomass for heat generation and other highly efficient end-conversion options. Policy makers should respond to the options with least overall environmental impact. They should make use of the power of their subsidy instruments and direct sourcing options towards most sustainable biomass production to end-use.

6.2 Arguments for the efficiency of subsidies for imported biomass

Considering the large amounts of co-fired biomass in Belgium, co-firing subsidies as market instrument turn out to be efficient and an important driver to use biomass. For electric utilities, choosing supply regions in closer proximity could be an approach for getting higher grants. This system is somehow consequent in terms of reducing the use of fossil fuels, but for the destination, Belgium delimits the utilisation of pellets offered on the market. First of all, the choice of the supply chain will highly depend on where, how much and at which costs biomass is actually available (see [20, 186]). Also, the assessments show that biomass sourced from intra-continental trade is not necessarily the best economic choice. It can even be uneconomic under the co-firing support schemes, e.g. when transported by truck. Furthermore, biomass support schemes should be reconsidered carefully regarding the use of primary biomass such as roundwood or biomass from plantations.
Co-firing in inland countries like Germany and Austria is a competitive option considering the much lower production and CO_2 mitigation costs compared with other renewables. With a financial gap of 3.6 to 4.1 €-Cent/kWh_{el}, co-firing is still more expensive than in countries with dedicated support. When aiming at a significant and low cost solution for increasing the share of renewable electricity, co-firing is a very good option for policy makers as well as electricity generators for fulfilling their renewable energy targets even without financial support. Biomass co-firing is just one current example for economic use of imported pellets. Within the next decades, more coal-fired plants could be closed in Europe [187]. Consequently, facing the relatively low conversion efficiency in power plants, more efficient technologies and resulting energy products with even higher added value should be considered for (industrial) pellet use. Yet, quality management and control according to valid European standards are increasingly leading to premium pellet imports to Europe, which can be used in highly efficient biomass boilers and stoves.

Finally, the investigations have shown that policy can effectively foster the process and attract sustainable import chains by introducing subsidy schemes as in the UK or in Belgium. Another influencing factor for co-firing (or in general for energy conversion) are the prices for coal (fossil fuel) and CO_2 allowances, which are still too low for making pellets a directly competitive fuel. But in turn, imported biomass can become cost-competitive against regionally sourced biomass, especially when the latter is getting scarce (interviews according to Appendix B.1), or compared to residential fossil fuels (heating oil). In this way, the present findings are important beyond the EU's co-firing market. When transferring the results to the big residential market and its increasing biomass imports, respective subsidy schemes or charges for imported biomass with unfavourable environmental footprint could contribute to fulfil the EU's energy target in an even more sustainable way.

6.3 Price risks and de-risk strategies in pellet supply chains

Total pellet supply costs are mostly affected by freight rate volatility, the EU market price, exchange rate variations and actual changes in the raw material prices. The exporter's share can be affected even harder by exchange rate variations when selling in a foreign currency. Nevertheless, volatility of fossil fuel prices is much stronger, and pellets can even slightly reduce it during co-firing. Also, due to easy substitution by coal and minor retrofit efforts, co-firing for electric utilities can be seen as a relatively riskless way to produce renewable electricity.

Pellet prices vary between -20 % and 36 % in a 10-year-period when considering the influence of individual price risks on the final supply costs. Recent price variations occurring simultaneously in the 3-year period 2008 to 2011 (exchange rates and shipping freight rates) were significantly higher with variations from -34 % to +57 % of a given base price. Main causes are the exchange rate and ocean freight rates in the last few years. In contrast, the achievable EU market price for imported pellets is far less subject to fluctuations. The recent experience has shown that pellet counterparties can easily succumb this high uncertainty along with competition and fail on the market. Another result is that 10-year price developments – in contrast to the 3-year examinations – hardly reflect critical risks, which occur in the meantime and can determine the success or failure of a supply project.

As for fossil fuels, pellet supply contracts include a number of provisions with fixed prices, inflators, specific index-based price adjustments or collars. Large market players occasionally use their access to currency, freight and fuel financial hedging.

Besides that, supply agreements are mainly made bilaterally directly between producers and traders or buyers. In this way, deep branch knowledge and personal experiences drive decisions in the complex biomass market. For instance, freight rates are generally fixed between pellet buyers and vessel operators, thus the price is effectively uncoupled from the market over this period. Besides, pellet buyers follow the strategy to diversify supply contracts and use a network of producers from different economies, thus the risk of extreme exchange rate variations is reduced. Vice versa, pellet producers should diversify their sales markets. Exclusive, even price fixed supply from one producer to one end-user bears high price risks when market prices have prohibitively changed after that period.

Exporting countries with developed pellets market benefit from specialised production and logistics. This allows market actors to jointly offer larger volumes to the market, to flexibly re-allocate supply and thus to stabilise prices. For suppliers, also regional, neighbouring or closely linked trade markets should be considered as this avoids both expensive and volatile transportation efforts and risks connected with exchange rate fluctuations. With growth of the global pellet market, a vast pool of pellet producers and buyers is expected to allow for better allocation and thus to economics and stability of pellet trade. These networks together with monitoring of market and price developments will strenghten confidence and reliability in the supply and thus can effectively contribute to increase the use of sustainable biomass in the EU.

6.4 Perspectives of torrefaction-based supply chains

For torrefied biofuels available on the European market, there is still no or only little advantage in economies from production to end-use, compared to conventional biofuels. However, even if the primary energy demand is quite high, the fossil energy and GHG balance during pretreatment can be favourable when biomass residues are used and the energy density of torrefied biofuels is increased. In this regard, the environmental impacts can be less than for conventional biofuels after long-distance trade. Nevertheless, a lot of technical and scientific questions are still not answered sufficiently: The relative advantage of torrefied biomass over conventional biomass has to be demonstrated, especially the higher energy density, connected with a favourable energy balance along production and the whole supply chain.

For market implementation of torrefied biofuels it seems important that industrial-scale plants are realised and economic efficiency can be demonstrated in real operation. Here, evidence should be provided that technology and economies are viable. The success of torrefaction also depends on pioneer plant operators, who can demonstrate this. From a big utility's point of view, industrial-scale volumes from several producers are required to have reliable supply of the fuel (cp. Section 6.3).

If the mentioned benefits of torrefied biomass exist, torrefaction can play a strong role for the biomass trade with standardised torrefied biofuels, e.g. for torrefied biofuel from low quality biomass produced in North America, shipped to Europe and used in suitable applications with high added value for the end-user. Nevertheless, torrefied biomass will very likely depend on favourable feed-in tariffs and other subsidy schemes for replacing fossil fuels in energy conversion plants.

Considering common lead times for research and for project realisation, it seems that torrefaction will play a marginal role only for achieving the EU's 2020 energy targets. Rather, torrefaction can gain importance for the EU's longer-term energy strategy.

6.5 Need for future research and biomass supply chain investigations

The scientific analysis of biomass supply chains and market activities demonstrates a considerable challenge. First, the biomass market is very complex and is characterised by interactions of numerous branches and actors with different background and interest. Second, the biomass market is quite young and underlies continuous changes. Resulting from that, data are scarce or not available for many market aspects. Many various drivers exist for investing in biomass projects and for increasing the use of biomass. In this respect, quite diffuse questions are, what drives and determines a certain investment decision and what makes biomass sustainable and efficient in economic and environmental regards. While this thesis found answers to some issues related to determining a biomass sourcing and supply option, other research questions are still open.

Related to the environmental impacts of biomass supply chains, further research is required on comprehensive emission accounting and suitable certification systems for (forest) land management practises. These systems should take into account carbon stock balances, land use changes, as well as quantitative and qualitative sustainability aspects for land management to end-use. For using available co-firing subsidies, more use of alternative biomass such as innovative energy crops produced on marginal land, biowaste fractions and agricultural and industrial residues should be taken into account. Also, even if globally sourced biomass is economic, regional or intra-continental supply should be the policy priority. Finally, new sustainable sourcing options will be of high importance facing the worldwide increasing demand for biomass. With less environmental impact and less costs for raw material, energy, CO_2 balances and supply costs could be optimised. This should finally result in a better performance in receiving co-firing support and in cheaper production costs for renewable electricity.

For further investigations of the price dynamics in the pellet supply chain, deep sector-specific knowledge, setting up indices and continuous price monitoring are necessary to observe the highly complex, interconnected market and to avoid risks. In this way, the biomass market would be opened up to nonspecialists too, which could release more investments into the sector. Anyway yet, the pellet market is professionalising with a growing number of experienced market actors and increasing investments in production and logistics (interviews according to Appendix B.1). Thus, further investigations and monitoring in the field of feedstock prices and the pellets market, analysis of and free access to FOB prices (prices at export harbours) are desirable. The development and observation of pellet related price indices on country level could foster confidence in newly emerging markets.

In terms of torrefied pellets, further investigations are necessary to define the fuel and combustion properties and particularly reliable data on the full torrefaction energy and mass balances from different producers and different kinds of origin biomass. Emphasis should be laid on optimising the whole production and supply chain for low-cost raw material and above all biomass residues. The specific combustion behaviour of torrefied fuels in large-scale conversion plants still has to be verified by scientific data. As result of the current findings, more research and development should be dedicated to define optimal parameters for producing torrefied biofuels with higher energy density at favourable energy and mass balances, higher durability and better hydrophobicity. Connected to that, there is also need for a common definition of the torrefaction degree and quality standards for torrefied pellets connected with their specific uses. Economics for torrefied biomass have to be proven for industrial plants in operation. Moreover, the technical feasibility for pelletising high quality torrefied fuel should be further investigated, above all in terms of required temperature, residence time, operational safety and life time of equipment. The specific costs for supply and handling of torrefied biomass can be determined

once relevant volumes are produced and traded on the market.
Concerning the co-firing of torrefied pellets, important decision factors for their use are the production in commercial volumes and a competitive market price, which can be proven when commercial production starts. The total energy input in terms of primary energy demand during production of torrefied biofuels is particularly high. Though, with increased energy density of the fuel, the fossil energy and CO_2 balances could be improved and therefore mean a better performance in receiving co-firing support or considering new sourcing options.

Besides the considered chains, there are a lot of other promising biomass producing regions such as Latin America or Africa, which should be considered further in specific studies in order to satisfy the growing demand for biofuels. On the other hand, it should be stated that the extension of biomass sourcing from regional origin should always be the optimum for environmental and energy policy makers. Nevertheless, the present analyses show that even biomass supply options from the other side of the globe can be economically and ecologically competitive to alternatives from closer origins. In this respect, the economics, sustainability requirements, and the reliability of biomass sourcing should be proved for other emerging biomass producing countries.

6.6 Concluding summary and policy recommendations

Main aim of this thesis is to investigate the economic influences on pellet supply chains in terms of environmental policies and subsidies and price risks along the supply chain. Furthermore, perspectives of the effect of torrefaction pretreatment on pellet supply chains are given. These analyses follow a case study approach in demonstrating the various effects on three real-case pellet supply cases: Australian pellets from plantation wood as well as Canadian pellets and Russian pellets from sawmill or forest residues shipped to Europe and used in co-firing coal power plants.

The present investigations give insight into the global biomass market developments, the driving forces of both exporting and importing countries and into the market dynamics within the supply chain. As intracontinental, but also worldwide trade with biomass is increasingly growing, this thesis provides insight and supports in understanding of the complex pattern of biomass market and its actors. The results are applicable for a large part of global and regional biomass markets and actors and can be transferred to other target areas such as premium pellets or emerging advanced solid biofuels. Particularly, for both biomass end-users and policy makers, the findings give a valuation basis to chose the right biomass sourcing options, to consider specific aspects (e.g. exchange rate volatility) and thus to help avoiding misconduct. Consequently, biomass actors can benefit from concrete guidelines on how to deal with concrete risks in the biomass supply chain and how to enhance security of prices and supply.

During the environmental analysis, the energy and carbon footprints of pellet imports from Australia, West Canada, and Russia for co-firing in Europe are investigated. Their ecologic and economic performances are proven by applying the Belgian and UK co-firing subsidy systems, which require dedicated sustainability evaluations. Based on the modelling of different subsidy schemes and price scenarios, the investigations identify even favourable conditions for the use of biomass co-firing in Germany and Austria, which currently do not have dedicated co-firing incentives. The findings show that under present conditions, co-firing has a narrow financial gap to coal with 4 to -3 €-Cent/kWh$_{el}$ and has low CO_2 mitigation costs compared to other renewables. Moreover, it is shown that co-firing together with related subsidies is one of the most cost-attractive options to reach the EU targets for 2020. For policy makers, the support of co-firing is found to be very efficient in terms of cost-benefit ratio. Also, co-firing allows energy producers to achieve large amounts of renewable electricity in short time, even if the conversion efficiency is often far below those of other utilisation options such as modern residential heating systems. Besides, the investigations have proven that the biomass subsidy schemes might direct supply chain decisions towards options with low energy and carbon impacts as shown for the applied policy schemes in UK and Belgium. This decision force should be further used by policy makers in priorising holistically sustainable sourcing options, taking into account the full range of biomass resource, production, pretreatment and end-use alternatives.

For the economical and price risk evaluation, the supply costs for three real case studies are assessed with Australia, Canada and Russia as exporting countries and the EU as target market. Based on these, most significant price indicators along the supply chain are identified and analysed. With these, the impact of several risks like raw material prices, exchange and freight rates on total prices is investigated.

Thus the study allows new insight into the interconnections between the sector, the various supply risks on the market and related de-risk strategies. This allows an estimation of risk margins in pellet trade and gives insight into crucial mechanisms, which drive the pellet price. As a result, it is found that coincidently occurring price fluctuations within the supply chain can effect a -34 % to 57 % variation of import prices. So, exchange rate volatility with more than 30 % variation between 2008 and 2011 has strongly hit individual pellet exporters to the EU. Nevertheless, the pellet price bears less risk than hard coal prices.

The assessment of various price data along the supply chain as well as interviews with pellets market actors allow to conclude how the pellet supply chain can be de-risked and how price risks are hedged to avoid project defaults.

The results might move policy makers and market actors to consider further actions to support and steer the market. First, more information is required to monitor regional market prices for biomass assortments (industrial and premium pellets), but also for suitable raw material and related freight rates. Second, it was shown that international pellet trade bears tremendous risk of varying exchange rates, which might turn a promising sourcing option into misinvestments. The investigations have shown that other relevant prices like freight rates can offset extra supply costs, but can also enhance inefficiency of trade routes. Simultaneously, the market price set at Rotterdam is rather on a low level and allows only little margins for suppliers. Market and policy actors can face this challenge when diversifying both exporting and sourcing portfolios and enter buyer and consumer networks. A reliable monitoring of price data and available volumes of biomass could stabilise pellet producer's and end-user's decisions. Nevertheless, market failures and trials and errors are likely in the closer biomass future and can help to learn establishing healthy and sustainable biomass sourcing and trade pathways.

Many actors in the biomass community expect that biomass upgrading through torrefaction can relevantly reduce biomass trade costs and emissions. Thus, it should provide notable advantages regarding the eco-balance and energy costs for the end-user. In this framework, the present work has defined up-to-date technical, energy related and cost parameters for the production, fuel properties, supply and end-use of torrefied pellets. The findings are used for comparing the three real-case wood pellet chains with the corresponding torrefied pellet supply chains.

As a result, torrefied pellets turn out to be a certain alternative for wood pellets. The cost comparison demonstrates that the production of torrefied pellets is still

much more cost-intensive, but can be partly compensated by reduced transportation and logistics costs. Co-firing torrefied pellets in large-scale coal plants can be cost-competitive to industrial wood pellets, when no additional retrofit and operation and maintenance costs incur.
The environmental analysis shows, that from the current state of knowledge the energy balance during production of torrefied pellets and from production to end-user can be slightly advantageous compared to conventional wood pellets. Crucial aspects are a favourable energy and mass balance along the whole supply chain, together with favourable fuel characteristics such as higher energy content, hydrophobicity, durability and suitable properties to convert torrefied biomass to products with high added value. Nevertheless, best configurations for torrefaction-based supply chains and their real economics can only be determined as soon as the technology is implemented in commercial scale and real examples exist to prove their performance. Thus, production and supply costs, energy balances and operation processes highly depend on the industrial implementation of the technology and their diffusion on the market. Finally, the availability of large-scale fuel volumes supplied by several producers will be a requirement to build confidence at end-users.
Policy actors can support torrefaction as advanced biofuel option in facilitating demonstration activities and diffusion of information on new technology efforts and their economic implications. Pilot torrefaction plants should be linked to end-users with most suitable and high value products. As always during the development of newly emerging markets, pioneers, success stories and failures are necessary to link technology developments in the most promising direction.

The main conclusions of this thesis can be summarised as follows:

- A sustainable supply chain is characterised by a high share of renewable energy, high efficiencies, reduced use of primary energy and carbon intensive fuels (using biomass for drying, train or vessel transportation in large volumes instead of truck, electricity generation mix). The distance itself is not a crucial factor.

- Energy balance and CO_2 emissions, but also the amount of connected subsidies strongly depend on the individual supply chain design. Among evaluated case studies, e.g. biomass imported from overseas or associated with high primary energy use partly receives more funding than biomass from much closer origins or biomass with less energy inputs.

- Co-firing imported wood pellets and related subsidies are cost-attractive and efficient options to contribute to the EU-20-20-20 targets. Though, policy makers could use these instruments even more effective when directing sourcing decision towards options with even less environmental impacts (regional biomass, high conversion efficiencies, low primary and fossil energy use).

- Price risks in the pellet supply chain can effect strong fluctuations, which seriously affect the profitability of individual supply chains (e.g. by exchange rate or freight rate variations). Above all, short term contract periods bear high risk of price fluctuations. Individual risks are scarcely observed and still underestimated in the sector, which is a barrier for increased biomass use and investments.

- A reliable biomass sourcing option is characterised by diversification of biomass origin and allocation, i.e. on the one hand by access to a large pool of different biomass assortments supplied by biomass producers from various regions, and on the other hand by the allocation of various biomass qualities and volumes to suitable end-utilisation options with highest added value.

- Management and securing of pellet supply chains is still characterised by individual experiences and networks. Systematic monitoring, gathering and sharing of joint knowledge and following guidelines for decision making is key for involving new market actors, achieving more market transparency and thus release of funding for reliable investments.

- Torrefied pellets can be economically and ecologically competitive to conventional pellets, if evidence on their favourable properties is provided in validised technical tests and in real plant operation.

- Market success of torrefied biofuels depends on research progress and industrial-scale demonstration concerning the fuel properties, their processing, handling and end-use behaviour. The production of potential large-scale volumes and thus a relevant market share are expected to be reached in the long-term only.

Chapter 7

Appendix

A Technology and cost parameters

A.1 Pellet production costs

Table 7.1: *Key technology and cost parameters for pellet production plants*
Sources: adapted from [47, 51]

	Medium-scale pellet production	**Large-scale pellet production**
Annual pellet production	40,000 t/a	120,000 t/a
Pellet production rate	5 t/a	15 t/a
Annual operating hours	8000 h	
Total investment costs	3,743,300 €	9,176,200 € (11,286,726 € when suitable for wood chips)
Interest rate	6 %	
Average service life of the pellets production facility	17.5 a	
Raw material storage Storage capacity	Paved outdoor storage 1.92 % of annual raw material demand	
Drying	Belt dryer	Belt dryer or rotary drum dryer
Heat demand	1,200 kWh/$t_{ev.w.}$ (belt dryer) 1,000 kWh/$t_{ev.w.}$ (rotary drum dryer)	
Required power for drying	140 kW_{el}	420 kW_{el}
Grinding/ sieving	Hammermill	Hammermill (additional coarse grinding unit for particle size > 7 mm)

continued on next page

	Medium-scale pellet production	**Large-scale pellet production**
Required power	110 kW_{el}	330 kW_{el}
Pellet mill	Ring die technology incl. driving motor for feeding raw material and mixing screw for hot water conditioning	
Required electric power for pellet mill	300 kW_{el}	900 kW_{el}
Cooling Required power for cooling	1 counterflow cooler 12 kW_{el}	3 counterflow coolers 36 kW_{el}
Storage capacity for pellet silo	2.3 % of annual amount of pellet production	
Peripheral equipment	Conveying systems, steel construction	
Required power for peripheral equipment	108 kW_{el}	216 kW_{el}
Simultaneity factor for electric consumptions	0.85	
Total electricity consumption	4.56 GWh/a	12.93 GWh/a (15.2 GWh/a for coarse grinding)
Efficiency of fuel use	90 %	
Shiftwork/ Personnel Shifts per day Working days per week Persons per shift (incl. deputyship) Personnel for marketing and administration	 3 7 1.25 2 full time employees	

A.2 Specific costs for export countries

Table 7.2: *Specific costs for considered export countries*

	Australia	Canada	Russia	Sources
Hourly rate of technical staff	30.53 €/h	26.82 €/h	12.96 €/h	[188, 189]
Electricity costs	51.06 €/MWh	44.40 €/MWh	50.00 €/MWh	[164, 190, 191]
Natural gas costs	18.65 €/MWh	18.26 €/MWh	7.33 €/MWh	[192–194]
Biomass costs (ex pellet plant)	9.06 €/t_{wet} for plantation chips with 45 % mc, purchased by co-located sawmill	24.73 €/t_{wet} for saw-dust/shavings with 36 % mc, externally purchased and transported 100 km by truck	17.42 €/t_{wet} for sawdust with 55 % mc, externally purchased and transported 30 km by truck	[10, 41, 51, 130, 150]

B Expert interviews

B.1 Interviewed experts

The following expert interviews have been conducted related to biomass supply security and de-risk measures along the supply chain. Due to confidentiality reasons, results are not traceable to individual interviewees and are used in aggregated form with the reference B.1.

Interviews and personal communication with European energy suppliers and operators of biomass fuelled power plants and related biomass trading departments or companies:

- Dusan, S., Black pellets manager of Vattenfall Europe AG, 08.08.2011
- Hermes, H.D., Director Business Development Biomass of Vattenfall Europe GmbH, 29.10.2012
- Mertens, J., Biomass Procurement Officer at GDF Suez, 07.02.2013
- Moser, W., Managing Director Commercial of torrefaction pilot plant Frohnleiten (Austria), 24.07.2013
- Pease, H., Senior Biofuel Portfolio Manager for RWE Supply and Trading, 18.04.2013
- Sumetzberger, H., Supply and Logistics Manager of fuel trade company Genol GmbH & Co KG, 08.02.2012

Interviews and personal communication with representatives of biomass exporters and pellet producers to Northwest/ Central Europe:

- Kuntze, C., Purchasing Manager of German Pellets GmbH, 28.07.2011
- Moser, W., Managing Director Commercial of torrefaction pilot plant Frohnleiten (Austria), 24.07.2013
- Murray, G., Executive Director of Wood Pellet Association Canada, 22.10.2012
- Lugner, M., Sales Manager Max Lugner from pellets producer Schweighofer, 15.06.2012
- Anonymous European pellet producer, 03.09.2013

B.2 Guidelines for expert interviews

Questions concerning organisation of international pellet supply chains and supply security raised to interviewed European energy suppliers and biomass trading departments or companies (see Section 4.5.5):

- From which regions are you importing biomass for larger power plants?
- What is your preferred biomass supply portfolio? (regional biomass versus those from overseas, preference regarding exporting countries, short- vs. long-term supply contracts)
- What are the critical risks in international biomass supply chains?
  - during raw material supply
  - during pellet production
  - during logistics and transportation
  - during end-use
- Which price aspects are hedged in frame of supply contracts? (hedging of complete supply chain or partly hedging, currency of contracts, duration of contracts, orientation on FOB (prices at export harbour) or CIF (prices at import harbour))
- Which other hedging strategies are applied from energy suppliers/ biomass traders?
- How is supply security of biomass imports dealed with in comparison to fossil energy trading?
- What are the advantages from upstream integration by energy suppliers?
- Which other de-risk measures for biomass imports do you consider as useful?
- How do you estimate the role of sustainability of raw material or biomass origin?
- Which possible advantages concerning supply security could arise when torrefied biomass are traded on the international market?
- What are the challenges concerning torrefied biomass fuels in the supply chain?

Questions concerning organisation of international pellet supply chains and supply security raised to interviewed representatives of biomass exporters and pellet producers to Northwest/ Central Europe:

- What are the critical aspects concerning possible price volatility in the biomass supply chains?
  - during raw material supply
  - during pellet production
  - during logistics and transportation (if applicable)
  - during end-use (if applicable)
- How are exporters (pellet producers) securing their raw material supply and related prices? What is the price trend concerning raw material prices (rising/ falling) in the exporting country?
- What is the influence of timber wood or other wood prices on raw material prices for pellet production?
- Are you trying to diversify your export markets?
- Which role do currency exchange rates play in the export of biomass to Europe?
- How do pellet suppliers hedge the risk of fluctuating exchange rates?

C Country specific and additional price indices

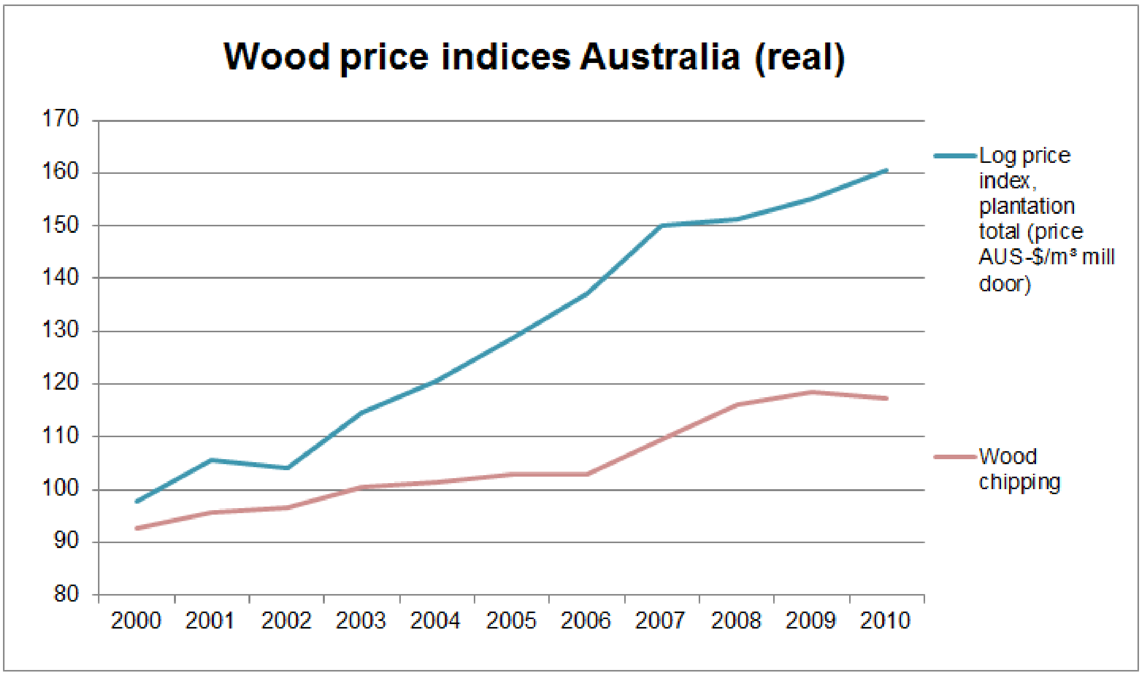

Figure C.1: *Australian plantation log price index and wood chip index (basis: 1989-90 = 100) Source: [120]*

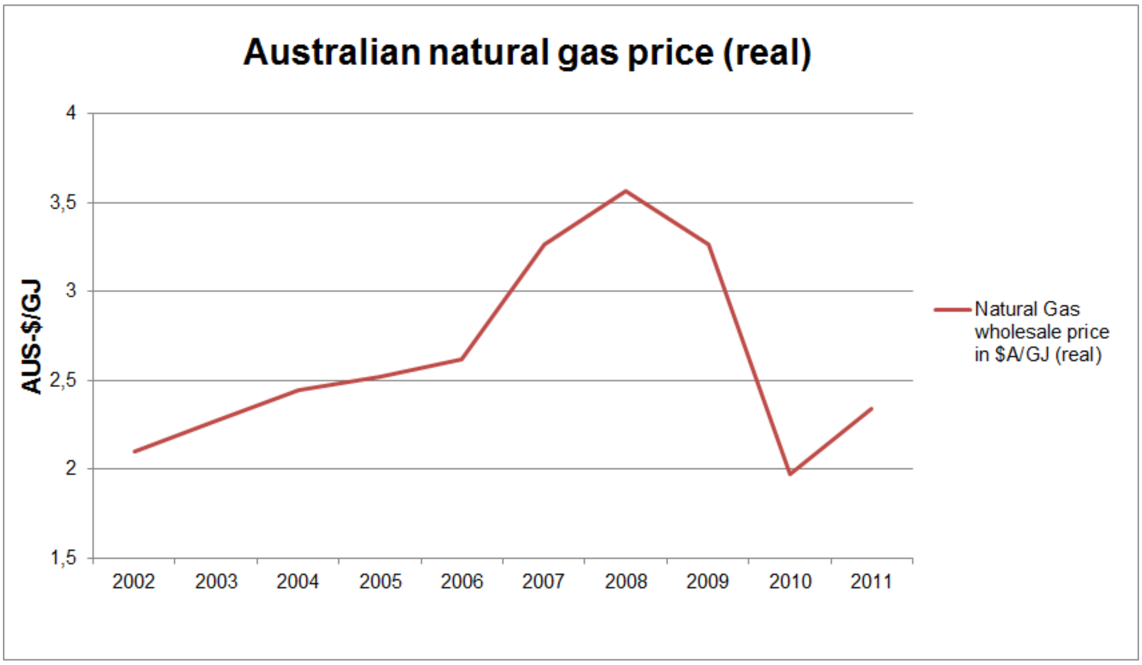

Figure C.2: Australian natural gas wholesale price 2002 to 2011
Source: [123]

Figure C.3: Canadian raw material price index, logs and bolts real (basis: 2002 average = 100)
Source: [124]

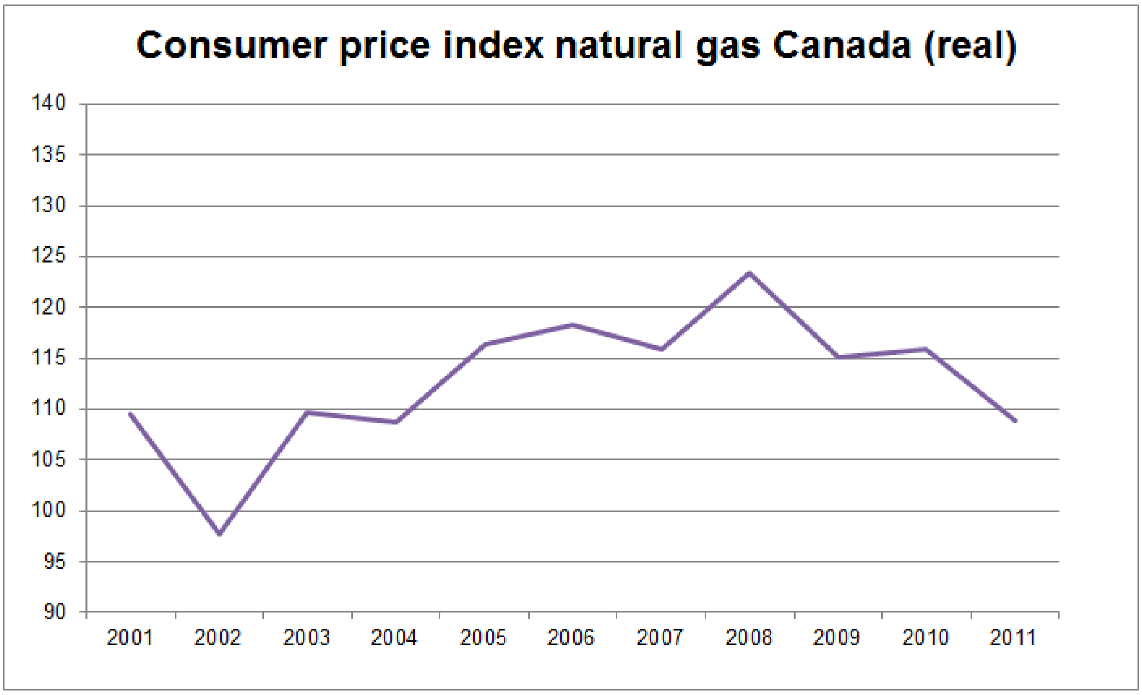

Figure C.4: *Canadian consumer price index natural gas 2001 to 2011 real (basis: 2002 = 100)*
Source: [121]

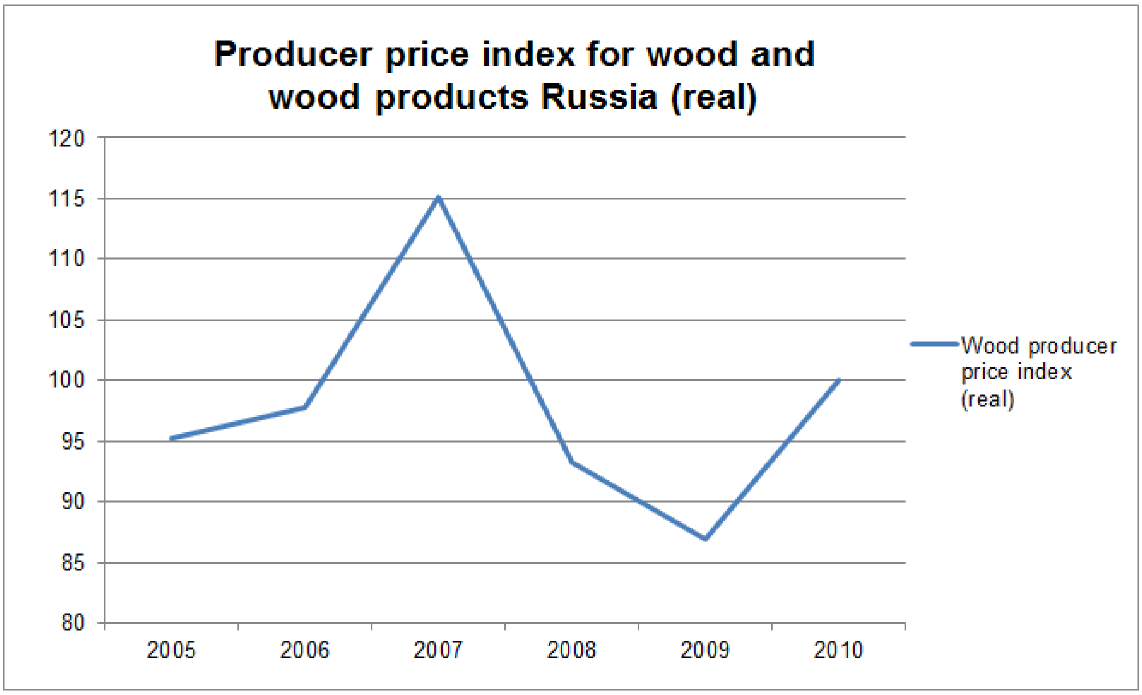

Figure C.5: *Russian wood and wood products producer price index 2005 to 2011 real (basis: end of year percentage to end of previous year)*
Source: [122]

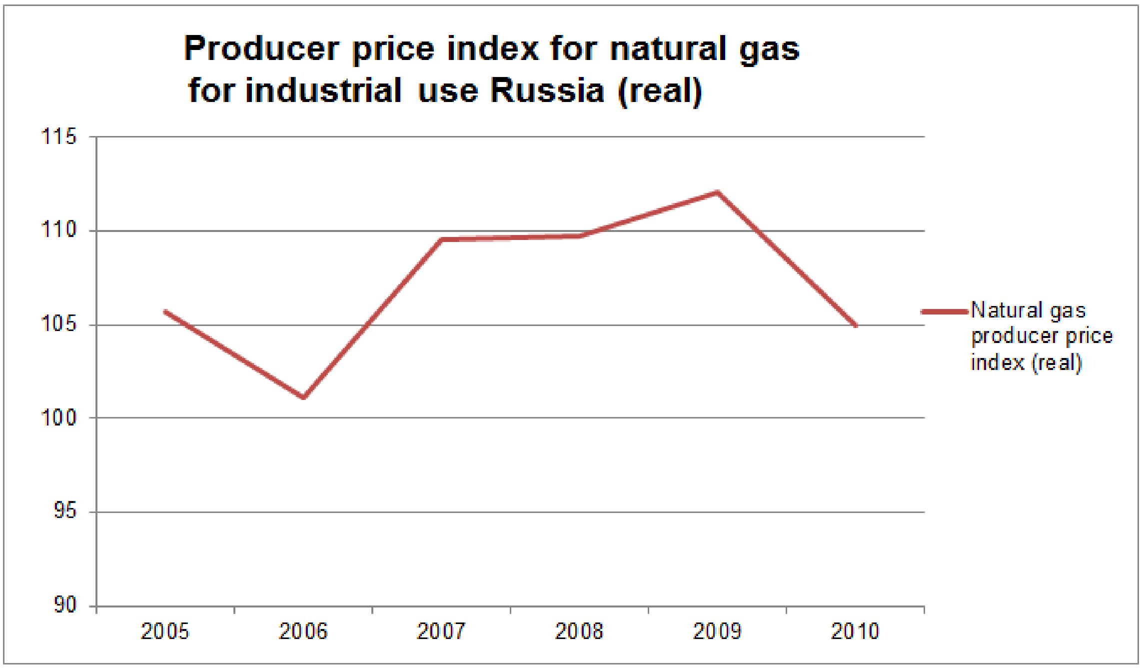

Figure C.6: *Russian producer price index for natural gas for industrial use real (basis: end of year percentage to end of previous year)*
Source: [125]

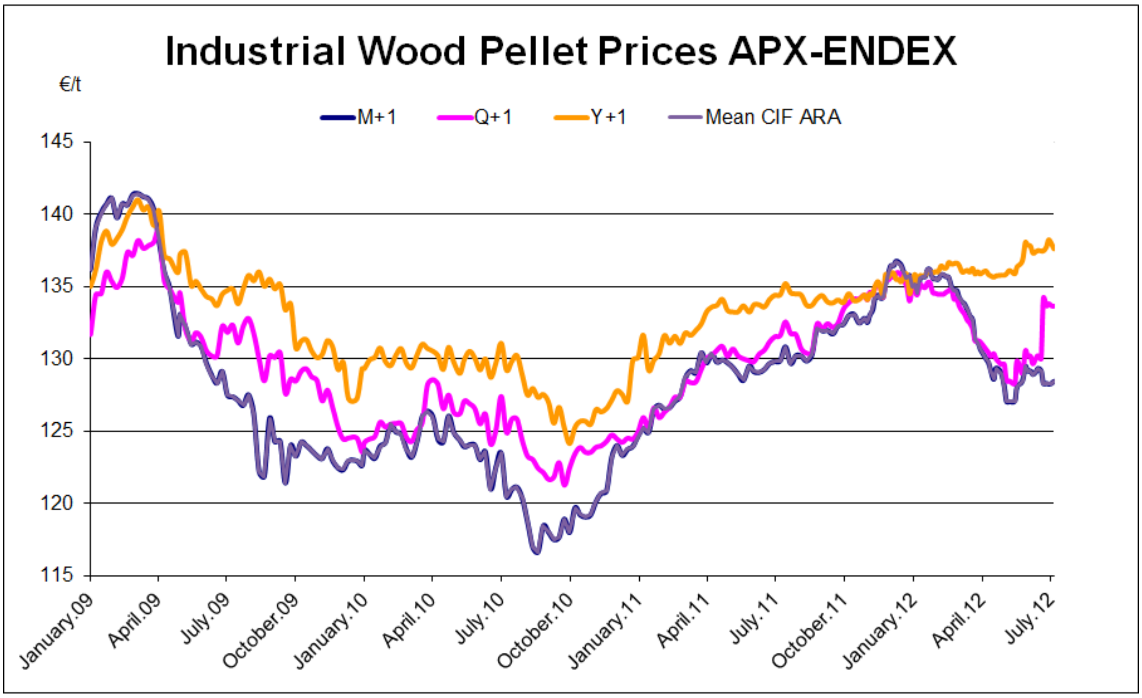

Figure C.7: *Industrial pellet prices at exchange APX-ENDEX in €/t (nominal) for sales 1 month ahead (M+1), 1 quarter ahead (Q+1) and 1 year ahead (Y+1)*
Source: [19]

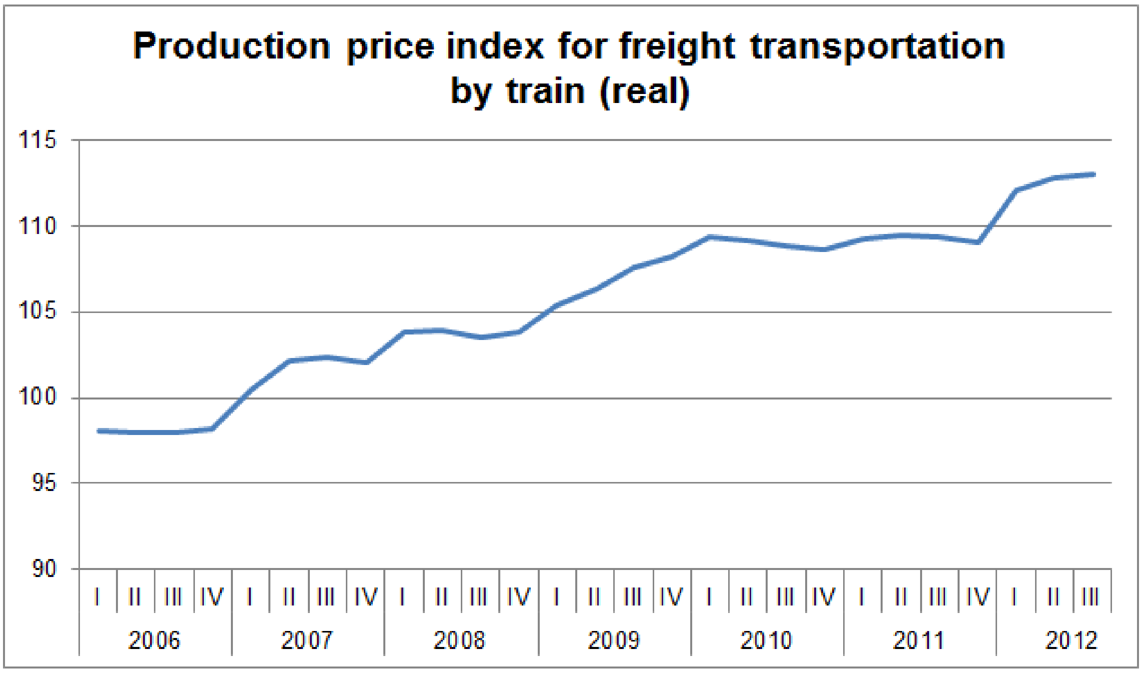

Figure C.8: *German producer price index for freight transportation by train real (basis: I 2006 = 100 (nominal))*
Source: [128]

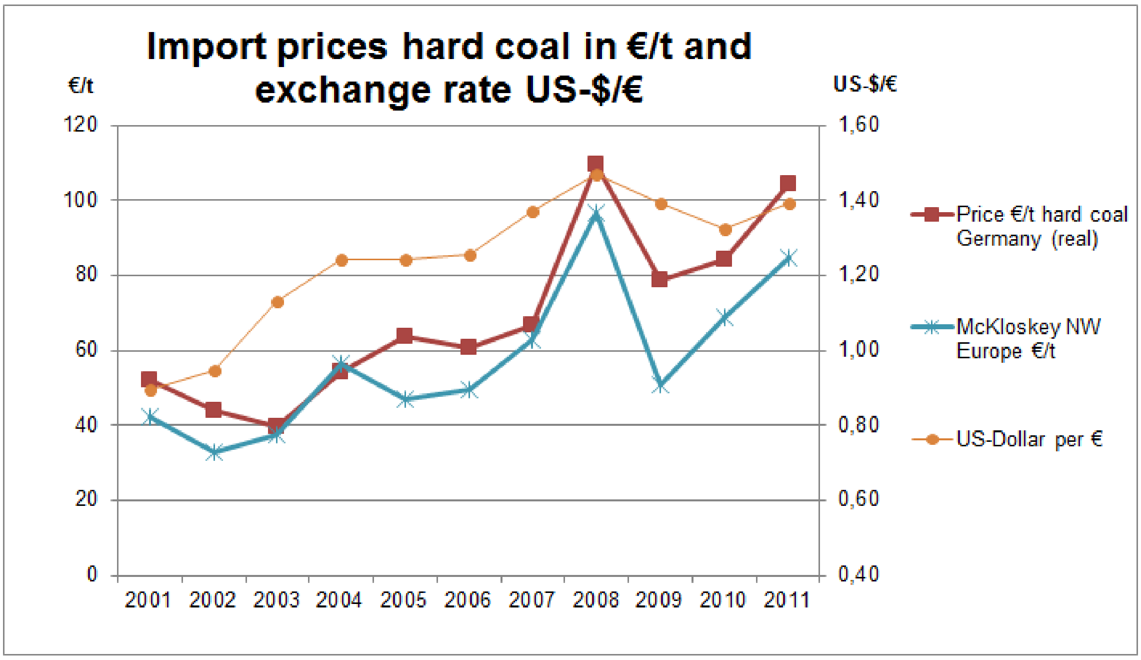

Figure C.9: *Import prices hard coal for Germany (price at crossing border point, real) and McKlosey for Northwest Europe in €/t and exchange rate US-$/€*
Sources: [108, 115, 195]

D Sensitivity analysis - additional charts

D.1 Supply cost variations due to exchange rate fluctuations

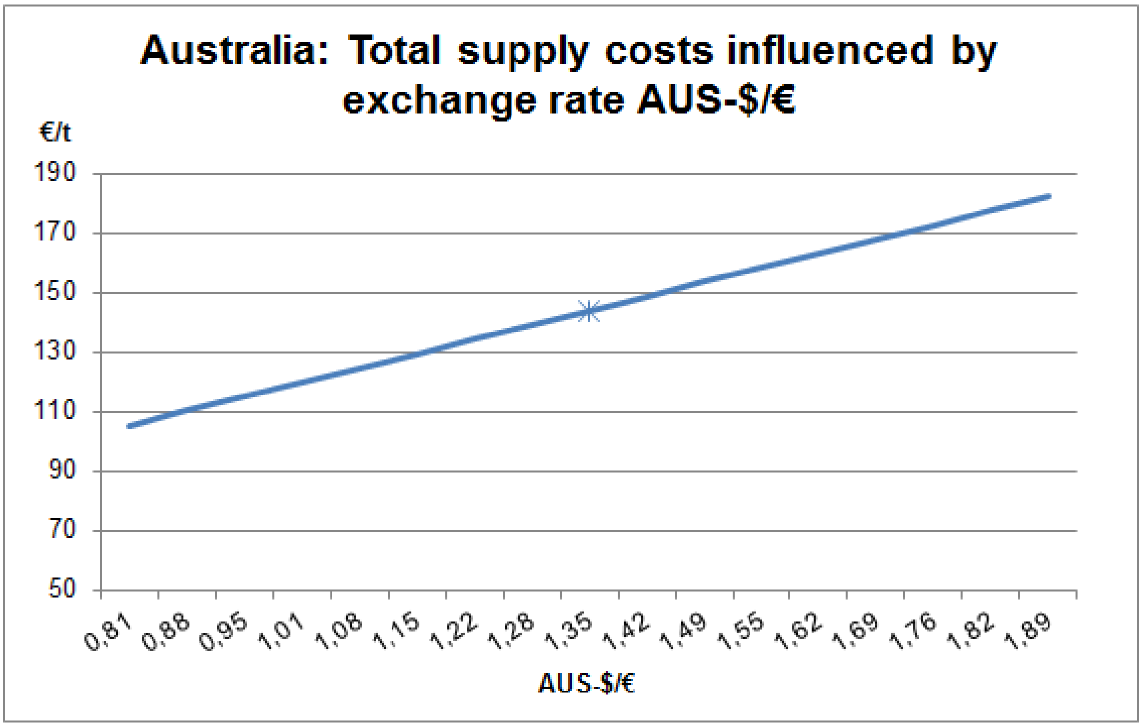

Figure D.10: *Total supply costs for Australian pellets influenced by exchange rate fluctuations*

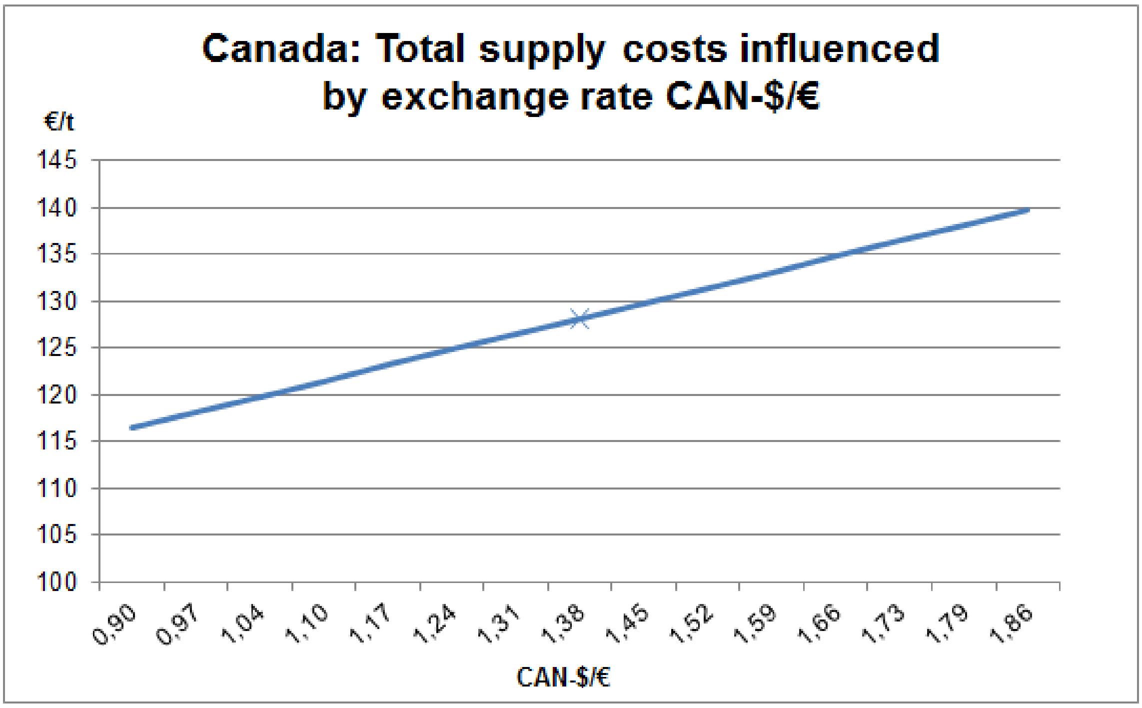

Figure D.11: *Total supply costs for Canadian pellets influenced by exchange rate fluctuations*

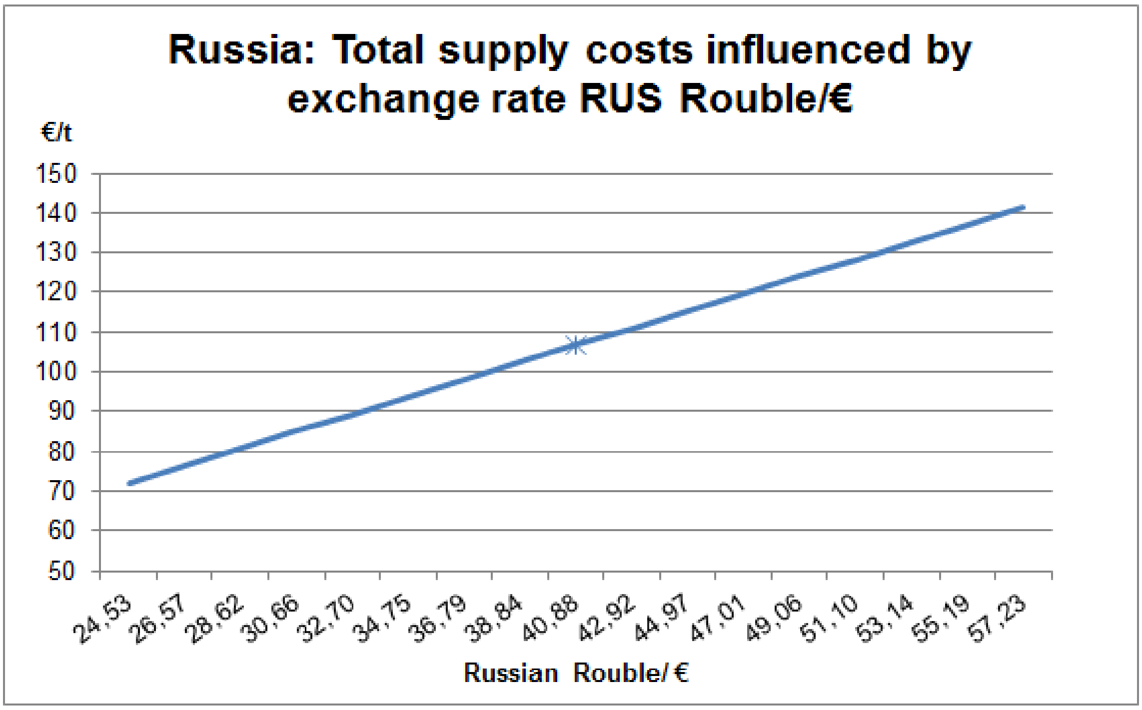

Figure D.12: *Total supply costs for Russian pellets influenced by exchange rate fluctuations*

D.2 Supply cost variations due to raw material price changes

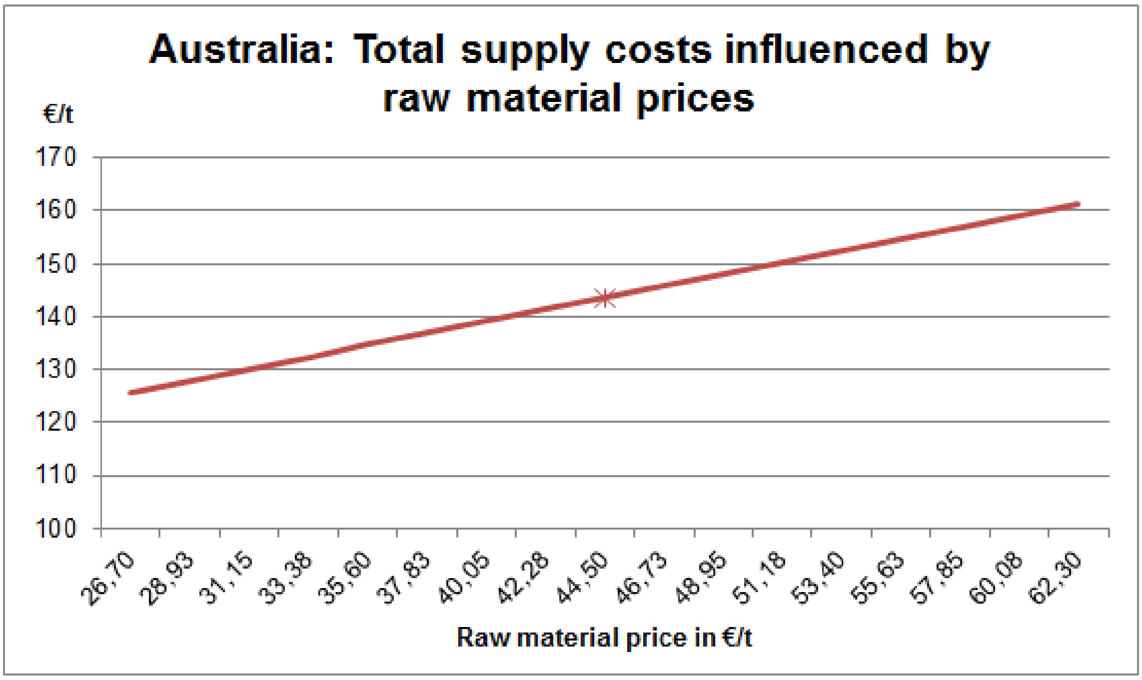

Figure D.13: *Total supply costs for Australian pellets influenced by raw material prices*

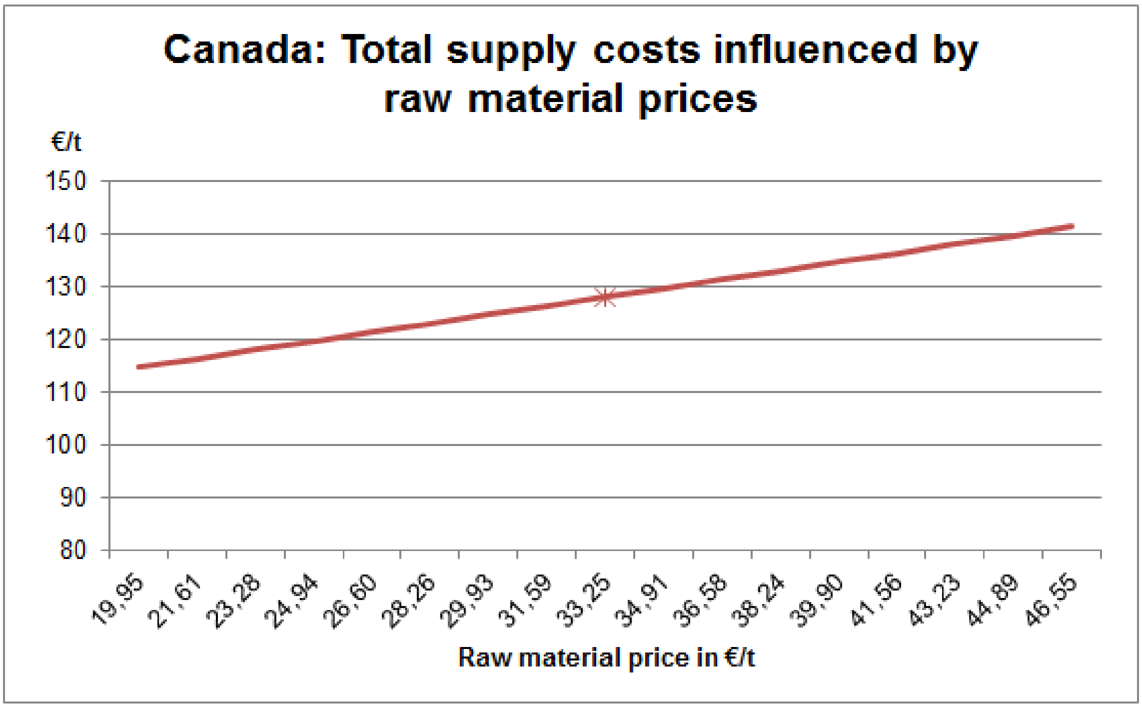

Figure D.14: *Total supply costs for Canadian pellets influenced by raw material prices*

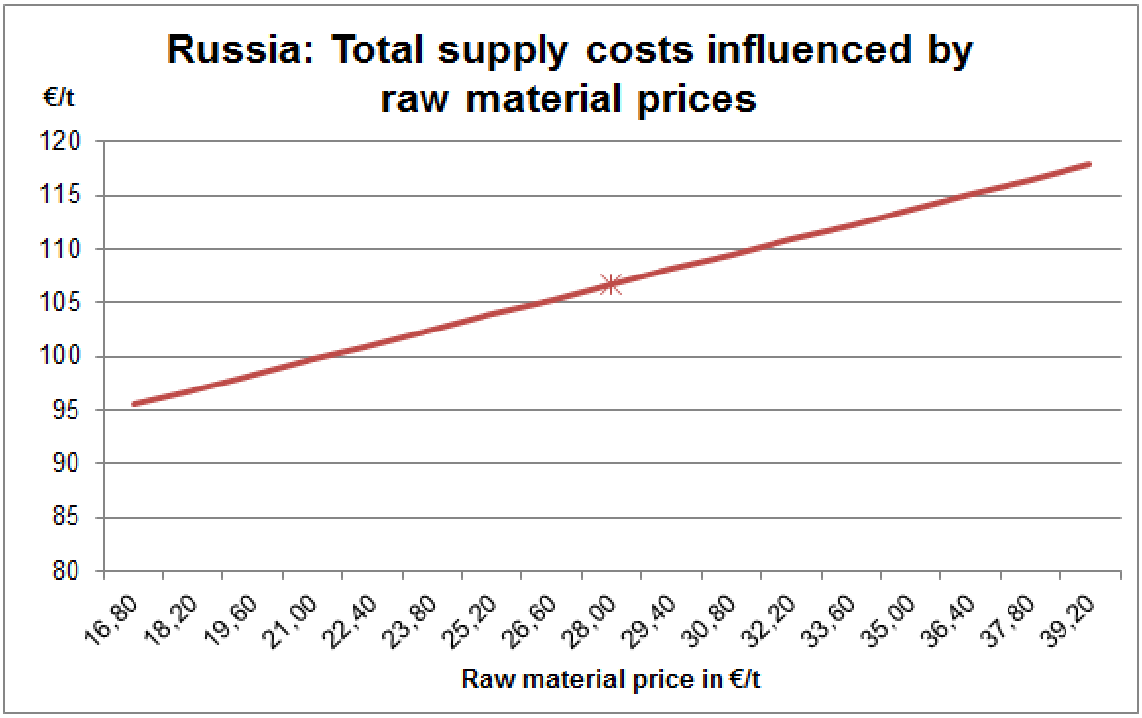

Figure D.15: *Total supply costs for Russian pellets influenced by raw material prices*

References

[1] Ehrig, R.; Behrendt, F.: Co-firing of imported pellets – an option to efficiently save CO_2 emissions in Europe. In: *Energy Policy* 59 (2013), p.283 – 300

[2] Ehrig, R.; Behrendt, F.; Strasser, C.; Wörgetter, M.: Economics and price risks in international pellet supply chains. In: *submitted journal paper* (2013)

[3] Ehrig, R.; Gugler, H.; Kristöfel, C.; Pointner, C.; Schmutzer-Roseneder, I.; Feldmeier, S.; Kolck, M.; Rauch, P.; Strasser, C.; Schipfer, F.; Kranzl, L.; Wörgetter, M.: Economic comparison of torrefaction-based and conventional pellet production-to-end-use-chains. In: *21th European Biomass Conference on 3 - 7 June 2013, Copenhagen*, Eta Florence, WIP Munich, 2013

[4] European Parliament and the Council of the European Union: Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. 2009

[5] Donnelly, M.: Biomass - Role in achieving the 20 In: *Presentation at European Biomass Power Generation Conference, 1st and 2nd October 2012, London*, 2012

[6] Beurskens, L.; Hekkenberg, M.; Vethman, P.: Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States, Summary report / Energy Research Centre of the Netherlands, European Environment Agency. Petten, Copenhagen, 2011. – Research report

[7] Observ'ER: The state of renewable energies in Europe. 11th EurObserv'ER Report. 2012

[8] European Commission, Eurostat: Energy statistics EU - main indicators. http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/. Oct 2013. – accessed 31.10.2013

[9] Lamers, P.; Junginger, M.; Hamelinck, C.; Faaij, A.: Developments in international solid biofuel trade – An analysis of volumes, policies, and market factors. In: *Renewable and Sustainable Energy Reviews* 16 (2012), no. 5, p.3176 – 3199

[10] Cocchi, M.; Nikolaisen, L.; Junginger, M.; Sheng Goh, S.; Heinimö, J.; Bradley, D.; Hess, R.; Jacobson, J.; Ovard, L.; Thrän, D.; Hennig, C.; Deutmeyer, M.; Schouwenberg, P.; Marchal, D.: Global Wood Pellet Industry Market and Trade Study / IEA Bioenergy Task 40: International sustainable bioenergy trade. Florence, Dec 2011. – Research report

[11] European Commission, Eurostat: EU27 trade since 1995 by CN8, Monthly data. http://epp.eurostat.ec.europa.eu/portal/page/portal/. – accessed 24. September 2013

[12] Junginger, M.: Overview of global solid and liquid biomass trade for energy. In: *Proceedings of IEA Bioenergy Conference 2012, November 13 - 15*. Vienna, 2012

[13] IHB Timber Network: The European wood pellets market: Towards a dependency on imports? *Press release 31. October 2013*

[14] Al-Mansour, F.; Zuwala, J.: An evaluation of biomass co-firing in Europe. In: *Biomass and Bioenergy* 34 (2010), no. 5, p.620 – 629

[15] Vakkilainen, E.; Kuparinen, K.; Heinimö, J.: Large Industrial Users of Energy Biomass / IEA Bioenergy Task 40: Sustainable Bioenergy Trade. 2013. – Research report

[16] European Committee for Standardization: EN 14961-2:2011, Solid biofuels – Fuel specification and classes – Part 2: Wood pellets for non-industrial use. 2011

[17] Murray, G.: Canada: Market Situation and Export Perspective on Italy. In: Forum, I. P. (Ed.): 3*rd* *International Pellet Forum, Verona, Italy*, 2012

[18] Biermayr, P.; Eberl, M.; Ehrig, R.; Fechner, H.; Kristöfel, C.; Leonhartsberger, K.; Martelli, S.; Strasser, C.; Weiss, W.; Wörgetter, M.: Innovative EnergietechnEnergie in Österreich. Marktentwicklung 2012. Biomasse, Photovoltaik, Solarthermie und Wärmepumpen / Technische Universität Wien, BIOENERGY2020+,Technikum Wien GmbH, AEE INTEC. Wien, 2013. – Research report

[19] APX-ENDEX: Historical pellets market prices. Weekly prices. Compilation by Commercial Manager Derivatives Sipke Veer. – Amsterdam, 14.07.2012

[20] Ehrig, R.; Wörgetter, M.; Pointner, C.; Kristöfel, C.; Strasser, C.: Biomass mobilisation for industrial-scale bioenergy plants. Practical approach

for establishing real biomass supply pathways in Austria. In: *19th European Biomass Conference and Exhibition on 6-10 June 2011*. Berlin, 2011

[21] Pöyry: Pellets – Becoming a Global Commodity? Pöyry View Point. Global market, players and trade to 2020 / Pöyry Consulting. Vantaa, 2011. – Research report

[22] Bergman, P.: Combined torrefaction and pelletisation. The TOP process / Energy Research Centre of the Netherlands. Petten, 2005. – Research report

[23] Koppejan, J.; Sokhansanj, S.; Melin, S.; Madrali, S.: Status overview of torrefaction technologies. IEA Bioenergy Task 32 report. Final report / Procede Biomass BV. Enschede, Dec 2012. – Research report

[24] Uslu, A.; Faaij, A.; Bergman, P.: Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. In: *Energy* 33 (2008), p.1206 – 1223

[25] European Commission: Biomass action plan. COM(2005) 628 final. Dec 2005. – Brussels

[26] European Commission: Report from the Commission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling. COM(2010) 11. 2010

[27] Hewitt, J.: Flows of biomass to and from the EU. An analysis of data and trends / FERN. Brussels, 2011. – Research report

[28] European Commission: Renewable energy - Biofuels - Recognised sustainability schemes. Online information: http://ec.europa.eu/energy/renewables/biofuels/. – accessed 25.10.2013

[29] Jossart, J.: Current proposals from EU Commission on sustainability criteria, ILUC and LULUCF. In: *Nordic Baltic Bioenergy 2013, Oslo, 21 May 2013*, 2013

[30] Pilzecker, A.: EU biomass policies. In: *European Pellet Conference 2013, February 28 in Wels, Austria*, 2013

[31] Intergovernmental Panel on Climate Change: Renewable Energy Sources and Climate Change Mitigation. Special Report of the Intergovernmental Panel on Climate Change. 2012. – Geneva

[32] van Stappen, F.; Marchal, D.; Ryckmans, Y.; Crehay, R.; Schenkel, Y.: Green certificates mechanisms in Belgium: A useful instrument to mitigate GHG emissions. In: *IEA Bioenergy Task 38 Workshop in Berlin, 11 May 2007*, 2007

[33] Vlaamse Overheid: Decree Establishing General Conditions for Energy Policy – Energy Law of 8 May 2009. 2009. – Brussels

[34] Department of Energy & Climate Change of the UK: Biomass Electricity & Combined Heat & Power plants – ensuring sustainability and affordability. Consultation on proposals to enhance the sustainability criteria and to ensure affordability for the use of biomass feedstock stocks the Renewables Obligation (RO) / Department of Energy & Climate Change of the UK. London, Sep 2012. – Research report

[35] Office of Gas and Electricity Markets, UK: Renewables Obligation: Sustainability Criteria for Solid and Gaseous Biomass for Generators (greater than 50 kilowatts). Dec 2011. – London

[36] Vogel, C.; Herr, M.; Edel, M.; Seidl, H.: Die Mitverbrennung holzartiger Biomasse in Kohlekraftwerken. Ein Beitrag zur Energiewende und zum Klimaschutz? / Deutsche Energie-Agentur GmbH. Berlin, 2011. – Research report

[37] Maciejewska, A.; Veringa, H.; Sanders, J.; Peteves, S.: Co-firing of biomass with coal. Constraints and role of biomass pre-treatment / DG JRC Institute for Energy. Petten, 2006. – Research report

[38] Freppaz, D.; Minciardi, R.; Robba, M.; Rovatti, M.; Sacile, R.; Taramasso, A.: Optimizing forest biomass exploitation for energy supply at regional level. In: *Biomass and Bioenergy* 26 (2004), p.15 – 25

[39] Hamelinck, C.; Suurs, R.; Faaij, A.: International bioenergy transport costs and energy balance. In: *Biomass and Bioenergy* 29 (2005), no. 2, p.114 – 134

[40] Uasuf, A.: Economic and environmental assessment of an international wood pellets supply chain: a case study of wood pellets export from Northeast Argentina to Europe, University Freiburg, PhD thesis, Dec 2010

[41] Sikkema, R.; Junginger, M.; Pichler, W.; Hayes, S.; Faaij, A.: The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. In: *Biofuels, Bioproducts, Biorefinery* 4 (2010), no. 2, p.132 – 153

[42] Bradley, D.; Diesenoeiter, F.; Wild, M.; Tromborg, E.: World Biofuel Maritime Shipping Study / Report accomplished for IEA Task 40. Ottawa, Vienna, 2009. – Research report. 01.07.2009

[43] Bradley, D.; Hektor, B.; Schouwenberg, P.-P.: World Bio-trade Equity Fund Study / IEA Task 40. Ottawa, 2010. – Research report. 18 April 2010

[44] HEINIMÖ, J.: Developing markets of energy biomass - local and global perspectives, Mikkeli University, Mikkeli, Finland, PhD thesis, 2011

[45] SUURS, R.: Long distance bioenergy logistics. An assessment of costs and energy consumption for various biomass energy transport chains / Utrecht University. Utrecht, 2002. – Research report at Utrecht University

[46] KALTSCHMITT, M.; HARTMANN, H.; HOFBAUER, H.: Energie aus Biomasse: Grundlagen, Techniken und Verfahren. 2nd. Springer, Sep 2009

[47] OBERNBERGER, I.; THEK, G.: The Pellet Handbook. London, Washington : Earthscan, 2010. – Published in frame of IEA Bioenergy Task 32

[48] SVANBERG, M.; HALLDÓRSSON, A.: Supply chain configuration for biomass-to-energy: the case of torrefaction. In: *International Journal of Energy Sector Management* 7 (2013), no. 1, p.65 – 83

[49] KALTSCHMITT, M.; THRÄN, D.; SMITH, K.: Renewable energy from biomass. Encyclopedia Physical Science and Technology, 203, 2004

[50] BIOENERGY INTERNATIONAL, SWEDISH BIOENERGY ASSOCIATION: The World of Pellets. *Poster mapping worldwide pellet plants in operation, Sweden.* 2013

[51] URBANOWSKI, E.: Strategic analysis of a pellet fuel opportunity in Northwest British Columbia, University of Saskatchewan, Master thesis, 2005

[52] ANDRITZ FEED & BIOFUEL A/S: Process flows for pellet production. *Personal communication and data submission by global marketing manager Anne-Mette Lund.* Oct 2013

[53] WIELÉN, C.; JUKOLA, P.; JÄRVINEN, T.; SIPILÄ, K.; VERHOEFF, F.; KIEL, J.: Wood torrefaction - pilot test and utilisation prospects / VTT, Energy research Centre of the Netherlands. Espoo, Jun 2013 (VTT Technology 122). – Research report

[54] INTERNATIONAL ORGANISATION FOR STANDARDIZATION: Solid biofuels - Fuel sspecification and classes - Part xxx: Graded torrefied pellets. Draft international standard ISO/TC 238/SC N. Feb 2013

[55] DEUTMEYER, M.; BRADLEY, D.; HEKTOR, B.; HESS, R.; TUMULURU, J.; NIKOLAISEN, L.; WILD, M.: Possible effect of torrefaction on biomass trade / IEA Bioenergy Task 40: International sustainable bioenergy trade. Oslo, Nov 2012. – Research report

[56] STELT, M. v. d.; GERHAUSER, H.; KIEL, J.; PTASINSKI, K.: Biomass upgrading by torrefaction for the production of biofuels: A review. In: *Biomass and Bioenergy* 35 (2011), S.3748–3762

[57] Ciolkosz, D.; Wallace, R.: Areview of torrefaction for bioenergy feedstock production. In: *Biofuels, Bioproducts, Biorefinery* 5 (2011), p.317–329

[58] Agar, D.; Wihersaari, M.: Bio-coal, torrefied lignocellulosic resources - Key properties for its use in co-firing with fossil coal - Their status. In: *Biomass and Bioenergy* 44 (2012), p.107 – 111

[59] Bridgeman, T.; Jones, J.; Shield, I.; Williams, P.: Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. In: *Fuel* 87 (2008), p.844–856

[60] Pirraglia, A.; Gonzalez, R.; Saloni, D.; Denig, J.: Technical and economic assessment for the production of torrefied ligno-cellulosic biomass pellets in the US. In: *Energy Conversion and Management* 66 (2013), p.153–164

[61] Lemus, F.; Gil, J.; Echecerria, I.: Torrefied biomass pellets as coal substitute in power plants. In: *Proceedings of the 20th European Biomass Conference and Exhibition, 18-22th June 2012, Milan, Italy*, 2012

[62] Li, H.; Liu, X.; Legros, R.; Bi, X.; Lim, C.; Sokhansanj, S.: Torrefaction of sawdust in a fluidized bed reactor. In: *Bioresource Technology* 103 (2012), p.453–458

[63] Chen, W.-H.; Hsu, H.-C.; Lu, K.-M.; Lee, W.-J.; Lin, T.-C.: Thermal pretreatment of wood (Lauan) block by torrefcation and its influence on the properties of the biomass. In: *Energy* 36 (2011), p.3012–3021

[64] Wang, C.; Peng, J.; Li, H.; Bi, L. R.; Lim, C.; Sokhansanj, S.: Oxidative torrefaction of biomass residues and densification of torrefied sawdust to pellets. In: *Bioresource Technology* 127 (2013), p.318–325

[65] Stelte, W.; Clemonsb, J.; Holm, J.; Ahrenfeldt, J.; Henoiksen, U.; Sanadi, A.: Fuel pellets from wheat straw - The effect of lignin glass transition and surface waxes on pelletizing properties. In: *Bioenergy Resources* 5 (2012), no. 2, p.450 – 458

[66] Pointner, C.; Ehrig, R.; Kristöfel, C.; Feldmeier, S.; Schmutzer-Roseneder, I.; Wörgetter, M.; Strasser, C.: Torrefied pellets for domestic use - production, properties and utilisation. In: *submitted journal paper* (2013)

[67] Li, J.; Brzdekiewicz, A.; Yang, W.; Blasiak, W.: Co-firing based on biomass torrefaction in a pulverized coal boiler with aim of 100 % fuel switching. In: *Applied Energy* 99 (2012), p.344–354

[68] Chiueh, P.-T.; Lee, K.-C.; Syu, F.-S.; Lo, S.-L.: Implications of biomass pretreatment to cost and carbon emissions. Case study of rice straw and Pennisetum in Taiwan. In: *Bioresource Technology* 108 (2012), p.185–294

[69] Svanberg, M.; Olofsson, I.; Flodén, J.; Nordin, A.: Analysing biomass torrefaction supply chain costs. In: *Bioresource Technology* 142 (2013), August 2013, p.287–296

[70] Magelli, F.; Boucher, K.; Bi, H.; Melin, S.; Bonoli, A.: An environmental impact assessment of exported wood pellets from Canada to Europe. In: *Biomass and Bioenergy* 33 (2009), no. 3, p.434 – 441

[71] van Dam, J.; Faaij, A.; Lewandowski, I.; van Zeebroeck, B.: Options of biofuel trade from Central and Eastern to Western European countries. In: *Biomass and Bioenergy* 33 (2009), no. 4, p.728 – 744

[72] Maderthaner, E.: Comprehensive assessment of the pellet supply chain from Romania to Austria. Wels/ Wieselburg, University of Applied Sciences Wels, Master thesis, Oct 2012. – Supervised by Bioenergy 2020+ GmbH

[73] Mitchell, C.; Bauknecht, D.; Connor, P.: Effectiveness through risk reduction: a comparison of the renewable obligation in England and Wales and the feed-in system in Germany. In: *Energy Policy* 34 (2006), no. 3, p.297 – 305

[74] Cleijne, H.; Ruijgrok, W.: Modelling risks of renewable energy investments (D6 reports) / Carried out by KEMA in frame of FP7 Green-X project. 2004. – Research report

[75] Kruyt, B.; Vuuren, v. D.; Vries, H.; Groenenberg, H.: Indicators for energy security. In: *Energy Policy* 37 (2009), no. 6, p.2166–2181

[76] Dixit, A.; Pindyck, R.; Princeton University Press (Ed.): Investments under Uncertainty. Dixit, A.K. and Pindyck, R.S., 1994

[77] Luehrman, T.: Investment Opportunities as Real Options: Getting Started on the Numbers. In: *Harvard Business Review* July-August (1998), p.1–15

[78] Fernandes, B.; Cunha, J.; Ferreira, P.: The use of real options approach in energy sector investments. In: *Renewable and Sustainable Energy Reviews* 15 (2011), S.4491–4497

[79] Fuss, S.; Johansson, D.; Szolgayova, J.; Obersteiner, M.: Impact of climate policy uncertainty on the adoption of electricity generating technologies. In: *Energy Policy* 37 (2009), p.733–743

[80] Adkins, R.; Paxson, D.: Forest Harvesting with Multi-Factor Uncertainty. In: *Real Options Conference, 15th Annual International Conference June 15-18, 2011, Turku, Finland*, 2011

[81] Wieland, A.; Wallenburg, C.: Dealing with supply chain risks. Linking risk management practices and strategies to performance. In: *International Journal of Physical Distribution & Logistics Management* 12 (2012), p.887–905

[82] Cavallaro, F.: An Integrated Multi-Criteria System to Assess Sustainable Energy Options: An Application of the Promethee Method. In: *Nota Di Lavoro, University of Molise* 22 (2005), p.1–15

[83] Buchholz, T.; Rametsteiner, E.; Volk, T.; Luzadis, V.: Multi Criteria Analysis for bioenergy ssystem assessments. In: *Energy Policy* 37 (2009), p.484–495

[84] Olsson, O.: European bioenergy markets: integration and price convergence. Uppsala, Uppsala University, Licenciate thesis, 2009

[85] Dahlberg, A.: Consequences of new sources of supply on wood fuel prices. Uppsala, Uppsala University, Diploma thesis, Dec 2010

[86] Alakangas, E.; Junginger, M.; van Dam, J.; Hinge, J.; Keränen, J.; Olsson, O.; Porsö, C.; Martikainen, A.; Rathbauer, J.; Sulzbacher, L.; Vesterinen, P.; Vinterbäck, J.: EUBIONET III – Solutions to biomass trade and market barriers. In: *Renewable and Sustainable Energy Reviews* 16 (2012), no. 6, p.4277 – 4290

[87] Sikkema, R.; Steiner, M.; Junginger, M.; Hiegl, W.; Hansen, M.; Faaij, A.: The European wood pellet markets: current status and prospects for 2020. In: *Biofuels, Bioproducts, Biorefinery* 5 (2011), no. 3, p.250 – 278

[88] Joskow, P.: Vertical integration and long-term contracts: The case of coal-burning electric generating plants. In: *Journal of Law, Economics, & Organization* 1 (1985), no. 1, p.33 – 80

[89] Ritschel, W.; Schiffer, H.: World Market for Hard Coal / RWE Power. Essen, Köln, 2007. – Research report

[90] Richards, K.; Domac, J.; Elbe, S.; Bird, N.; Cowie, A.; Chum, H.; Saddler, J.; Junginger, M.; Pelkmans, L.; Jungmeier, G.; Wellisch, M.; Stichnothe, H.; Asikainen, A.; Berndes, G.; George, B.; Krigstin, S.; Neary, D.; Röser, I.; Thiffault, E.; Smith, T.: IEA Bioenergy Inter-Task Strategic Project Proposal "Mobilizing Sustainable Bioenergy Supply Chains". *Working document released on 17 April 2012*

[91] Röder, H.: Global development of bioenergy. In: *Lecture at University of Applied Sciences Wiener Neustadt*. Wieselburg, Nov 2012

[92] Gugler, H.: Torrefizierung. Technologische Anwendungen / TBU Stubenvoll GmbH for TorrChance project. Schlierbach, 2013. – Report prepared for TorrChance project

[93] Andritz Separation: Torrefaction of biomass. The ACB process. Online handout: http://www.andritz.com/de/se-downloads-torrefaction.pdf. 2012. – Graz

[94] Englisch, M.: Torrefaction, fundamentals and basic principles of torrefaction. In: *IEA Bioenergy Task 32 workshop*. Graz, January 2011

[95] Wojcik, M.; Englisch, M.: Report Round Robin I, Validation of "standard" test methods / Report in frame of FP7 Sector project. Vienna, Feb 2013 (Deliverable D8.1). – Research report

[96] Hogan, M.; Otterstedt, J.; Morin, R.; Wilde, J.: Biomass for heat and power - Opportunity and economics / European Climate Foundation, Södra, Sveaskog, Vattenfall. Berlin, Brussels, 2010. – Research report

[97] Feldmeier, S.; Pointner, C.; Schmutzer-Roseneder, I.; Schwabl, M.: Brennstoffqualität torrefizierter Pellets / Bioenergy 2020+ in frame of TorrChance project. Wieselburg, 2013. – Research report

[98] European Commission: Commission decision of 18 July 2007 establishing guidelines for the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council (2007/589/EC). Aug 2007. – 31.08.2007

[99] PE International GmbH and IKP University of Stuttgart: GaBi 4 Software and data base for Life Cycle Engineering, Version 4.4. Jan 2012. – Leinfelden-Echterdingen

[100] Ökoinstitut: GEMIS 4.7 software and database. 2011. – Freiburg

[101] University of Technology Vienna: BIOBIB - A Database for biofuels. http://www.vt.tuwien.ac.at/biobib/. – accessed 31.10.2011

[102] Verein Deutscher Ingenieure: VDI 2067: Economic efficiency of building installations.Fundamentals and economic calculation. 2010. – Düsseldorf

[103] Umweltbundesministerium: Leitstudie 2010 - Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global. Datenanhang II / Umweltbundesministerium. Stuttgart, Kassel, Teltow, Dec 2010. – Research report

[104] European Environment Agency: Opinion of the EEA Scientific Committee on Greenhouse Gas Accounting in Relation to Bioenergy / European Environment Agency, Scientific Committee. Copenhagen, 2011. – Research report. 15.09.2011

[105] Jansen, J.; Lensink, S.; Ozdemir, O.; Stralen, J. v.; Welle, A. v. d.: Cost-benefit analysis of alternative support schemes for renewable electricity in the Netherlands / Energy Research Centre of the Netherlands. Petten, 2011 (ECN-E–11-002). – Research report

[106] European Energy Exchange: ARA Coal Year Futures. Request of historical prices and volumes. http://www.eex.com/de/Marktdaten/Handelsdaten/Kohle/Coal. – accessed 15.02.2012

[107] European Energy Exchange: Prices and trade volume of EU Emission Allowances. Request of historical prices and volumes. http://www.eex.com/de/Marktdaten/Handelsdaten/Emissionsrechte. – accessed 15.02.2012

[108] European Commission, Eurostat: Euro/Ecu Exchange rates 2000 - 2011. Quarterly data. http://epp.eurostat.ec.europa.eu/portal/page/portal/. Jul 2012. – last update 4 July 2012

[109] Office of Gas and Electricity Markets, UK: Renewables Obligation: Guidance for generators. May 2011. – London

[110] Kalt, G.; Kranzl, L.: Assessing the economic efficiency of bioenergy technologies in climate mitigation and fossil fuel replacement in Austria using a techno-economic approach. In: *Applied Energy* 88 (2011), no. 11, p.3665 – 3684

[111] Schwarz, M.; Schmidthaler, M.; Goers, S.; Tichler, R.: Vermeidungskosten von Treibhausgasemissionen in Oberösterreich. In: *7. Internationale Energiewirtschaftstagung an der TU Wien*. Vienna, Linz, 2011

[112] European Renewable Energy Council: Belgium. Renewable energy policy review. 2009. – Brussels

[113] Schachtschneider, R.: Flanders: Quota system (Groenestroomcertificaten). Renewable energy policy database and support. http://176.9.160.135/search-by-country/belgium/single/s/res-e/t/promotion/aid/flanders-quota-system-groenestroomcertificaten/lastp/107/. – accessed 30.10.2012

[114] UK Secretary of State: The Renewables Obligation Order. Electricity, England and Wales. Mar 2009

[115] Bundesamt für Ausfuhrkontrolle; für Ausfuhrkontrolle, B. (Ed.): Drittlandskohlepreis. Durchschnittliche Einfuhrpreise frei deutsche Grenze für Kraftwerkssteinkohle. http://www.bafa.de/bafa/de/energie/steinkohle/drittlandskohlepreis. – accessed 20.02.2012

[116] Prognos AG: Variantenvergleich Küste versus Binnenland. Ein volkswirtschaftlicher Vergleich der Kosten, Versorgungssicherheit und Umweltverträglichkeit von Kraftwerksstandorten / Prognos. Berlin, 2006. – Research report

[117] Sumetzberger, H.: Personal communication with the supply and logistics manager of fuel trade company Genol GmbH & Co KG. – 08.02.2012, Vienna

[118] Mumm, M.; Physica Verlag (Ed.): Kosten- und Leistungsrechnung: Internes Rechnungswesen für Industrie- und Handelsbetriebe. Hamburg : Springer, 2008

[119] European Commission, Eurostat: Harmonised Consumer Price Index – Inflation rate 1997 – 2011 European and Non-European countries. http://epp.eurostat.ec.europa.eu/. 2012. – accessed 12.12.2012

[120] Australian Government, Department for Environment, Fishery and Forestry: Forest and wood products statistics / Department of Agriculture, Fisheries and Forestry. Canberra, Dec 2011. – Research report

[121] Statistics Canada: Table 330-0007 - Raw materials price indexes – 2306. Monthly data, 2002=100". Data request. http://www.statcan.gc.ca. – accessed 19.07.2012

[122] Russian Federation, Federal State Statistics Service: 25.15. Producer price indices by kinds of economic activities. Manufacture of wood and wood products. 2000, 2005 – 2010. Oct 2012. – Moscow

[123] Australian Government, E.; in Australia, T. E.: Energy in Australia / Bureau of Resources and Energy Economics. Canberra, Feb 2012. – Research report

[124] Statistics Canada: Prices and price indexes. Consumer price index natural gas. Data request. http://www.statcan.gc.ca. – accessed 19.07.2012

[125] Russian Federation, Federal State Statistics Service: 25.12. Indices of Producer and purchase prices for basic types of fuel-energy resources purchased by industrial organizations. Combustible natural gas at purchase price. 1995, 2000, 2005 – 2010. Oct 2012. – Moscow

[126] Maersk, M.: Baltic Dry Index. Compilation of daily data 1984 - 2010 from Bloomberg. Edited by Copenhagen Business School. 2010. – Frederiksberg

[127] Korea Maritime Institute: Shipping indexes. Baltic Dry Index. Daily data since 2010. Online information: http://www.kmi.re.kr/Daily.do?command=List. – accessed 15.08.2012

[128] Statistisches Bundesamt Deutschland: Erzeugerpreisindizes für Verkehrs- und Logistik-Dienstleistungen, Quartalswerte Deutschland 2006 bis 2012. Nov 2012. – Wiesbaden

[129] Bluenext exchange: Statistics. BlueNext Spot EUA. Historical transactions from 24.06.2005 to 15.08.2012. http://www.bluenext.eu/statistics/downloads.php. – accessed 20.08.2012

[130] May, B.: Personal communication about biomass prices and the Australian biomass market with former researcher at Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia's national science agency. Communication by e-mail. – 06.08.2012

[131] Baruya, P.: Supply costs for internationally traded coal / IEA Clean Coal Centre. London, 2007. – Research report

[132] Euracoal: EURACOAL Market reports 2006 - 2013. Published online: http://www.euracoal.be/pages/medien.php?idpage=707. – Accessed 07.07.2013

[133] Bradley, D.: Canada - Biomass Supply/Demand, Export Availability. In: 2012, W. B. (Ed.): *Proceedings of World Bioenergy 2012*. Jönkoping, May 2012

[134] Schuck, S.: Bioenergy Industry / Clean Energy Council. Killara, Jun 2010. – Research report

[135] Stucley, C.; Schuck, S.; Sims, R.; Bland, J.; Marino, B.; Borowitzka, M.; Abadi, A.; Bartle, J.; Giles, R.; Thomas, Q.: Bioenergy in Australia, Status and Opportunities / Bioenergy Australia. Surrey Hills, Victoria, Nov 2012. – Research report

[136] Smith, D.: Australia Pellet Export Outlook. In: Meeting of the Executive Committee of IEA Bioenergy in Nara City, J. o. . M. .. (Ed.): *IEA Bioenergy ExCo65 Workshop Developing Sustainable Trade in Bioenergy*. Nara City, Japan, 2010

[137] Waring, J.: Developing a pellet energy business in Australia. In: *Proceedings of Bioenergy Australia Conference 2010, 8-10 December 2010, Sydney*, 2010

[138] Goh, C.; Junginger, M.; Bradley, D.; Hektor, B.; Wild, M.; Deutmeyer, M.; Schouwenberg, P.; Hess, R.; Tumuluru, J.; Bradburn, K.: Low Cost, Long Distance Biomass Supply Chains / IEA Bioenergy Task 40: Sustainable International Bioenergy Trade. Utrecht, Ottawa, 2013. – Research report

[139] Grieve, O.: Albany biomass pellet plant winds up. News release of ABC rural broadcast service: http://www.abc.net.au/rural/news/content/201202/s3422461.htm. – accessed 02.03.2012

[140] Lang, A.: Australia and New Zealand: a future pellet exporter? In: *European Pellet Conference 2013, Wels*, 2013. – 28.02.2013

[141] Electricity Forum: Plantation Energy signs contract with Electrabel for fuel pellets. Press release: http://www.electricityforum.com/news/may09.html. – accessed 20.09.2012

[142] South East Region Conservation Alliance Australia: First Australian native forest wood pellet plant set to shore up logging and increase risk of fire inferno in South East. Media Release. Feb 2012. – 2 February 2012

[143] AXS Marine: Ocean shipping distances. http://www.axsmarine.com/distance/. – accessed 31.01.2012

[144] Allen, D.: Energy pellet production experience. In: *CRC for Forestry workshop: 'Generating renewable energy from forest residues: Opportunities, challenges and the latest research' on 14 April 2011.* Canberra, April 2011

[145] Freight Metrics Pty Ltd: Truck Operating Cost Calculator. http://www.freightmetrics.com.au/CalculatorsRoad/. Oct 2012. – accessed 10.10.2012

[146] Authority, A. P.: Port Talk. Albany Port Community Newsletter. Mar 2010

[147] Alderton, P.: Personal communication with bulk parcel operator Furness Withy Australia about ocean transport freight costs for wood pellets. – 23.07.2012

[148] Ökoinstitut; Enerko: Vergleich von Heizkraftwerksvarianten für die Stadtwerke Kiel. Technische, wirtschaftliche und ökologische Bewertung / Stadtwerke Kiel. Aldenhoven, Berlin, 2008. – final report

[149] Ferguson, S.: Bioenergy Development in British Columbia, Canada. Mutual Exchange with Europe. In: *4biomass workshop on 5th October 2010.* Vienna, 2010

[150] Bradley, D.: Canada Report on Bioenergy 2010 / Canadian Bioenergy Association, Natural Resources Canada, Wood Pellet Association of Canada. Ottawa, Sep 2010. – Research report

[151] Verkerk, B.: Current and future trade opportunities for woody biomass end-products from British Columbia, Canada, Utrecht University, Diploma thesis, 2008

[152] Wiik, C.; Heiskanen, V.; Kallio, M.; Antilla, P.: Wood pellet raw material from British Columbia. Global potential of modern fuelwood / VTT. 2009. – Research report VTT-R-10283-08

[153] Riezinger, A.: Die Ermittlung der ökologischen Effizienz der Bereitstellungskette von Waldhackgut anhand ausgewählter Fallstudien. Vienna, University of Applied Life Sciences Vienna, Diploma thesis, 2008

[154] Spelter, H.; McKeever, T.: North America's Wood Pellet Sector / United States Department of Agriculture, Forest Service, Forest Products Laborator. Madison, 2009 (Research Paper FPL–RP–656). – Research report

[155] Canadian National Railway Company: Price proposal for appr. 500 km rail transport of pellets to port of Vancouver by covered hopper. http://www.cn.ca. Dec 2011. – accessed 13.12.2011

[156] Melin, S.: Design of logistics for regular and torrefied pellets. In: *BC-Korea Bioenergy Collaboration, Vancouver, 20 March 2012.* Vancouver, 2012

[157] Karjalainen, T.; Gerasimov, Y.: Energy wood resources availability and delivery cost in Northwest Russia. In: *Proceedings Third International Symposium on Energy from Biomass and Waste, 8 - 11 November 2010.* Venice, 2010. – 8 - 11 November 2010

[158] Rakitova, O.; Ovsyanko, A.; Sikkema, R.; Junginger, M.: Wood Pellets Production and Trade in Russia, Belarus & Ukraine / Subcontracting to Pellets@las project. Utrecht, May 2009. – Market research report

[159] Rakitova, O.: The development of pellet production in Russia 2011. In: *EU-BIONET workshop on 19 April 2011* National Bioenergy Union, The Bioenergy International, Russia Infobio, 2011

[160] JSC Vyborgskaya Cellulose: Information on cellulose and pellet plant in Vyborgskaya. http://www.vybcell.ru/en/production.html. – accessed 13.11.2012

[161] Reisenbichler, R.: Energieeffizienzsteigerung durch standardisierte Energieaudits in Industrie und produzierendem Gewerbe. Vienna, University of Technology Vienna, Diploma thesis, 2009

[162] Ovsianko, A.: Possibilities and threats for European business in the Russian bio-energy sector under its current condition. In: *Russian Forestry Review* - (2006), no. 01, p.94–103

[163] Rakitova, O.; Kholodkov, V.: The pellet market and wood resources in the North-West of Russia / Baltic 21 Lighthouse project The Baltic Sea Bioenergy Promotion Project. St. Petersburg, 2009. – final report

[164] Gerasimov, Y.: Personal communication with Russian biomass expert at Finish research centre Metla. Feb 2012. – E-mail communication on 1 February 2012

[165] Eco World Styria: Energiekennzahlen und Energiesparpotentiale in der Sägeindustrie / Wirtschaftskammer Oberösterreich, Ökologische Betriebsberatung und O.Ö. Energiesparverband. Linz, 1997. – Research report

[166] Jawjit, W.; Kroeze, C.; W., S.; Hordijk, L.: An analysis of the environmental pressure exerted by the eucalyptus-based kraft pulp industry in Thailand. In: *Environment, Development and Sustainability* 8 (2006), no. 2, p.289 – 311

[167] Department of Energy & Climate Change of the UK: Biomass Electricity & Combined Heat & Power plants – ensuring sustainability and managing costs. Impact Assessment / Department of Energy & Climate Change of the UK. London, Sep 2012. – Department of Energy & Climate Change of the UK

[168] McGowin, C.: Renewable Energy Technical Assessment Guide TAG-RE:2007 / Electric Power Research Institute. Palo Alto, CA, 2008. – Research report

[169] Bain, L.: Biopower Technologies in Renewable Electricity Alternative Futures / National Renewable Energy Laboratory. Golden, CO, 2011. – Research report

[170] Obernberger, I.; Thek, G.; Reiter, D.: Economic evaluation of decentralised CHP applications based on biomass combustion and biomass gasification. In: *Proceedings of the Central European Biomass Conference 2008*. Graz, 2008

[171] E-Control: CO_2 reduction costs of generating renewable energy compared to expenditure on support payments / E-Control. Wien, 2009. – Research report

[172] Office of Gas and Electricity Markets, UK: Feed-in Tariff scheme: Tariff Table 1 December 2012 - 31 March 2013 Non-PV Only and PV Only. – 13.08.2012, update 18.10.2012

[173] OEMAG: Ökostrom - Einspeisemengen und Vergütungen (inkl. Marktwert) in Österreich 1. Halbjahr 2012 sowie Vergleich zum 1. Halbjahr 2011. Aug 2012. – 21.08.2012

[174] Geiver, L.: Contract concepts. From spot purchases to multi-year deals, producers, buyers and brokers must know their way around supply agreements. In: *Biomass Magazine* 6 (2012), no. 7, p.25 – 29

[175] Senechal, S.; Grassi, G.; Nordenmark, M.; Vivarelli, F.; Junginger, M.; Sikkema, R.: Logistic management of wood pellets: Data collection on transportation, storage and delivery management. Development and promotion of a transparent European Pellets Market / in frame of the task "Creation of a European real-time Pellets Atlas" for Pellets@las project. Brussels, 2009. – Research report

[176] International Energy Agency: World Energy Outlook 2011. Paris : OECD, International Energy Agency, 2011

[177] WIP Renewable Energies: Pellets market data. Request and data collection in database: http://www.pelletsatlas.info/cms/site.aspx?p=9138. – accessed 20.07.2012

[178] AUBOIN, M.; RUTA, M.: The relationship between exchange rates and international trade: A literature review / World Trade Organization (WTO). Geneva, Oct 2011. – Staff Working Paper ERSD-2011-17

[179] LARSSON, S.; RUDOLFSSON, M.; NORDWAEGER, M.; OLOFSSON, I.; SAMUELSSON, R.: Effects of moisture content, torrefaction temperature, and die temperature in pilot scale pelletizing of torrefied Norway spruce. In: *Applied Energy* 102 (2013), p.827 – 832

[180] NL AGENCY: Bioenergy Status Document 2010 / Ministry of Economic Affairs and Agriculture The Netherlands. Utrecht, Mar 2011. – Research report

[181] RWE: Tilbury Power Plant Information. http://www.rwe.com/web/cms/en/1295424/rwe-npower/. Nov 2012. – accessed 20.11.2012

[182] ZANCHI, G.; PENA, N.; BIRD, N.: The upfront carbon debt of bioenergy / Joanneum Research. Graz, May 2010. – Study commissioned by BirdLife International

[183] MITCHELL, S.; HARMON, M.; O'CONNELL, K.: Carbon debt and carbon sequestration parity in forest bioenergy production. In: *Global Change Biology Bioenergy* 4 (2012), no. 6, p.1 – 10

[184] NABUURS, G.; THÜRIG, E.; HEIDEMA, N.; ARMOLAITIS, K.; BIBER, P.; CIENCIALA, E.; KAUFMANN, E.; MÄKIPÄÄ, R.; NILSEN, P.; PETRITSCH, R.; PRISTOVA, T.; ROCK, J.; SCHELHAAS, M.; SIEVANEN, R.; SOMOGYI, Z.; VALLET, P.: Hotspots of the European carbon cycle. In: *Forest Ecology and Management* 256 (2008), no. 3, p.194 – 200

[185] PELKMANS, L.; DEVRIENDT, N.; GOOVAERTS, L.; SCHOUWENBERG, P.: Prospective study: Implementation of sustainability requirements for biofuels and bioenergy and related issues for markets and trade / vito study accomplished within IEA Bioenergy Task 40. Mol, Feb 2012. – Research report

[186] RÖDER, H.: European biomass market and trends. In: *Stakeholder dialogue „Verfügbarkeit forstlicher Biomasse", 29 November 2010, OMV headquarter*. Vienna, 2010

[187] BUNDESNETZAGENTUR: Kraftwerksliste Bundesnetzagentur zum erwarteten Zu- und Rückbau 2013 bis 2018. Stand 16.10.2013. http://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/. Oct 2013. – accessed 20.01.2014

[188] US DEPARTMENT OF LABOR: International Comparison of hourly compensation costs in manufacturing. *Statistical report*. 2011

[189] Raitila, J.; Virkkunen, M.; Flyktman, M.; Leinonen, A.; Gerasimov, Y.; Karjalainen, T.: The pre-feasibility study of biomass plant in Kostomuksha / VTT. Jyväskylä, 2009 (Research Report VTT-R-08372-08). – Research report

[190] BC Hydro: Electricity tariff request. http://www.bchydro.com/youraccount/content/. Jun 2011. – accessed 20.06.2011

[191] World Nuclear Association: Australia's Electricity. Online information: http://www.world-nuclear.org/info/inf64.html. – accessed 20.06.2012

[192] Engineroom: Gas Pricing – Cost Drivers and Scenarios for Future Price Directions / report funded by the Consumer Advocacy Panel. Sydney, . – Research report. 12 October 2009

[193] Energyshop: Request of regulated natural gas tariff for industrial consumers in British Columbia. http://www.energyshop.com/es/prices/BC/. May 2012. – accessed 12.05.2012

[194] Federal Tariff Service Russia: Natural gas wholesale price for industrial consumers for 2010. http://www.fstrf.ru/eng/tariffs/. 2012. – accessed 20.06.2012

[195] BP: BP Energy Outlook 2012. Data sheets. http://www.bp.com/. Jul 2012. – accessed 15.07.2012

[196] Australian Government, Department of Infrastructure, Transport, Regional Development and Local Government: Freight rates in Australia. 1964-65 to 2007-08 / Bureau of Infrastructure, Transport and Regional Economics. Canberra, 2008. – Information sheet 28

[197] Bank of Canada: Exchange rates per Canadian dollar. Historic monthly data 2000 – 2012 / Bank of Canada. Ottawa, Oct 2012. – Research report

[198] Barel, C.: Pellet market country report BELGIUM / ADEME. Metz, Oct 2009. – Report prepared in frame of Pelletsatlas project

[199] Dusan, S.: Personal communication with Vattenfall Black Pellet Manager about testing the co-firing of torrefied pellets in a Vattenfall coal power plant. Aug 2011. – 08.08.2011

[200] Food and Agricultural Organisation of the United Nations: FAOStat data request. http://faostat3.fao.org. Sep 2012. – accessed 20.09.2012

[201] Forest & Wood Products Australia: Opportunities for using sawmill residues in Australia / Forest & Wood Products Australia. Melbourne, Nov 2007. – working paper

[202] Hermes, H.: Personal communication with Director Business Development Biomass of Vattenfall Europe GmbH. Oct 2012. – 29.10.2012