Studies on the Agricultural and Food Sector in Transition Economies

Lioudmila Chatalova

Market uncertainty, project specificity and policy effects on bioenergy investments

A real options approach

Leibniz Institute of Agricultural Development in Transition Economies

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by

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Summary

While renewable energy is considered as an indispensable component of the energy mix from the political and societal perspective, its economic relevance remains questionable. Especially bioenergy production from agricultural crops and its promotion have generated a highly emotional and controversial debate. Indeed, the currently very small global share of crop-based bioenergy is opposed by the disproportionately high macroeconomic and social costs of its production. Thus, it is unsurprising that this topic continues to attract much research attention.

Crop-based bioenergy production takes place at the intersection of the energy and food markets. The hybrid nature of the bioenergy sector brings about typical cost and volatility structures, duration of investment project realization and degrees of managerial flexibility that may significantly differ from other types of bioenergy. Besides, crop-based bioenergy is not only expected to be alternative, sustainable and cost-efficient, but also not to impair the food security. These particularities pose manifold economic, political and methodological challenges.

Scientific and societal debates on agricultural bioenergy remain dominated by the discussion concerning the food-fuel conflict. Being doubtlessly important this perspective however reduces the role of bioenergy producers to a medium of price and volatility transmittance, directing the focus away from the bioenergy producer as a decision-maker. Against this background, the present dissertation aims to analyze the strategic investment decisions of bioenergy producers under explicit consideration of the specificity of crop-based bioenergy and different policy regimes. The dissertation places its key focus on the following three research questions: (I) Do multiple uncertainties reduce the investment incentives of bioenergy producers? (II) Do specifics of crop-based bioenergy production affect the investment rule? (III) What are the macroeconomic implications of bioenergy production under alternative policy regimes?

The *first research question* draws attention to the fact that for a consistent valuation of bioenergy projects, not only should the output market uncertainty be of interest (as is often the case in the relevant research), but also the non-negligible uncertainties on the input market. Although the general investment literature provides sufficient evidence that the effect of multiple uncertainty sources

is not always additive, the simultaneous effect of the volatilities on the factor and sales markets has hardly been discussed in the bioenergy literature. In fact, an expected price decrease on the input market may to some extent neutralize unfavorable price movements on the output market, thus influencing business plans.

In order to investigate this effect and its implications for the interrelated markets, we develop a stylized stochastic dynamic partial equilibrium model of bioenergy investments under two uncertainties. The latter are assumed to stem from the stochastic shocks on the energy market (uncertain output price) and the agricultural market (uncertain food demand) and to follow the geometric Brownian motion. Within this model, the equilibrium investment threshold price of the aggregated bioenergy producer (i.e. bioenergy sector) is derived numerically in repeated real options-based stochastic simulation experiments in combination with genetic algorithms. The analysis utilizes empirical parameter values reported for crop-based bioenergy (particularly biogas) production in the EU. Because assessments of investments under uncertainty – particularly those lacking an analytical solution – not only depend upon the investment conditions and assumptions but also on the applied methodology, the dissertation elaborates upon the reliability of the real options approach (ROA) as its underlying methodological tool.

The *second research question* addresses distinct specifics of crop-based bioenergy projects and their role in investment valuations within the ROA framework, namely the relatively high variable cost, a long time-to-build and the managerial ability to take corrective actions during the projects. The ROA-based studies typically highlight the role of high sunk costs of irreversible projects. Indeed, the magnitude of the sunk costs of many agricultural investments is significant, which – together with projects' irreversibility and flexibility – warrants the application of the option pricing theory. However, practically no attention is given to the fact that a project's variable cost may exceed its annualized fixed cost by several times (up to a factor of three). In combination with producers' ability to respond to contingencies (e.g. by temporarily pausing production) and hence economize on a part of production costs, high variable costs may significantly affect the curvature of the profit functions. Therefore, the net effect of uncertainty on investment incentives may not necessarily be monotonously negative: a conclusion that seemingly contradicts the central proposition of the option pricing theory. An explicit analysis of the role of these three specifics of irreversible crop-based bioenergy investments under two uncertainties is the central concern of the present work and constitutes its novelty.

To answer the first and the second research questions, it is assumed that there are no policy support programs for the bioenergy sector. The results obtained demonstrate that the simultaneous presence of a long time-to-build, high variable costs and the possibility to flexibly respond to changes in business conditions may reduce or even overcompensate the generally depressing effect of uncertainty on investment activities. This effect is shown to be the stronger the higher the variable cost and the longer the time-to-build. This implies that investment thresholds in agricultural ROA applications that do not consider the time-to-build and the available flexibility tend to be overestimated. A further finding is that crop-based bioenergy investments do not necessarily lead to a food price increase. By contrast, agricultural prices may even decline (albeit not below the equilibrium food price in the case of no bioenergy production), especially if the factor market uncertainty is higher than the uncertainty of the output price.

The *third research question* directs attention to the welfare implications of two most prevalent bioenergy support policies, namely the fixed cost subsidy and the guaranteed bioenergy price floor. For this aim, we first derive equilibrium investment thresholds under these two policies using our investment model. The total macroeconomic welfare and its components (sectoral surpluses) are subsequently calculated and set in relation to the case of no bioenergy support program. Because our investment model is based upon stylized facts, the primarily aim of the welfare analysis involves identifying the scale and the main directions of the bioenergy promotion effects, while placing emphasis on the role of bioenergy projects' specificity in these macroeconomic effects.

An important result of the welfare analysis is that both financial and regulative bioenergy policies – aiming at reducing uncertainties in bioenergy business – amplify the observed positive effect of a project's specificity on investment incentives. Therefore, bioenergy policies not acknowledging the specificity of crop-based bioenergy – and thus the possible positive uncertainty-investment relationship – tend to encourage investments but discourage production activities, causing hidden macroeconomic costs and undesired allocational effects. Under both policies, the stimulated increase in investment activities results in a welfare loss. The only positive effect could be stated for crop producers and accordingly land owners, while tax payers and especially food consumers bear the costs of bioenergy promotion. The considered policies primarily differ regarding their impact on the food price and production capacity utilization.

The results obtained in the present dissertation point out the complexity of the valuation of irreversible crop-based bioenergy projects under multiple uncertainties on both the firm and economy level. The key finding of the present work is that under certain conditions characteristic of many agricultural investments increasing uncertainty stimulates rather than dampens the propensity to investment. This finding qualifies the central proposition of the option pricing theory about the steady positive relationship between the level of uncertainty and the threshold price of investment. At the same time, it motivates a careful model tuning, which would allow unfolding the explanatory promise of the real option approach.

ZUSAMMENFASSUNG

Während erneuerbare Energien gesellschaftlich und wirtschaftspolitisch zunehmend als ein unverzichtbarer Bestandteil der Energieversorgung betrachtet werden, bleibt ihre ökonomische Relevanz fraglich. Besonders kontrovers wird dabei die Energiegewinnung aus Agrarrohstoffen diskutiert. In der Tat stehen dem aktuell geringen Anteil agrarbasierter Bioenergien im globalen Energiemix unverhältnismäßig hohe makroökonomische und soziale Kosten gegenüber. Deshalb ist es kaum überraschend, dass diese Energieart nach wie vor für ein großes Forschungsinteresse sorgt.

Bioenergieproduktion aus landwirtschaftlichen Rohstoffen findet an der Schnittstelle des Energie- und Nahrungsmittelmarktes statt. Ihre hybride Natur bedingt typische Kosten- und Volatilitätsstrukturen, Realisationszeiten und Flexibilitätsgrade, welche sich von anderen Bioenergiearten deutlich unterscheiden können. Darüber hinaus soll sie nicht nur eine nachhaltige und kosteneffiziente Alternative sein, sondern auch die Nahrungsmittelsicherheit nicht beeinträchtigen. Aus diesen Besonderheiten ergeben sich vielfältige wirtschaftliche, politische sowie methodische Herausforderungen.

In der Bioenergieforschung sowie in der gesellschaftlichen Bioenergiedebatte steht vor allem der sogenannte Teller-Tank-Konflikt im Vordergrund. Die Rolle des Bioenergiesektors wird dabei oft auf die Transformation und Übertragung der Preiseffekte reduziert. Die vorliegende Dissertation setzt sich deshalb zum Ziel, die strategischen Investitionsentscheidungen der Bioenergieproduzenten unter Berücksichtigung der Investitionsspezifika und gängiger Förderpolitiken zu untersuchen. Im Mittelpunkt des Interesses stehen dabei die drei folgenden Forschungsfragen: (I) Welche Auswirkungen hat eine explizite Berücksichtigung multipler Unsicherheiten auf strategische Entscheidungen der Bioenergieproduzenten? (II) Welche Rolle spielen Projektspezifika auf die Investitionsentscheidung unter Unsicherheit? (III) Was sind die makroökonomischen Implikationen der politischen Bioenergieförderung?

Die *erste Forschungsfrage* richtet die Aufmerksamkeit auf die Tatsache, dass bei der Bewertung der Investitionen in Bioenergie aus landwirtschaftlichen Rohstoffen nicht nur der unsichere Outputpreis zu berücksichtigen ist (wie in der Investitionsliteratur oft vereinfachend angenommen wird), sondern auch die nicht unwesentlichen Unsicherheiten auf dem Inputmarkt. Obgleich die allgemeine Investitionsliteratur darauf hinweist, dass multiple Unsicherheiten

nicht unbedingt additiv wirken, ist der gleichzeitige Effekt der Unsicherheiten auf Faktor- und Absatzmärkten in der Bioenergieforschung kaum untersucht worden. Dabei kann beispielsweise eine erwartete Verbilligung der Inputfaktoren einen möglichen Preisrückgang auf dem Energiemarkt teilweise oder ganz kompensieren und somit Investitions- und Produktionspläne beeinflussen.

Um die Effekte verschiedener Unsicherheitsquellen auf irreversible Bioenergieinvestitionen zu analysieren, entwickeln wir ein stilisiertes stochastisch-dynamisches partielles Gleichgewichtsmodell, welches den Bioenergiemarkt als Verbindungsglied zwischen dem Energie- und dem Nahrungsmittelmarkt abbildet. Die angenommenen Unsicherheiten stammen von stochastischen Schocks auf dem Energiemarkt (unsicherer Absatzpreis) und dem Nahrungsmittelmarkt (unsichere isoelastische Nachfrage) und werden über geometrische Brownsche Prozesse abgebildet. Die gleichgewichtige Investitionsschwelle (d.h. der Preis, bei dem eine rentable Investition möglich ist) des aggregierten Bioenergieproduzenten wird numerisch in wiederholten realoptionsbasierten stochastischen Simulationen in Kombination mit genetischen Algorithmen bestimmt. Da die Bewertung unsicherer Investitionen, insbesondere, wenn der Investitionsschwellenpreis bzw. der Investitionstrigger analytisch nicht bestimmbar ist, nicht nur von den Investitionsbedingungen und den getroffenen Annahmen, sondern auch von der gewählten Bewertungsmethode abhängt, wird die Verlässlichkeit des hier angewandten Realoptionsansatzes (ROA) ausführlich thematisiert.

Die *zweite Forschungsfrage* befasst sich mit den Spezifika der agrarbasierten Bioinvestitionen und ihren Implikationen auf die Projektbewertung anhand des Realoptionsansatzes. Zu diesen Spezifika zählen hohe variablen Kosten, lange Bauzeiten (anderthalb Jahre und länger) und die Option einer vorübergehenden Produktionsunterbrechung als eine Möglichkeit, den Unsicherheiten zu begegnen. Die ROA-basierte Investitionsliteratur fokussiert sich hauptsächlich auf die Rolle der hohen gesunkenen (fixen) Kosten in der strategischen Planung. In der Tat sind die Fixkosten der meisten Agrarinvestitionsprojekte sehr hoch; jedoch wird dabei nicht beachtet, dass die jährlichen variablen Kosten solcher Projekte die periodisierten Fixkosten um das Mehrfache übersteigen können. Zusammen mit der langen Bauzeit der Projekte und der Option, die Produktion bei ungünstigen Bedingungen zu unterbrechen und so einen erheblichen Anteil der Produktionskosten zu vermeiden, können hohe variablen Kosten die Kurvatur der Gewinn- und Kostenfunktionen maßgeblich beeinflussen. Folglich kann der Gesamteffekt der Unsicherheit auf die Investitionsentscheidung nicht unbedingt negativ ausfallen. Die Untersuchung der Rolle dieser drei Spezifika in den Bioenergieinvestitionen unter Unsicherheit ist der zentrale Gegenstand der vorliegenden Dissertation und konstituiert ihre Neuheit.

Bei der Bearbeitung der ersten beiden Forschungsfragen wird angenommen, dass es keine Bioenergie-Förderprogramme gibt. Die Ergebnisse der empirisch unterlegten Simulationen zeigen, dass die erwähnten Spezifika, wenn gleichzeitig vorhanden, den negativen Effekt der zunehmenden Unsicherheit auf die Investitionsbereitschaft neutralisieren oder gar überkompensieren können, und dass dieser Effekt umso ausgeprägter ist, je höher die relativen variablen Kosten und je länger die Projektrealisierungsdauer sind. Diese Beobachtung deutet darauf hin, dass in den meisten ROA-Anwendungen die Schwellenpreise landwirtschaftlicher Investitionsprojekte tendenziell überbewertet sind. Die Ergebnisse zeigen auch, dass Investitionen in agrarbasierte Bioenergie nicht zwangsläufig zu steigenden Nahrungsmittelpreisen führen. Im Gegenteil können die Letzteren sogar sinken (jedoch nicht unter die Gleichgewichtspreise im Falle keiner Bioenergieproduktion), vor allem, wenn die Volatilität auf dem Faktormarkt höher als auf dem Absatzmarkt ist.

Die *dritte Forschungsfrage* beschäftigt sich mit der Bewertung der Wohlfahrtseffekte alternativer Bioenergieförderprogramme, nämlich der Fixkostensubventionen und Absatzpreisgarantien (Preisuntergrenze) für Bioenergieproduzenten. Hierfür werden anhand des Investitionsmodells gleichgewichtige Investitionstrigger für beide Arten der Förderung berechnet. Die gesamte absolute Wohlfahrt sowie deren Komponenten (Renten) werden dann in Relation zu dem Szenario ohne politische Bioenergieförderung gesetzt. Da das zugrunde liegende Investitionsmodell eine stilisierte Abbildung intersektoraler Verflechtungen darstellt, steht bei der Wohlfahrtanalyse vor allem eine Einschätzung des Ausmaßes und der Hauptrichtungen der Folgen der Bioenergieförderung im Vordergrund.

Ein wichtiges Ergebnis der Wohlfahrtsanalyse ist, dass beide betrachteten Förderinstrumente den positiven Effekt der Projektspezifika auf die Investitionsbereitschaft unter zunehmender Unsicherheit verstärken. Dadurch wird die Relevanz dieses Effekts auch für die Bewertung der makroökonomischen Effizienz politischer Förderinstrumente deutlich. Des Weiteren zeigt die Analyse, dass eine förderungsbedingte Investitionszunahme zum Wohlfahrtsverlust führt. Einzig die Produzenten von Agrarrohstoffen, und somit letztendlich die Agrarlandbesitzer, profitieren von der Bioenergieförderung, während Steuerzahler und insbesondere Nahrungsmittelkonsumenten die Kosten der Bioenergieförderung tragen. Unterschiede in den Implikationen der Fixkostensubventionen und der Absatzpreisgarantie bestehen vor allem in den resultierenden Nahrungsmittelpreisen sowie der Produktionskapazitätsauslastung.

Die in der vorliegenden Dissertation gewonnenen Ergebnisse verdeutlichen die Komplexität der Bewertung irreversibler Bioenergieinvestitionen unter multiplen Unsicherheiten sowohl aus der mikro- als auch makroökonomischer Perspektive. Zugleich weisen sie darauf hin, dass unter bestimmten Bedingungen, die für mehrere agrarbasierte Investitionen charakteristisch sind, die zunehmende Unsicherheit die Investitionsbereitschaft eher erhöht als senkt. Diese Beobachtung relativiert die zentrale Aussage der Investitionstheorie über den stetig positiven Zusammenhang zwischen der Höhe der Unsicherheit und des Investitionstriggers und liefert somit eine Motivation für eine genauere Kalibrierung realoptionsbasierter Modelle.

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LIST OF ABBREVIATIONS

AfA	Absetzung für Abnutzung
Bn	billion
BStBl	Bundessteuerblatt
cf.	compare
CEV	Constant elasticity of variance
Ch.	Chapter
COM	Communication
CS	Consumer Surplus
DAI	Deutsches Aktieninstitut
DESTATIS	Das Statistische Bundesamt
EC	European Commission Communication
EEG	Erneuerbare Energien Gesetz
ed/eds	editor/editors
EIA	Energy Information Agency
ESCP-EAP	Ecole Supérieure de Commerce de Paris & European School of Management
EU	European Union
EUROSTAT	Statistical Office of the European Union
FAO	Food and Agriculture Organization of the United Nations
FC	Fixed cost
GA	Genetic algorithm
GB	Government budget
GBM	Geometric Brownian Motion
GDP	Gross Domestic Produc
IEA	International Energy Agency
ILUC	Indirect land use change
IMF	International Monetary Fund
Inv	Investment
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft
kw	Kilowatt

kWh	Kilowatt hour
LEMNA	Laboratoire d'Économie et de Management de Nantes-Atlantique
MJ	Megajoule
NBER	National Bureau of Economic Research
MNRE	Ministry of New and Renewable Energy
NGO	Non-governmental organization
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PS	Producer surplus
PV	Production value
REN21	Renewable Energy Policy Network for the 21st Century
R&D	Research and development
RO	Real option
ROA	Real option approach
RQ	Research question
UNCSD	United Nations Conference on Sustainable Development
UNCTAD	United Nations Conference on Trade and Development
URL	Uniform resource locator
US	United States
USD	US-Dollar
USDA	United States Department of Agriculture
VBA	Visual Basic for Applications
VC	Variable cost
WASDE	World agricultural supply and demand estimates
WF	Welfare

Chapter 1

Motivation and research questions

1.1 WHY DEAL WITH CROP-BASED BIOENERGY?

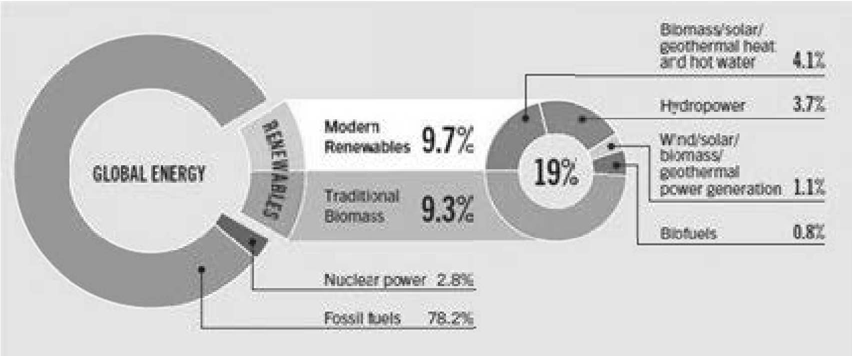
Bio stands for life, while *energy* – namely its conversion – is an inherent characteristic of all living. Thus, taken literally, *bioenergy* is the only existent kind of energy in a living world. The practical usage of this term is much more heterogeneous, given that the forms, sources, productions technologies and utilization of bioenergy are manifold. Nonetheless, the contemporary understandings of *bioenergy* can be summarized under the term *renewables*, indicating a necessity for the sustainable usage of resources to derive energy. This is not least due to the meanwhile perceptible limits of the fossil resources along with the world's population growth and associated ecological strains, which have brought about a substantial reassessment of energy economics. As a result, sustainability requirements for the use of biomass and other natural resources for energy and fuel production have become part of many national and supranational policies.

For instance, the International Energy Agency (IEA, 2012) defines bioenergy as "…energy derived from natural processes (e.g. sunlight and wind)…", highlighting that these processes should be "…replenished at a faster rate than they are consumed".[1] Bioenergy from agricultural crops – which is in focus of the present work – is understood as a renewable fuel or electricity substitute derived through the conversion of biomass crops and bearing potential advantages compared to conventional energy sources (cf. IBID.). Such an understanding of bioenergy extends beyond the simple exploitation of biological resources, emphasizing an environmentally sound utilization of resources, their technological expedience as well as the cost competitiveness of the derived energy.

While bioenergy has been recognized as an indispensable component in the energy mix and a major player in the future energy market on the political level (cf. EC COM, 2012: 271 final), the economic relevance of the bioenergy remains questionable. On the one hand, this relevance can be witnessed by the fact that more than 30 countries had introduced mandates for blending biofuels (REN21, 2013) and other regulatory policies by the end of 2012 (cf. also Appendix, Table A4.1). On the other hand, despite considerable policy programs and the fast growth of bioenergy industries in many countries, the share of renewables in the national and global energy mix remains insignificant. As shown in Figure 1.1, the share of modern renewables accounted for about 10 % of world total primary energy in 2012, which is 3 % less than in 2006 (cf. IEA, 2006 and 2012; INDEX MUNDI, 2012; IPCC, 2011).

1 IEA, FAQs: Renewable Energy. URL: http://www.iea.org/aboutus/faqs/renewableenergy/ (17.03.2012).

Figure 1.1: Share of bioenergy in the world primary energy mix by the end of 2011



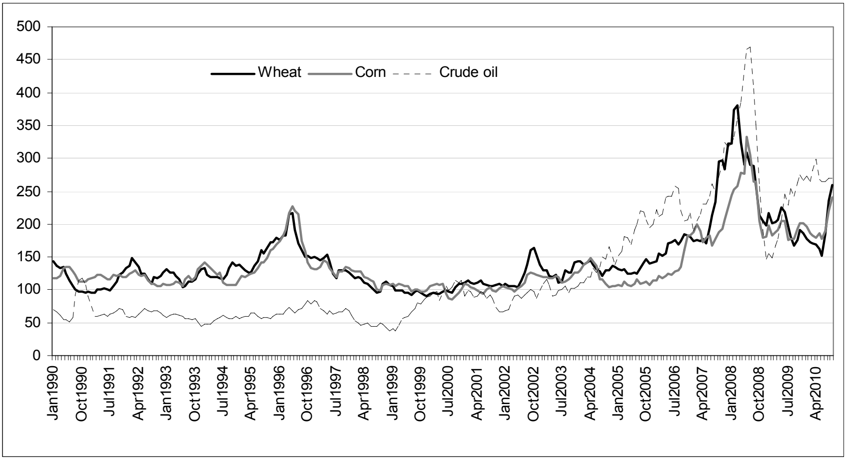
Source: IEA (2014, p. 21).

The contribution of bioenergy from agricultural crops and by-products to the global amount of renewables is estimated at between 3 % and 6 % during 2006-2011 (IEA, 2012 and 2006; IPCC, 2007). However, these numbers remain too optimistic given that the estimates of first-generation renewables and biomass used for open fires or simple stoves are vague. According to IEA (2012), if this kind of biomass is excluded from statistics, the share of the low carbon advanced renewables would only reach 1 % to 2 %. The share of the crop-based bioenergy would correspondingly be reduced to about 0.3 %. However, this small share of bioenergy produced from agricultural crops warrants attentions for a number of reasons.

Probably the most evident reason is the fundamental change in the correlation between the energy and food prices caused by the entry of the agricultural sector into the energy market. Until recently, energy and agricultural commodity prices used to have a relatively low or even negative correlation (cf. TYNER, 2009)[2]. With the boost of the bioenergy production during 2000-2005, prices for wheat, corn and other agricultural goods reveal a strong correlation with energy prices (GOHIN and CHANTRET, 2010; DU et al., 2009; ROSEGRANT, 2008). Indeed, as Figure 1.2 shows, the close link between crude oil prices and wheat and corn prices is a relatively recent phenomenon, coinciding with the start of the political promotion of bioenergy production in the USA and EU in 2000.

2 TYNER (2009) demonstrates for the US ethanol market that the correlation between annual crude oil and corn prices, which used to be negative (-0.26) in the 1988-2005 period, reached a positive value of 0.80 during the 2006-2008.

Figure 1.2: Price indices for wheat, corn and crude oil, 1960-2010, (2000=100)



Source: UNCTAD: Free market commodity price indices, monthly, 1960-2010.

The increasing utilization of corn, wheat and other crops as bioenergy substrates has enhanced the scarcity of agricultural land needed for food and feed production. Such a rededication of agricultural crops and land along with the orientation of bioenergy producers towards conventional energy prices has tightened the agricultural sector's dependence on the energy market development and contributed to the food price increase. For the period 2006-2008, TANGERMANN (2011: p. 22) estimates this contribution as ranging between 10 %-30 %. According to the OECD/FAO (2010, p. 54) Agricultural Outlook, this intersectoral linkage will remain one of the most pronounced sources of agricultural price volatility during 2010-2019.

Despite the fast development of bioenergy industries, in most countries bioenergy production from agricultural crops is still not cost efficient and thus it is dependent on political support programs. Such programs unavoidably result in macroeconomic allocations, often coupled with significant welfare losses. Furthermore, if the effect of the indirect land use change (ILUC) is taken into account, the crop-based bioenergy becomes no longer carbon neutral, whereby its production and promotion pose additional economic, environmental and ethical questions (cf. LEOPOLDINA, 2012). This means that although the current share of the agriculturally-based bioenergy in the energy mix is very small, the side effects that it has already entailed are substantial. This fact calls for a reassessment of the role of the crop-based bioenergy in the energy policy.

1.2 BIOENERGY FROM AGRICULTURAL CROPS: A LITERATURE OVERVIEW

The issue of crop-based bioenergy has attracted much research effort. Table 1.1 lists some recent studies dealing with agriculturally-based bioenergy. The present selection aims to show the range of the main research interests of these studies. As seen from Table 1.1, most of these studies are concerned with the question of the effect of the energy price and its volatility on food price dynamics. Within this group of studies, estimates of this effect widely differ and its causes are discussed controversially. For instance, MCPHAIL and BABCOCK (2008) conclude that the gasoline price volatility of 25 % entails volatility in the corn price of 17.5 %. In a similar study, THOMPSON et al. (2009) also demonstrate a positive pass-through of fuel prices on the corn price, showing that a 1 % increase in the crude oil price leads to a 0.31 % increase in the corn price.

By contrast, in his ad-hoc multifactor model, MITCHELL (2008) found that although fossil fuel prices contribute to the food price increase, their impact is relatively weak compared to the effect of other factors such as the exchange rate, low grain stocks, export constrains or land use shifts. In Mitchell's view, the largest part of the food price increase is due to the rise in biofuel demand. GILBERT (2010) studied the causation of the price rises during boom episodes, concluding that macroeconomic and financial factors (e.g. world GDP growth and monetary expansion) are the main determinants of changes in overall agricultural prices, while there is hardly any effect of biofuels on food prices.

In their survey of indirect land use models, CHAKRAVORTY et al. (2009) show that the effect of the increasing fossil fuel price on the food price is an indirect one, as it significantly depends on the amount of agricultural land diverted for biofuel production and hence the progress of biofuel and agricultural technologies. ZILBERMAN et al. (2013) support this finding, demonstrating that it is not fuel or biofuel prices that affect the food prices and their fluctuations, but primarily the competing land use interests of food and biofuel producers. They also show that the directional effect of the energy price on the food price is ambiguous and can only be determined if the causes of the biofuel price change are specified.

The assessment of the effect of bioenergy (or biofuels) on food prices also differs. For instance, WRIGHT (2009) finds this effect to be substantial. OECD/FAO (2008) and BANSE et al. (2008) estimate that biofuels will continue to moderately influence (from 5 % to 16 %) the food price increase during 2008-2018, whereas von WITZKE and NOLEPPA (2014) and TIMILSINA et al. (2012) show that the impact of biofuels on agricultural commodity price is rather limited or even negligible, especially in the long run. ZHANG et al. (2010) conclude that neither fossil fuel nor biofuel prices significantly affect food prices, while the vice versa effect of energy crops prices on biofuel prices is rather significant.

Table 1.1: Main research interests of studies on crop-based bioenergy (2000-2015)

	Main focus: Impact of…					
	(bio)energy price or its volatility on		bioenergy policies on		bioenergy invest-ment on food prices	food pri-ces on bioenergy invest-ment
Authors	food prices	bioenergy invest-ments	food prices	bioenergy invest-ments		
Tareen et al. (2000)		•		•		
Vedevov et al. (2006)		•		•		
Balcombe/Rapsomanikis (2008)	•	•				
Banse et al. (2008)	•		•			
McPhail/Babcock (2008)	•		•			
Rosegrant (2008)	•		•			
Mitchell (2008)	•		•		(•)	
Serra et al. (2008, 2010)	•	•	•			
Chakravorty et al. (2009)	(•)		•		•	
Du et al. (2009)	•		•			
Thompson et al. (2009)	•		•			
Wright (2009)	•					
Gilbert (2010)	•					
Gohin/Chantret (2010)	•		•			
Hertel et al. (2010)	•	•	•			
Roberts/Schlenker (2010)	•		•			
Zhang et al. (2010)	•		•		•	•
Tangermann (2011)	•					
Timilsina et al. (2012)	•		•			
Chen/Khanna (2013)	•		•		•	
Zilberman et al. (2013)	(•)		•		•	
Von Witzke/Noleppa (2014)	•		•			
Present study (2015)		•	(•)	•	(•)	•

Note: (•) Indirect impact through the effect of land use change.

Another strongly pronounced focus is directed at the effects of bioenergy policy regimes on food prices. This question is notably dealt within the same group of studies discussed above, which can be attributed to the fact that in the most countries bioenergy production only takes place due to the existent support programs. The impact of the latter is estimated by ROSEGRANT (2008) as accounting for 30 % of the increase in weighted average grain prices during 2000-2007 compared to a hypothetical scenario without bioenergy promotion programs, whereby the greatest impact was on the corn price (39 %). CHEN and KHANNA (2011) arrive at even higher values (up to 52 %) in their food price projection in the US for 2022. ROSEGRANT et al. (2008) highlight a strong correlation between the food and fuel price but argue that the main reason for the upward pressure on food prices is the use of agricultural land for biofuel feedstock production.

HERTEL and BECKMAN (2010) found that the world grain price volatility has been boosted by 25 % in the presence of the renewable fuel standards and binding blend quotas, while the US coarse grains price volatility in response to corn supply shocks is 57 % higher than in the case of no support regimes[3]. ROBERTS and SCHLENKER (2010) largely concur with this assessment but highlight the role of factors' and technology choice. ZILBERMAN et al. (2013) again highlight that the extent to which bioenergy policies influence the correlation between the energy and agricultural prices depends on the availability of agricultural land and the intensity of its use.

By contrast, less attention has been devoted to the bioenergy sector itself. In particular, the impact of energy prices (e.g. BALCOMBE and RAPSOMANIKIS, 2008; SERRA et al., 2010; HERTEL et al., 2010) and food prices (ZHANG et al., 2010) on bioenergy investments has not been sufficiently investigated. Even less studied is the effect of policy regimes on the activities of the bioenergy sector (e.g. TAREEN et al., 2000; VEDEVOV et al., 2006). Being a tie between the energy and food markets, this sector is directly affected by the dynamics on these markets, while for its part it also affects these markets.

HERTEL et al. (2010) estimate for the EU that the increase in the crude oil price during 2001-2006 accounted for about two-fifths of the expansion in biofuel production. Inversely, the bioenergy production itself may substantially influence prices on the food market, since it demands crops as input factors. Moreover, the bioenergy sector also indirectly influences food and feed prices through land rededication or an income effect. Due to its relatively small size (cf. Figure 1.1), the bioenergy sector currently has no significant influence on the energy market. However, this can quickly change with the phasing out of bioenergy policy programs, as is envisaged in most countries over the coming decades.

Common to all studies listed in the Table 1.1 is the acknowledgement of high volatilities on the interrelated energy and agricultural markets. The studies by TAREEN et al. (2000) and VEDENOV et al. (2006) additionally consider the effect of the volatility drift rates of biofuels and conventional fuels that can be used as alternative inputs. However, the *simultaneous* effect of different uncertainties sources on bioenergy investments is barely investigated (e.g. SERRA et al., 2010). For strategic decisions of bioenergy producers operating at the intersection of the volatile energy and food markets, accounting for multiple uncertainties is a

[3] The Renewable Fuel Standard (RFS) program from 2005 established the first binding renewable fuel volume in the United States. According to this standard, 7.5 billion gallons of renewable fuel are to be blended into gasoline by 2012.

necessity. It is all the more surprising that the role of multiple uncertainties – particularly those originating from the different markets – is rarely considered in the relevant literature.

The brief overview of some prominent recent studies on crop-based bioenergy reveals marked differences in the quantitative assessments of the interactions between the energy and agricultural markets. VON WITZKE and NOLEPPA (2014, p. 19) explain these differences by the fact that "the methodological and empirical foundation of scholarly analyses of the impacts of biofuel production and consumption is just beginning to emerge".[4] Indeed, the choice of appropriate methodological tools and relevant assumptions is decisive for any accurate analysis. The latter is additionally challenged by the fact that agriculturally-based bioenergy is of a hybrid nature, since it combines the features of the energy and agricultural markets. The selection of an appropriate methodology should thus not only account for the mutual economic interdependences of the energy, bioenergy and agricultural markets, but also for specifics of crop-based bioenergy production, including ecological and societal requirements concerning these kinds of renewables.

The second evidence from the literature review is that the main focus of the relevant research is placed upon the impact of crop-based bioenergy production on food security. The established interdependences between the energy, bioenergy and food markets, strengthened by the politically driven orientation towards renewable energy, suggest that this impact is likely to persist after the envisaged liberalization of the bioenergy market. Against this backdrop, the present work devotes attention to the strategic decisions of bioenergy producers and their macroeconomic consequences.

1.3 OBJECTIVES OF THE WORK

The present dissertation is concerned with possible future scenarios of bioenergy production from agricultural crops. Of particular interest are the following three research questions (RQ):

(RQ I) Do multiple uncertainties reduce investment incentives of bioenergy producers?

(RQ II) Do specifics of crop-based bioenergy production affect the investment rule?

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4 In this article, the authors contrast the assessments of the effect of biofuel production on agricultural commodity prices provided by the scholarly research and NGO publications, while addressing the issue of the possible bias of research results, depending on its motivation. The interested reader is also referred to the article by SWINNEN et al. (2011), which deals with the explanation of the biased views of international organizations on the causes of food scarcity.

(RQ III) What are the macroeconomic implications of crop-based bioenergy production under alternative policies?

The first research question (RQ I) is concerned with the impact of uncertainties stemming from the output (energy) and input (agricultural crops) market on investment activities within the bioenergy sector. Both markets are characterized by highly volatile price dynamics. While the volatility transmissions on the interrelated energy and food markets have attracted much research attention, the simultaneous effect of multiple volatilities on the bioenergy sector remains less analyzed. However, accounting for all uncertainties in place may strongly influence the assessment of investment plans, given that more uncertainty sources do not necessary lead to an increase in the total uncertainty. In fact, a significant price decrease on the input market would be expedient for bioenergy producers. Therefore, we hypothesize that accounting for multiple uncertainties affecting expected costs and revenues would not only better reflect the real-world conditions of bioenergy production, but it would also lessen rather than increase the total net effect of contingencies on bioenergy investments.

The second research question (RQ II) addresses the ability of the bioenergy producers to cope with uncertainties. Here, particular attention is given to specifics of bioenergy projects such as the cost structure, required time-to-build and the possibility to temporarily suspend production. Previous studies on uncertain investment projects, especially those applying the real options approach, have emphasized the role of the high fixed investment cost and irreversibility in strategic capital budgeting. However, for bioenergy and many other projects, the annual variable cost is also high and may exceed the annualized fixed cost by several times (cf. KTBL, 2012).[5] Besides, such projects usually require a certain construction or gestation period before the first cash flows can be generated. In the case of crop-based bioenergy, the time-to-build may average 2.5 years (sometimes even longer), which is likely to affect the expected investment value (cf. IBID.). On the other hand, even uncertain and irreversible projects can often be adjusted to changing business conditions. This can be achieved, for instance, by pausing production, creating variation in the production scale or other managerial actions that may determine the curvature of the profit and cost functions. We suppose that these project specifics may help bioenergy firms to hedge uncertainties out of their own resources, whereby the net effect of uncertainty on the optimal investment threshold might be ambiguous. Indeed, scrutinizing the effect of crop-based bioenergy specificity on investment incentives under uncertainty constitutes the novelty of the present work.

The third research question (RQ III) places attention on the welfare implications of the crop-based bioenergy production under different policies regimes. The

[5] For detailed references and examples, see Table 3.1 (Chapter 3).

overall goal of various existent bioenergy support instruments is to ensure society's welfare through increasing the supply of sustainable and clean energy. However, the expected positive effect of bioenergy promotion on society's well-being cannot be proven to date. By contrast, the recent academic debate agrees upon a clearly negative impact of proactive renewables policies on the economic rents and environmental figures, thus questioning the practicality of measuring bioenergy-induced welfare effects. Against this background, we reorient the focus of welfare analysis away from the traditional quantification of an economy's utility gains due to bioenergy production towards the specificity of crop-based bioenergy projects. In particular, we aim to prove whether accounting for specifics of crop-based bioenergy influences the effectiveness of proactive bioenergy policies designed to reduce contingencies of bioenergy businesses. We hypothesize that both regulatory and financial policy instruments ignoring projects' specificity tend to cause additional deadweight costs and undesired macroeconomic allocations.

1.4 Structure of the work

The remainder of this dissertation is organized into five chapters. The following three chapters (Chapters 2 to 4) are essays on crop-based bioenergy investments under uncertainty, their micro- and macroeconomic implications and their valuation within the real options-based framework. Chapter 2 starts with an introduction into the real options approach as the underlying methodology of the present work, while guiding the reader through the general economic and agricultural literature on the real options, their theoretical aspects, methodological development, extensions and applications. Strong attention is given to the central assumptions of the real options approach and some unique characteristics of real options, which are supposed to condition significant differences in investment valuations. The chapter also briefly reviews applications of the real options approach in an agricultural context.

Chapter 3 is the centerpiece of the present work, exploring the question of how strategic investments in crop-based bioenergy are affected by multiple uncertainties on the output and input markets (RQ I). The chapter first addresses to the role of managerial flexibility, time-to-build and a high variable-to-fixed cost ratio in determining the uncertainty-investment relationship (RQ II). Despite being typical for many agricultural projects including bioenergy investments, these investment specifics have not yet been considered in agricultural studies. The review of the prior research on agriculturally-based bioenergy investments is provided to summarize the current state of the relevant literature and encircle the scope of our investigation.

In the following sections of Chapter 3, the stochastic dynamic partial equilibrium model is developed and explained along with its assumptions and components. Due to the mutual dependences in the energy, bioenergy and food markets and an explicit consideration of two volatility sources (the output price and the food demand), the model can only be solved numerically. Specifically, we define real options-based stochastic simulation experiments in combination with genetic algorithms. These methodological tools and their combination with a numerical approach are introduced in the subsequent section, before the chapter closes with a summary and discussion of the obtained simulation results.

The assessment of the possible macroeconomic implications of bioenergy production under different policy regimes (RQ III) is the focus of Chapter 4. For this purpose, three different scenarios of policy support programs to bioenergy sector are defined: the case of no policy support, the guaranteed minimum sale price for bioenergy and fixed-cost subsidies paid to bioenergy producers. Subsequently, the chapter describes the necessary modifications to the original model (developed in Chapter 3) to analyze the macroeconomic welfare effect of these policy regimes. The formal framework for calculating the absolute and relative welfare and its components are provided, before the results are presented and interpreted.

Chapter 5 summarizes the main findings of the work and outlines questions that could motivate further research. Readers interested in details on the source code for stochastic simulations, energy unit conversion, an overview of the existent bioenergy policies, and additional simulation results are referred to the Appendix.

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CHAPTER 2

REAL OPTIONS APPROACH AND ITS APPLICATIONS

Chapter 2 introduces the real options approach as a new theoretical concept of investment valuation with a broad practical reach. The chapter guides through the relevant general economic and agricultural literature on real options, their theoretical aspects, methodological development and applications. Because the real options analysis is deeply rooted in financial economics, the chapter devotes attention to demonstrating the direct analogy between financial and real options, while highlighting some technical restrictions for the practical application of the latter resulting from this analogy. Significant attention is paid to the critical assumptions of the real options approach such as uncertainty profile of an investments project and the combined importance of uncertainty, irreversibility and flexibility. The review of applications of the real options analysis to agricultural investment decisions closes the chapter.

2.1 INTRODUCTION

A doctoral dissertation may sometimes emerge as much more than a purely academic piece of work. Louis Bachelier's dissertation "*Théorie de la Speculation*" from 1900 is a prominent example of this. Its rediscovery in 1955 is commonly seen as the beginning of the real options approach development. In his work on the application of probability calculus to stock markets, Bachelier developed the mathematics of Brownian motion for analyzing stock price fluctuations and evaluating contingent claims such as forward contracts and options.[6] In the next 25 years, the option pricing theory was further developed by financial economists and it was substantially finalized in the 1980s. Since then, mathematics of stochastic processes have become an integral part of the modern finance. Identifying new types of financial instruments and methods of risk management has laid the foundation for the emergence of a huge global marketplace for option trading, simultaneously triggering new areas of economic research. Due to its mathematical conclusiveness and boundary-spanning nature, the option price theory was soon adopted in many other areas dealing with uncertain and changing business conditions, e.g. in information technology, strategic management, the valuation of insurance contracts, investments in non-financial assets and many other areas.

While this method has earned a solid position in financial practice, its applications to investments in physical assets remain mostly theoretical deliberations. This is not least due to the computational complexity of the approach and its restrictive assumptions such as risk neutrality or asset tradability. Besides, the advantages that the option pricing concept may hold for assessing irreversible capital-intensive real investments projects under uncertainty are still not broadly understood. The purpose of this chapter is to motivate the use of the real options approach (ROA) by overviewing the general idea, advantages and shortcomings of this methodological tool. This chapter argues that financial and real options bear a sketchy rather than direct analogy, whereby the validity of the key proposition of the financial option pricing – namely the negative uncertainty-investment relationship – for real options remains open to question.

2.2 ORGANIZATION OF THE CHAPTER

The following section traces the double-tracked development of the ROA from the stochastic analysis and financial economics. It subsequently compares this method with the standard net present value technique and discusses the components of the option value. Section 2.4 continues with a discussion of the main

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[6] In 1877, before Bachelier, Charles Castelli described the hedging and speculation aspects of options, but provided no theoretical underpinnings of option valuation.

conclusion, critical assumptions and some unique characteristics of the ROA, focusing on their technical restrictions for practical application. The section proceeds to illustrate the role of the uncertainty-flexibility trade-off, cost structure and investment rate in the valuation of agricultural projects under uncertainty. Finally, Section 2.5 summarizes and concludes the chapter.

2.3 Theoretical origins of the ROA

2.3.1 The Black-Scholes Model

The ROA has its trailhead in the theory and methodology developed for the valuation of financial options. Put differently, the ROA is a translation of the set of techniques used for the valuation of financial instruments to firms' investment management. In turn, the option pricing technique has its roots in stochastic analysis and financial economics. The seminal work on financial option pricing was provided by Black and Scholes (1973) and Merton (1973)[7]. Their model – which has come to be known as Black-Scholes model – is built upon the works of their predecessors, particularly the papers of Samuelson (1965), Sprenkle (1961), Thorp and Kassouf (1967) and Chen (1970), but primarily on Boness (1962). Despite a considerable number of precursors, the Black-Scholes model remains distinctive due to its mathematical accuracy. Its major improvement on the Boness' model comprises the use of the risk-free (since constant and known) interest rate as a discount factor, implying that the price of an option is independent of the individual risk preferences of investors. In the treatises by Black, Scholes and Merton, a *financial* option is understood as "a security giving the right to buy or sell an asset, subject to certain conditions, within a specified period of time" (cf. Black and Scholes, 1973, p. 637). Such security is designed to leverage uncertainty and limit the downside risk of an investment through quantifying the strategic value of flexibility, namely the flexibility to exercise the option or not depending on the market developments. The authors use the exercise terms of the simplest kind of option, namely the European call option.

As with every model of reality (or some parts of it), the Black-Scholes model is built upon simplified assumptions and thus disagrees with the real processes in a number of ways. The most significant of these are the assumptions of random walk and log-normal distribution of the stock price, as well as the assumption of the constant volatility. Log-normal distribution of the stock price requires that the interest yield follows a continuous geometric Brownian motion. However, there is no empirical evidence that the price process follows a random walk and has no significant jump component in the long run (i.e. for more than 30 years)

[7] In their Nobel Prize winning work, Robert C. Merton and Myron S. Scholes developed in collaboration with Fischer Black a pioneering formula for the valuation of stock options.

(cf., e.g. PAPE and MERK, 2003, p. 12; DIXIT and PINDYCK, 1994, p. 404; PINDYCK and RUBINFELD, 1991, pp. 462-465)[8]. Discontinuous jumps in stock prices – which are often the case in the real world – are thus disregarded by the model. The constant (implicit) volatility assumption is also less realistic and in the long term results in an inaccurate stock price. Furthermore, the accuracy of the Black-Scholes model is highly dependent on the precision of volatility estimation, given that it does not allow for a direct derivation of volatility.

Criticism of the Black-Scholes model has led to a wide array of alternatives and advancements being proposed. For instance, ROBERT MERTON (1973) relaxed the assumption of no dividends and later (1976) removed the restriction of the constant interest rates. These modifications yielded very accurate valuation models for stock options. Models assuming volatility not as constant but rather as an inversely related function of the underlying's price (e.g. constant-elasticity-of-variance model (CEV) developed by COX and ROSS (1976)) also provide more realistic results. Studies by MACBETH and MERVILLE (1980), BECKERS (1980), RUBINSTEIN (1985), PAPE and MERK (2003) have shown that the Black-Scholes model systematically overprices the option with respect to the exercise price and time to maturity. The mispricing is especially significant the more the option gets out of the money and the longer its duration. BLACK and SCHOLES (1972, p. 408) considered such overpricing possible, albeit only in the case of high stock volatility.

BLACK and SCHOLES were aware of their unrealistic assumptions (cf. IBID., p. 639). The "ideal conditions" – as they call the model's assumptions – for deriving their formula were chosen for simplicity reasons (IBID., p. 640). Despite (or possibly even due to) some simplified yet not overly-restrictive assumptions, the Black-Scholes model offers a balanced compromise between the degree of complexity and practical manageability, which made it a useful approximation technique for the valuation of financial derivatives. The pivotal methodological contribution made by Black, Scholes and Merton was in demonstrating that is not necessary to use the risk premium for option valuation, because it is already included in the stock price. The other significant merit of the Black-Scholes model involves generating an impetus for developing new methodological tools for the valuation of investment decisions beyond financial markets.

2.3.2 Option value and net present value

The standard investment theory, which the option pricing theory is rooted in, is based upon the net present value (NPV) criterion. The NPV method became a

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8 The unit root tests (e.g. Dickey-Fuller test or Phillips-Perron test) that are usually performed to test for a random walk of price series often fail to reject the random walk hypothesis for short time series, even if the series follows some different stochastic process such as mean reversion or Poisson jump process.

dominant investment decision support in the early 1970s, replacing the use of simple ratios such as the average return on assets and payback period. While the option pricing theory quickly found its way to the financial market, the NPV criterion long remained the foremost method of valuation of corporate investment projects. The reason primarily lies in a significant trade-off between the accuracy of the option pricing method and its complexity. Both methods are based upon the discounted cash flow technique, which converts the future value of assets into cash flows and discounts them over the investment period.

For investments decisions made under *certainty*, project valuation with the real options technique and the NPV criterion leads to identical results. The fundamental difference between the two methods comprises dealing with *uncertainty*, more precisely with the uncertainty-flexibility trade-off. Flexibility reflects an investor's ability to respond to uncertainties by adjusting investment plans or production schemes. Formally, this trade-off is expressed by the time value, namely the discounted value of the expected appreciation of the option due to additional uncertainty-reducing information. The NPV method takes into account the intrinsic advantages of an investment when compared to capital markets. These advantages are primarily due to market imperfections such as entry barriers, economy of scale, etc. The investment threshold according to the NPV criterion is given whenever the expected present value of future cash flows of a given project is higher than its investment cost, namely whenever the net present value for the project is positive (cf., e.g. TRIGEORGIS and MASON, 1987; RUSSEL, 1970).

By contrast, the ROA maintains that for uncertain yet irreversible and flexible investments, it is not necessarily optimal to invest whether the expected present value of the future returns covers the investment outlays (cf., e.g. PINDYCK, 2004; HENRY, 1974; MCDONALD and SIEGEL, 1985). Other that the NPV rule, the real options paradigm considers along with the intrinsic value the time value of an investment opportunity. In this case, the option should only be exercised if its intrinsic value exceeds the time value. This implies that the investment threshold according to the ROA is higher than according to the NPV rule. The NPV does not take into account managerial flexibility to respond to uncertain events, reevaluate the project or refine the strategy with respect to additional information, whereby it tends to underprice uncertain investment projects. As a result, low-risk projects can incorrectly assume priority over higher flexibility projects with higher risk. Therefore, an options-based investment valuation has to ensure a profit above a certain level or insure the project against a loss. Indeed, this feature makes the ROA superior to the NPV rule.

2.3.3 Components of the option value

When creating an option, an investor "buys" time during which he hopes to obtain more information and thus reduce uncertainty (cf., e.g. MUßHOFF, 2003, p. 27).

The value of buying time is directly dependent on the time remaining until the option's expiration and it decreases as the option approaches its expiration. At expiration, the *time value* is zero and the option value is simply its *intrinsic value*. The total value or continuation value (cf. IBID.) of an option at every point of time is thus the sum of its time value and its intrinsic value.

The time value, namely the value of better information about future costs and benefits, originates from the fact that the decision-maker is assumed to learn about future returns by waiting. Therefore, the option value is synonymous with the value of information (CONRAD, 1980). New information about uncertain events such as the evolving demand and other parameters accrues over time and – provided that investor has the flexibility to defer or adjust his investment project – can lead to a better decision. However, the relationship between the duration of waiting and the expected option value is not strictly positive, because waiting is associated with costs, reflecting the foregone benefits from the investment during the waiting period. Besides, it is not given that new information will be better information and the benefits from the possibly better decision based upon new information will be higher than the costs of waiting. The option value thus is a *conditional* value of information (HANEMANN, 1989).

Unlike time value, the intrinsic value of an option is not dependent on the time left until expiration, given that it only reflects the option's minimum value. Hence, time value is the amount by which the option price exceeds its intrinsic value. Consequently, if learning proceeds more slowly than the capital depreciation, the intrinsic value decreases and waiting makes no difference. More specifically, time value reflects the probability that the option will gain in intrinsic value or become sufficiently profitable to be exercised before the option's expiration. In the Black-Scholes model, the theoretic value corresponds to the option's intrinsic value, as it calculates the price of an option at the expiration date.

2.4 MODELING WITH REAL OPTIONS

The ROA has become an appealing line of research in many fields where strategic capital planning faces high uncertainty about future cash flows. A growing body of literature deals with the theoretical aspects of real options and provides examples of ROA applications to several empirical questions. A comprehensive and almost exhaustive overview of the development stages of the ROA, covering a historical and a contextual perspective, early criticism, analytic contributions and empirical applications, is provided by SCHWARTZ and TRIGEORGIS (2004) and TRIGEORGIS (1993). For this reason, we abstain from a detailed overview of related literature and instead elaborate upon the central assumptions of the ROA and their technical restrictions, and discuss some distinct features of irreversible agricultural projects that are likely to decisively influence the investment decision.

2.4.1 Uncertainty-flexibility trade-off

The first detailed analysis of the application of the option pricing technique to the capital investment decisions of firms was provided by DIXIT and PINDYCK (1994). In their seminal work on real options, the authors identify the simultaneous presence of uncertainty, irreversibility and flexibility as the *precondition* for a meaningful application of option pricing theory to investments in real assets. Uncertainty is an expression of insecurity about future development (primarily about returns) due to a lack of required information or knowledge. The possibility to delay an investment or choose its timing (i.e. flexibility) reflects the managerial scope of decision-making and the ability to respond to uncertainty.

The notion of irreversibility means that for a given capital-intensive asset (e.g. a factory or other facilities), there is no alternative use or any use other than initially intended entails significant costs. For irreversible projects, investment outlays are entirely or mostly sunk costs, whereby the choice of an optimal investment strategy matters. According to Dixit and Pindyck, irreversible investments are especially sensitive to uncertainty about future revenues, the costs of capital and investment timing. When making irreversible investment expenditures, an investor forfeits the possibility of waiting for new information that might influence the future cash flows. This implies that the chance to adapt and revise investment decisions later (if conditions for an investment improve or worsen) is lost.

DIXIT and PINDYCK (1994) conclude that this lost value of the option must be included as a part of the investment cost.[9] Hence, different to the NPV investment criterion, the present value of its expected cash flows must exceed the investment cost by the value of the lost flexibility. However, their most important finding comprises demonstrating the *combined importance* of uncertainty, flexibility and irreversibility as the preconditions for a meaningful application of option pricing theory to modeling corporate investment decisions. COPELAND und ANTIKAROV (2003) have specified this precondition by relating the significance of ROA for firms' strategic decisions to the *degree* of uncertainty, irreversibility and flexibility (Table 2.1).

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[9] The significance of irreversibility for financial investments was first highlighted by BERNANKE (1983), who also demonstrated that the informational value of flexibility not only includes quantitative but also qualitative sides; namely, not only additional information matters, but also the fact that bad news might entail more harm than good news might help.

Table 2: Relevance of the real options approach for decision-making

		Uncertainty	
		low	**high**
Irreversibility & flexibility	**high**	moderate	high
	low	low	moderate

Source: Own presentation based upon COPELAND and ANTIKAROV (2003, p. 14).

As shown in Table 2.1, the higher the uncertainty and irreversibility, the more likely it is that an investor will benefit from waiting for additional information on an uncertain event. Having strong room for flexibility of decisions allows an investor to respond to the additional information in his favor. Under these conditions, the relevance of the ROA for decision-making is particularly high. By contrast, if flexibility and uncertainty are low, the investment valuation can also be made quite accurately by using the NPV criterion.

The trade-off between the flexibility and uncertainty manifests itself in an alternative understanding of uncertainty components, such as in the study by ANTIKAROV (2001). ANTIKAROV (2001, p. 49) distinguishes between the uncertainty about future events (*market uncertainty*) and the means available to the firm to deal with the effects of this uncertainty (*firm-level uncertainty*). The latter reflects the investor's degree of confidence about the advantages of the planned investment and hence its capability to adjust its own actions. New investment projects that require additional knowledge and skills have a higher degree of firm-level uncertainty than those that build more directly on existing capacities. Other than market uncertainty, firm-level uncertainty can be influenced by the firm and thus it can be seen as the negative expression of a firm's flexibility, whereby the higher this uncertainty, the lower the capacity to flexibly respond to changes in business conditions and vice versa.

The central implication of the uncertainty-flexibility trade-off in irreversible investments is the proposition about the positive relationship between the level of uncertainty and the threshold price of investment. Higher uncertainty about project's profitability (i.e. a higher volatility of uncertain parameters) increases the value of flexibility, which in turn necessitates a higher mark-up for an optimal investment threshold. This positive relationship creates a value from holding an investment option, thus warranting the practicality of ROA applications.

However, a number of ROA-based studies have observed an ambiguous trigger response to increasing uncertainty. For instance, BAR-ILAN and STRANGE (1996) have demonstrated that in the presence of time lags, high operating costs in relation to the investment costs and the possibility to suspend production, some uncertainty can be hedged, whereby the investment threshold may decline with increasing volatility. TEISBERG (1994) concludes that an investment's lead time and the possibility to take corrective actions during the project by delaying or abandoning it may counter the generally depressing effect of uncertainty on investment incentives, lessening, neutralizing or even reversing it. AGUERREVERE'S (2003) study of incremental time-lagged investments in non-storable commodities shows that flexibility in production schemes (in terms of varying output amount) enables firms to limit their losses, whereby the net effect of uncertainty on investment activities is not necessarily negative. MAOZ (2008) emphasizes the concurrent presence of the time-to-build and the convexity of the profit function in the output price – caused by flexible adjustments during the project – as a precondition for the depressing effect of increasing volatility on the investment threshold.

BERTOLA (1988, Chapters 1 and 2) observes an ambiguous effect of two uncertainties (on the input and output side) on investment decisions without a time-to-build. He explains this by the prohibitively high costs of capital decumulation of investment projects with little (if any) resale value, which create a ratchet for disinvestments and increase the long-run capital intensity of production. Similar to DIXIT and PINDYCK (1994, Chapter 5 to 7), who analyze an optimal switching between production and suspension as a response to changing economic conditions, Bertola concludes that exercising one option creates an asset with pay-offs containing the option to switch again. The simultaneous pricing of two options may decisively affect the optimal investment threshold at increasing volatility.

The findings of the above-discussed studies suggest that under certain conditions, higher uncertainty may stimulate rather than dampen investment activities. The potential relevance of this implication necessitates reconsidering the role of project specificity in shaping the net effect of uncertainty and flexibility on investment incentives.

2.4.2 Technical restrictions in ROA applications

The opportunity to invest in a *real* asset closely resembles the mechanisms of buying an option on financial markets. Analogous to financial options, real options[10] reflect the choice of a strategy in an uncertain environment that evolves over time. Similar to an owner of a call option, an investor has the right but not the obligation to pay a fixed amount of investment costs for a chance to receive stochastic revenues, discounted at an expected rate. Accordingly, an investor will take an opportunity to invest or disinvest in an asset with uncertain payoffs only in the case of a favorable development of an asset's price. Nonetheless,

[10] The term *real option* was coined by MYERS (1977).

the analogy to financial options not only brings about advantages for the assessment of irreversible projects under uncertainty, but also substantial methodological restrictions, which will be discussed in the following.

Lack of historical time series

The main challenge for practical implementation of the ROA resulting from the direct analogy to stock markets is that real assets are usually neither traded nor can they be related to other traded commodities that can be used as a proxy for estimation of prices, cash flows or their statistical properties. While for financial options the value of the underlying asset and its statistical properties (such as the standard deviation) can be directly taken or derived from the market data, there are no such data for real investments, meaning that these values must be approximated by replicating a market-traded portfolio of related assets. Most agricultural real assets such as barns, biogas plants or arable land upon which the owner has the option cannot be easily sold if business conditions worsen. The options themselves (e.g. the option to extend the production capacity or to invest in a new technology) are not tradable either.

The straightforward consequence of the non-tradability of the underlying asset is that the price of the underlying cannot be extracted from the market data. As noted by MAJD and PINDYCK (1987, p. 25), in such cases an accurate estimation of the key model inputs such as the project's volatility and dividend yields is difficult or even impossible. One possibility to estimate the volatility of the underlying stochastic processes is to estimate the standard deviation of stock market equity returns (cf. MCDONALD and SIEGEL, 1986; MAJD and PINDYCK, 1987; DIXIT and PINDYCK, 1994) or the standard deviation of the underlying state variable (cf. PICKLES and SMITH, 1993; DAVIS, 1998).

However, the lack of historical time series on asset price and the absence of perfect correlation with a financial asset hinders creating a replicating portfolio to estimate the underlying stochastic properties of uncertain parameters. For new investment projects or such that focus on the implementation of innovative technologies, historical data on a project's market value may not be available at all. The main driver of the real options value is thus not the value of the underlying asset but rather the variability in the present value of cash flows. An asset's non-tradability further implies that a real option lacks any chartered contract. The holder of a real option is the only party involved, whereby speculations with real options are not possible.

Defining real options in a strict analogy to financial options - namely as "the subset of strategic options in which the decision to exercise the option is basically determined by financial instruments or assets traded on markets" (AMRAM and KULATILAKA, 2000, p. 10) – would mean that only few investment projects (such as oil drilling concessions) could be considered as real options. It is thus important to note that a real option is actually a quasi-option, namely an action in which real assets such as buildings or equipment have option-like characteristics for use, non-use or other alternatives actions.

Risk neutrality

A further level of difficulty in modeling with real options is added by the assumptions of the risk neutrality of an investor. The principle of risk-neutral valuation means that the value of an uncertain parameter (e.g. facilities' or product price) corresponds to its expected future value discounted to the present value at a risk-free rate. In this regard, the risk-neutral valuation is similar to the certainty equivalent method.[11] This assumption significantly simplifies the calculation of the option value (and that of derivatives in general). For options of the European type (namely when an investment has a fixed maturity date), it may lead to the same result as a risk-averse calculation (cf. ROBICHEK and MYERS, 1966).

Because an appropriate discount rate is often unknown, the economic literature dealing with the effect of uncertainty on the investment behavior of firms usually follows the idea of a risk-neutral profit maximizing investor. Risk-neutral investors do not demand a risk premium above the risk-free rate of return that can be gained in an alternative risk-free way, such as putting the money in the bank rather than investing it in real assets. The risk-neutral rate reduces the project value in the period when the option is exercised. However, the effective use of the risk-neutral approach requires that the current value and variance of the growth rate of the underlying asset are known. This is a particular challenge for real investment projects, for which not only the market value is rarely existent but also the underlying source of risk is not always an asset.

Under real-world business conditions with incomplete markets, decision-makers are risk-averse and as such they try to reduce uncertainty when realizing investment projects. However, the incorporation of the more realistic assumption of risk aversion (cf. ISIK, 2005; MCDONALD and SIEGEL, 1985) into the analysis of strategic investment decisions puts an extra level of mathematical calculus and entails different implications from the standard setting.[12] For instance, HUGONNIER

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[11] A risk-neutral valuation proceeds similarly to the certainty equivalent method, although not the discount rate but rather the value of the uncertain future cash flows is first reduced and then discounted at the risk-free rate. Accordingly, the adjustment for risk is made to the numerator in the net present value calculation.

[12] ISIK (2005) criticizes the option pricing theory for ignoring an investor's subjective degree of risk aversion and thus for not accounting for the impacts of reductions in variability of the firm's portfolio. In order to overcome this disadvantage by capturing the joint effects of risk aversion and irreversibility associated with corporate investments, Isik suggests a framework that links the expected utility analysis to real options models. MCDONALD and SIEGEL (1985)

and MORELLEC (2005) demonstrate that risk aversion provides an incentive to delay investment (cf. also BOMMIE and ROCHET, 2006). In their view, later investments significantly reduce the probability of investment over a given horizon and erode the value of investment projects. A risk-neural attitude of an investor may thus lead to an incorrect option pricing, which may turn to be crucial for sequential investments (cf. also ROBICHEK and MYERS, 1996).

A widespread alternative to the risk-free rate of return is a risk-adjusted discount rate. Within this method, the changing project uncertainty is dealt with by adjusting the discount rate: projects with above-average risk are discounted at a higher rate, those with below-average risk at a rate below the firm's corporate cost of capital, which in turn is used for valuation of projects with an average risk. Financial literature (e.g. BRIGHAM and EHRHARDT, 2008; CHEN 1967; ROBICHEK and MYERS, 1966) agrees that if uncertainty about project's pay-offs increases over time, this method is advantageous to both risk-neutral and certainty equivalent valuations. However, this advantage only holds if the underlying asset is traded or can be perfectly replicated, whereby the average discount rate can be estimated from observable market data.

Underlying stochastic process

Dealing with uncertainty is a central concern of the ROA. Uncertainty implies that the value of a parameter may change totally or partially randomly in a discrete or continuous time. The choice of the stochastic process that best describes the behavior of such parameters holds great relevance for modeling investments with high level of managerial flexibility, since its misspecification may influence not only the projects value, but also the investment rule itself (cf. WANG, 2010, p. 772).[13] In financial options analysis, the project value is often assumed to follow a *geometric Brownian motion* (GBM) (cf. BLACK and SCHOLES, 1973; COX et al., 1979). The use of Brownian motion for modeling stock price fluctuation was already proposed by Bachelier in 1900, subsequently becoming one of the integral parts of the modern finance and probability theory. Brownian motion belongs to the class of Markov processes, in which only the latest observed value of a stochastic parameter is relevant for modeling its future values. Brownian motion is broadly applied also to valuation of real options (e.g. ABEL, 1983;

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explicitly consider investors' risk-aversion, which influences financial investment decisions by affecting the cost of capital, arriving results that differ greatly from those obtained under assumption of risk-neutrality.

13 As demonstrated by BASTIAN-PINTO et al. (2009) for the bio-ethanol investments, the valuation of switch options may lead to option values that differ up to 20 % compared to base scenario when assuming the mean reversion and up to 70 % when modeled with the geometric Brownian motion.

BERTOLA, 1998; BRENNAN and SCHWARTZ, 1985; MCDONALD and SIEGEL, 1986; PADDOCK et al., 1988).

Another often assumed process is the *mean reversion* (cf. DIXIT and PINDYCK, 1994; GIBSON and SCHWARTZ, 1990; SCHWARTZ, 1997)[14]. This concept assumes that the stochasticity of a value is given only in a shirt term. In a long run, it converges to the average value over time. In the valuation of real investment projects with uncertain cash flows, the mean reversion and the random walk, as the two most common alternatives, have been debated especially extensively (cf. BRENNAN and SCHWARTZ, 1985; PINDYCK, 2001; GERMAN, 2005; METCALF and HASSETT, 1995). For instance, METCALF and HASSETT (1995) argue that mean reversion[15] is advantageous if the investor can adjust the output to increasing prices, while for cumulative investments both processes lead to very similar results.

The main criticism of the GBM assumption is that investments assessments, using this assumption, can misleadingly promise infinite profits. Increasing volatility implies that higher prices can be achieved, which provides incentives to more investment[16]. However, this objection would only be true in the case of no competition otherwise new firms would enter the market until the profits of the marginal entrant tend to zero (cf. BALMANN and MUßHOFF, 2002; METCALF and HASSETT, 1995; LILIEN and YOON, 1990). On the other side, a mean reverting process may induce expectations that price variance will decrease in the long run, leading to more investments as well[17]. The specification of an appropriate stochastic process is indeed not easy and is guided by different criteria such as asset's lifetime, the equilibrium assumption, the type of the model (analytical or numerical), the number of uncertain parameters and the feasibility of parameters' calibration.

Constant volatility and infinite time horizon

The ROA further assumes that variance of uncertain parameters remains constant over time, that is, the relative changes of stochastic parameter are normally

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[14] There are further alternative approaches to model the underlying stochastic processes, such as pure mean reversion in predictable stochastic processes (SCHWARTZ, 1997) mean reversion with jumps (DIAS and ROCHA, 2001), arithmetic Brownian motion (ALEXANDER et al., 2012), two (or three) factor models (SCHWARTZ and SMITH, 2000) as well as the variations of these models by taking into account the drift or discrete time steps instead of continuous time. However, in this section, we focus only on the discussion of the mean reverting process and geometric Brownian motion as the most often used and rivaling assumptions of the underlying stochasticity in the real options research.

[15] It has to be noted that the authors use the *geometric* mean reversion to enable a better comparability of the investment rates gained under assumption of mean reversion and geometric Brownian motion.

[16] METCALF and HASSET (1995, p. 1472) call this implication the effect of the "realized price".

[17] This effect is referred to by METCALF and HASSETT (1995, p. 1472) as the "variance" effect.

distributed[18]. This assumption is also a part of the rational behavior principle underlying the neoclassical economic paradigm to which the ROA belongs. Regarding uncertain parameters, rational expectations of the decision-maker mean that investor has information on the volatility of these parameters. This assumption can be justified when applied to short-term options on traded stocks (which, on the other side, could be problematic with respect to the infinite time assumption). However, it does not hold in real markets, especially for long-term options (cf. DAMODARAN, 1999) because over a long time period, the variance itself is of a stochastic nature and as such cannot be estimated correctly.

As demonstrated empirically by GOMPERS (1995) and theoretically by COSSIN et al. (2002), the volatility is not constant and is inversely related to the project's lifetime. The closer the project is to its completion, the lower are the cost of capital risk and the volatility level decreases over time. For different lengths of option's lifetime the assumption of a constant volatility may consequently have implications on the pattern in which investment pay-offs (cash inflows plus net appreciation of the capital value) are realized. Constant volatility also does not account well for the possibility of extreme values, which can be particularly relevant for pricing of compound options (such as e.g. option to suspend and resume production).

The assumption of parameter constancy seems difficult to reconcile with another underlying assumption of the option pricing theory, the infinite time horizon. This assumption reduces the complexity of the option pricing by removing the time dependence and hence, reducing the investment decision to a system of linear equations that can (sometimes) be solved analytically. For long-term investments, this is a useful approximation of a long duration of an investment project, or for such with no natural fixed time bound (e.g. insurances).

Nonetheless, most real investments have no very long-term goals.[19] As known from the financial investment theory, if the investment horizon is short, an investor is likely to develop a myopic loss aversion, which may lead to a loss in the project value.[20] The infinite time assumption hence tends to produce too high investment incentives. The remedy established in the ROA consist in the application of alternative numerical methods such as simulations, finite differences (HILL, 1875; EPSTEEN, 1904) and lattice methods, which allow for discrete time

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[18] Generally, in the models based upon the Black-Scholes price equation with random walk, uncertain parameters are assumed to follow a *lognormal* distribution.

[19] In agriculture, e.g. the lifetime of most machineries and facilities is limited up to 10 and 20 years correspondingly (cf., BStBl, 1996 (I), p. 1416).

[20] The concept of myopic loss aversion was first introduced in KAHNEMAN and TVERSKY (1979) and was further explored by BENARTZI and THALER (1995).

models with finite time horizons (cf., e.g. BRENNAN and SCHWARTZ, 1978; GRASSELLI, 2011).

The ROA is for sure not a final say in methodological approaches to investment decisions and has undoubtedly many shortcoming, such as ignoring the interactions among agents or a need for significantly more data than, e.g. the standard NPV approach. Despite these and other limitations the ROA still offers a framework which allows for a reliable approximation of investment behavior, suggesting that its practical benefits and formal restrictions are well-balanced.

2.4.3 Uncertainty-investment relationship in agricultural projects

As discussed above, making irreversible investment expenditures at the same time means forfeiting the possibility to wait for new information on an uncertain event. The forgone option value of this information should thus be considered as a cost component to warrantee the full investment cost valuation. The threshold price thus has to be higher than without considering the opportunity cost, since the total value of the investment project must cover – along with the purchase and installation cost – the opportunity cost of keeping the investment option alive. The opportunity cost increases with increasing uncertainty of project returns, leading to a higher threshold price. Consequently, investments will not be triggered until the threshold price substantially exceeds the long-run average costs (cf. DIXIT and PINDYCK, 1994, p. 7).

Accordingly, applications of the new investment theory to agricultural investments have arrived at investment triggers clearly higher than the NPV-based triggers. Table 2.2 summarizes some agricultural studies showing that triggers (expressed in terms of option multiples[21]) obtained within the ROA framework are often twice as high as the NPV-based ones. The selection of the studies was guided by the wish to reflect the variety of aspects identified by the authors as decisive for investment strategy. As seen from Table 2.2., options multiples may vary significantly, ranging from 1 to 5.3, but they never reach the value below one. This indicates that the ROA-based investment thresholds are at least as high as the NPV-based one.

[21] Option multiple is the ratio of the expected present value of profit steams and the cost of investment (or their marginal values) (cf., DIXIT and PINDYCK, 1994, p. 184; ABEL et al., 1996, p. 766). It denotes the relative quantity by which the expected present value of profits must exceed the investment outlays at the threshold that triggers the investment. It is an alternative way to express the additional value arising through the presence of optionality in uncertain irreversible investments.

Table 2.2: Examples of option multiples in agricultural investment projects

Studies	Main focus	Stochastic factors	Option multiple	Volatility (range)
Winter-Nelson and Amegbeto (1998)	Investments in soil conservation under different price policies (maize price)	Investment returns	1.6-5.3	10-20%
Pietola and Wang (2000)	Value of price fixing contracts for piglets	Prices	2.1	0-40%
Carey and Zilberman (2002)	Investments in irrigation technology	Price and initial capacity	2.3	15%
Maung and Foster (2002)	Investment in cooperatively owned hog facility	Input and output prices	3.1	19-27%
Turvey (2003)	Land prices, land price bubbles	Land price, cash flows	1.3-1.5	16-23%
Tzouramani and Mattas (2004)	Investments in greenhouse technology (tomatoes)	Price and yield	2	30%
Odening et al. (2005)	Investments in hog finishing	Revenues, variable costs	1.2-2.3	10-20%
Musshoff and Hirschauer (2008)	Adoption of organic farming	Revenues	1-4	10-20%

Source: Own presentation.

In the study by PIETOLA and WANG (2000), the real option approach is utilized to show that investment reluctance is lower in integrated production systems compared to separate production systems where piglets and hogs are traded on the spot market. The authors arrive at a negative uncertainty-investment relationship with an option multiple over two. Their results also show that the possibility to temporarily suspend production leads to a reduction in investment trigger, which clearly exceeds the Marshallian trigger. Maung and Foster numerically analyze the impact of alternative marketing contracts on the investments in cooperatively owned hog farms. Under explicit consideration of multiple uncertainties (uncertain input and output prices), they arrive at option multiples higher than 3 (3.1-3.5). The authors also demonstrate that the threshold price response to increasing volatility is contingent on the curvature of the profit function.

ODENING et al. (2005) consider revenues and variable costs as stochastic variables and find that triggers are highly sensitive to the assumption about the stochastic processes, underlining the importance of an accurate understanding of the dynamics of the stochastic variables. Option multiples are found to be within the range between 1.2 and 2.3, depending on the assumptions for the underlying uncertainty. MUSSHOFF and HIRSCHAUER (2008) apply the ROA for a comparative analysis of German and Austrian farmers' decision to adopt organic farming practices. For the German farm model, the authors observed investment thresholds being four times higher than those obtained with the NPV rule, while for the Austrian farm model flexibility was found to have no effect on investment incentives. The authors attribute this result to the differences in the stochastic processes found in the two countries. TZOURAMANI and MATTAS (2004) study investments in greenhouse technology using both the traditional NPV and the ROA-based investment rules and arrive at the option multiple of two. They conclude in line with the most options-based studies on irreversible investments that ROA provides a more accurate investment valuation than the NPV criterion regarding the critical investment price and the choice of investment timing.

WINTER-NELSON and AMEGBETO (1998) analyze investments in soil conservation technologies under different price policies. Their study focusses on the separate as well as the combined effect of price levels and price variability on the investment decision. The authors find that while increasing output prices tend to improve investment incentives, increases in price volatility dampen them and may even offset this positive impact of price level increase primarily due to the option value of delaying project. They conclude that due to the ambiguous net effect of the price level and its variability the option multiple may vary significantly, ranging from 1.6 to 5.3.

The study by TURVEY (2003) is concerned with the role of options in emerging discrepancies between observed land prices and its value predicted in terms of the present value of future cash flows, i.e. the annualized returns. Turvey explains the resulting differences through asymmetry in the options of sellers (options to sell immediately and postpone the sale) and buyers (option to buy or not). Using empirical data for cash flows and land prices, Turvey shows that the asymmetry in the options may create a cascading of price growth expectations by potential sellers. This, in turn, results in even longer delay and higher land and option prices (including land price bubbles), which may explains hysteresis on the land market. However, the option multiples obtained by Turvey are relatively small (1.3-1.5) compared to other studies. Notably, although the option multiples gained in these studies vary significantly, they never go below one, confirming the standard conclusion that in optimum the present value of expected revenues exceeds the investment cost.

The study by CAREY and ZILBERMAN (2002) numerically examines the effect of emerging water markets on farm's decision to invest in water-conserving irrigation technology. The authors show that the introduction of the water market (i.e. creating an option) leads to delaying of technology adoption; and the lower the initial water supply the longer the delay. This behavior is concordant with the key idea of the option pricing, namely that the presence of optionality makes it imperative for investors to delay the project and wait for additional information. The option multiple reflecting the optimal threshold of water market introduction is found to be over two (2.3). CAREY and ZILBERMAN (2002) also analytically show that while an increase in the fixed cost causes the investment threshold price to increase, a reduction of the fixed cost, e.g. through significant investment tax credits, may lead to a decrease in the threshold price. However, they emphasize that a relatively large reduction in the fixed cost is necessary to generate a significant reduction in the threshold price (IBID., p. 182). Although the authors do not measure this effect numerically, this observation provides an important hint that the ratio of variable-to-fixed costs plays an important role in uncertainty-investment relationship.

While few of the above reviewed studies highlight the positive or ambiguous impact of some project characteristics (such as the cost structure, curvature of the profit function, or degrees of managerial flexibility) and uncertainty structure on uncertainty-investment relationship, all of them confirm the standard conclusion about the generally negative net effect of increasing uncertainty on investments. This is less surprising as these studies, being paradigmatically concerned with the additional value through waiting, largely aim at contrasting the real option-based investment rule against the NPV criterion. Strikingly, on the other hand, is that the literature dealing with investments in livestock or fruit trees, adoption of organic farming or other projects involving time-to-build ignores the effect of the resulting time lag on the optimal investment policy. Like many other specifics of agricultural investments, such as the fixity of agricultural assets, land suitability for particular crops or high dependence on weather conditions, time-to-build and gestation periods affect the degree of uncertainty and irreversibility of investment decisions.

With few exceptions (e.g. FEIL et al., 2013), the existing literature applying the ROA to *agricultural* investments has paid hardly any attention to the role of these specifics in irreversible agricultural projects under uncertainty thus far[22]. The economic investment literature discussed in Section 2.4.1, nevertheless provides evidence that the occurrence of time-to-build and relatively high variable costs

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[22] AGRAWAL and HEADY (1968, p. 207) – who analyze decision-making under uncertainty from the game-theoretic perspective – emphasize the particular importance of these specifics in agricultural context: "Due to the time lag between investment and payoff, the price-taking nature of agriculture, stochastic weather variables and other factors, the uncertainty faced by decision makers in agriculture is greater than and different from that confronting managers of most other sectors of economy".

in combination with convexity of profit in output price may essentially influence investment triggers. The studies by BAR-ILAN and STRANGE (1996), MAOZ (2008) and CAREY and ZILBERMAN (2002) additionally suggest that the higher the share of the variable cost in the total costs the greater loss-reduction potential can be achieved through flexible response to changing business conditions.

There may be thus an additional effect working in the opposite direction than predicted by, e.g. DIXIT and PINDYCK (1994) and the longer the time-to-build the stronger this effect might be. Accordingly, the net effect of increasing volatility on investment incentives might be not necessary negative. This intuition motivates us to explore the role of time lags, cost structure and the flexibility capacity, being typical features of many agricultural projects, in irreversible agricultural investment decisions that face uncertainty on both input and output markets.

2.5 Summary of the chapter

The central idea behind the option valuation approach suggests that waiting for more information on uncertain events has a value and this value, which is given up by exercising an investment, must be integrated into project valuation as a component of investment costs. The recognizing the managerial flexibility in investment timing as a factor able to crucially influence the profitability of projects under uncertainty (cf. EKERN, 1988, p. 91) along with an explicit consideration of the opportunity costs of investment delay makes the option pricing method superior to the NPV criterion and other methods which tend to underestimate the value of investment projects. Incorporating the cost of the forgone or potential information allows limiting the downside risk of uncertain decisions and concurrently capturing the upside potential associated with the different choices. An option thus can be understood as a hedging part of a planned investment and the ROA as an analytic framework to address dynamic decision problems under uncertainty.

The ROA's conceptual advantages are rooting in the analogy to financial options (cf. BLACK and SCHOLES, 1973). However, for practical application of the ROA this analogy is not unproblematic. Unlike financial options, the underlying assets of corporate investment projects are not traded and not necessarily correlated with other (traded) assets. This entails further unrealistic assumptions such as risk neutrality, constant volatility and infinite time horizon. These assumptions not only contradict the real business conditions, since investors face incomplete markets and are exposed to non-diversifiable risks, but are often mutually conditioned; for instance, risk-neutral decisions are only possible if the agent has information on volatility distribution and the option is exercised instantaneously. As a result, an accurate ROA-based valuation of investment projects requires more data for estimation of the input parameter.

Since its development, the ROA has undergone a number of improvements and extensions that allow a successive relaxation of restrictive assumptions, the accounting for further stochastic parameters, or combinations with other methodological techniques (e.g. game theory or agent-based modeling). Many studies discussed in this chapter have demonstrated that the underlying assumptions of the ROA, although very restrictive, still allow for a reliable approximation of investment behavior, suggesting that their practical benefits and formal restrictions are well-balanced.

However, the methodological advances of the real options technique not only reveal advantages or further potentials for its applications, but also raise new questions. In particular, as the review of the relevant studies has shown, in more complex settings such as time-lagged investments, multiple volatilities or compound options, the ROA-based investment valuation may result in a positive relationship between the level of uncertainty and investment incentives. This observation contradicts the key conclusion of the option pricing theory about the generally depressing effect of uncertainty on investment incentives, suggesting the need to scrutinize the ambiguous uncertainty-investment relationship for its reasons and implications.

In agricultural context, where cost-intensive irreversible investments usually face more than one uncertainty and require a non-negligible time-to-build, this concern appears to be particularly relevant. Although the ROA enjoys broad and increasing applications in agricultural research, the ambiguous effect of uncertainty on investment incentives in agriculture has not been thus far a subject of inquiry. These considerations motivate us study the relevance and possible implications of this theoretical effect for irreversible agricultural projects within a real options framework.

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CHAPTER 3

UNCERTAINTY AND FLEXIBILITY EFFECTS ON BIOENERGY INVESTMENTS

Chapter 3 focusses on investments in bioenergy as highly uncertain and irreversible projects characterized by time-to-build, high share of variable costs and managerial flexibility. The chapter first highlights these characteristics and their empirical values for crop-based bioenergy production, contrasting them against other agricultural investments. The effects of different uncertainty sources, project's specifics and varying investment conditions on strategic investment plans are then studied in a stochastic dynamic partial equilibrium model which represents the interplay of the energy, bioenergy and food markets. In this chapter, the impact of uncertainty on bioenergy investments is studied only for the case of no policy support regimes. The model is solved numerically using real options-based stochastic simulation experiments in combination with genetic algorithms. The results demonstrate that for time-lagged bioenergy projects with relatively high variable costs the possibility to limit losses through temporary production suspension may create incentives to invest even at high uncertainty. Chapter 3 closes with discussion of findings and directions for further research.

3.1 INTRODUCTION

This section places attention on the non-trivial role of project specificity in responding to uncertain business conditions. It then discusses alternative theoreticcal perspectives on uncertainty-investment relationship and introduces objectives of the chapter.

3.1.1 Specifics of bioenergy investments

Investment literature, including agricultural studies, usually assumes an immediate realization of projects. Yet, in reality, agricultural investments take time, whereby accounting for the lag between the investment decision and its effectiveness is a part of the decision-making process of investors. This time-to-build, as shown in Table 3.1, can be too significant to be ignored.

Table 3.1: Typical time-to-build and cost ratios in agricultural investment projects

Examples of agricultural investments	Time-to-build (years)	Variable-to-fixed cost ratio(*)	Data sources
Crop-based bioenergy (biogas, bioethanol, biodiesel)	1-2.5	2-3	KTBL (2012), Chamber of Agriculture Lower Saxony (expert interview, October 2012)
Soil conservation	0-5	1-2	KTBL (2012), EC Regulation (EC) No 1254/2008
Piglet production	0.5-2	1.5-2.6	KTBL (2012), Chamber of Agriculture North Rhine-Westphalia (expert interview, October 2012)
Hog finishing	0.5-2	4.3-7.7	(Same as for piglet production)
Irrigation technology	0.5-3	1-3	Aquastat/FAO (2012), Koeva (2000, p. 12)
Greenhouse technology (tomatoes, cucumbers, lettuce)	0.5-2	4-5	KTBL (2012), SLL (2004, p. 56-57), Rakocy and Bailey (2003, p. 62), Koeva (2000, p. 12), Doroodian et al. (1999, p. 689)
Adoption of organic farming	2-5	(**)	EC Regulation 1254/2008, Schwarz et al. (2010), Nieberg et al. (2011)

Notes: (*) Period costs; (**) figures difficult to estimate due to unclear indirect effect of subsidies paid during the conversion period in many EU countries.

This non-negligible duration makes the time-to-build, which is alternatively designated as time lag (MAOZ, 2008), investment lag (HUANG et al., 2006), gestation period (HOLLINGER, 2004), time to maturity (KARALI and THURMAN, 2010), lead time (TEISBERG, 1994) or entry lag, (KALECKI, 1937, p. 81), a distinctive feature of many agricultural investment projects. In the investment literature, the term *time-to-build* is sometimes used to denote the lag that arises due to interruptions in the rate of expenditures on the project (e.g. MAJD and PINDYCK, 1987); in this case, project's completion is deliberately delayed by managers to learn more about the market value. However, in the present work, time-to-build only refers to the time needed to set up production assets and the gestation of agricultural produce such as crops or livestock.

The relative importance of time-to-build differs across the agriculture.[23] Investments in crop-based bioenergy usually require a time-to-build of 1 to 2.5 years. This length is due to various reasons. Some delays that result from administrative procedures (e.g. land acquisition) are rather short and can thus be ignored. This does not hold for time-to-build associated with construction works (e.g. bioenergy plants and other facilities), which vary between 2 months and 3 years (CHAMBER OF AGRICULTURE LOWER SAXONY, 2012), depending on the technological complexity. Moreover, gestation time associated with natural growth rates of crops may be up to 10 months (IBID.). Weather- and season-related delays are important as well as they determine the application of fertilizers and interstage products. Investment lags resulting from institutional factors such as laws and government policies are also often significant. Lags of 2-3 years may arise due to special requirements for land conversion; additional lags of 0.5-1.5 years may also result from the need to obtain construction permits (ibid.).

An important peculiarity of bioenergy projects that has to be recalled here is that they take place at the intersection of the agricultural and energy markets. The hybrid nature of bioenergy sector implies that some regulations for energy industries (e.g. concerning power grid access) apply for bioenergy as well, adding a potential source of time-to-build. While the average time-to-build in the most industries is about 2 years (KOEVA, 2000, p. 12; GRENADIER, 1995, p. 116), investments in large-scale energy plants or related infrastructure projects may take longer than 8 years to complete (IBID.; cf. also MACRAE, 1989, p. 42). This implies that with a possible increase of the bioenergy production scale, the importance of time-to-build in project valuation is also likely to increase.

Although time-to-build doubtlessly adds complexity to investment decisions (cf., e.g. AGRAWAL and HEADY, 1968, p. 207), it would be wrong to suggest that firms planning investments characterized by long gestation periods would automatically be at a disadvantage compared to quick-yielding projects. This supposition

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23 Investment lags were first mentioned in the economic literature during the 1920s and 1930s when discussed as a potential explanation of macroeconomic cyclical output fluctuations (PIGOU, 1927; KALECKI, 1935). Prior to the development of the real options approach, the role of investment lags in firms' investment behavior was first emphasized by NERLOVE (1972). Later, NICKELL (1977) analyzed their role for *uncertain* real investments.

is maintained by the fact that expected prices (or other uncertain parameters) do not depend on the uncertainty during the lag and thus are indifferent to possible extreme price movements until the investment's effectiveness. Besides, uncertainties associated with time-to-build (such as dependence of planned capacity on future demand and prices) may be somewhat absorbed by firm's operational flexibility (cf. AGUERREVERE, 2003; TEISBERG, 1994). The ability to adjust operations to changing business conditions, for instance, by temporary production suspension or other corrective actions during the project, brings about the notion that a significant part of variable costs can be avoided. The higher the share of variable costs, the higher the loss-reduction potential might be achieved during the discontinuation of production.[24] This suggests that the period costs structure might decisively determine the effectiveness of managerial flexibility in responding to increasing uncertainty.

As in the case of time-to-build, the ratios of the cost components vary considerably among investment types (cf. Table 3.1). For crop-based bioenergy projects, this ratio ranges between 2 and 3. However, these numbers should be interpretted with caution, given that they reflect the current average costs of bioenergy projects characterized by policy support programs. An abolishment or redesign of such programs might thus noticeably affect the ratio of period costs, depending on whether the policy regimes were directed on the fixed or variable costs reduction, or rather on the warranties of the market access, or a minimum sale price. For instance, fixed-cost subsidies would lead to a higher ratio of variable-to-fixed costs. Being a form of income that is not directly related to the output level, fixed-cost subsidies may weaken the negative effect of time-to-build on the expected revenues. Vice versa, if not affected by support payments, the imputed period cost ratio would be lower, making time-to-build more decision-relevant.

The outlined investment specifics (managerial flexibility, time-to-build and relatively high variable costs), which can be asserted for many agricultural projects, seem to be interdependent in their impact on the optimal investment decisions under uncertainty. This prompts us to closely look on their role in uncertain bioenergy projects.

[24] However, if, for instance, delivery contracts exist, such flexibility is not achievable or only at very high costs.

3.1.2 Objectives of the chapter

In this chapter, we develop a real options-based investment model to examine the impact of:

(Q1) multiple uncertainties on the output (energy) *and* input (food) market,

(Q2) the option to temporarily suspend production as a part of managerial flexibility and as a response to increasing uncertainty, and

(Q3) long time-to-build and relatively high variable-to-fixed cost ratios as distinct characteristics of many agricultural investment projects

on strategic investment decisions of bioenergy producers.

Answering these questions constitutes the *major research objective* (RQ I and RQ II) of this work defined in Chapter 1. The motivation to analyze the impact of *multiple* uncertainties (Q1) arises from the fact that most studies dealing with agricultural investments under uncertainty consider only one single uncertainty source, which is typically the output price (e.g. PIETOLA and WANG, 2000; CAREY and ZILBERMAN, 2002; ODENING et al., 2005). The prevalence of a single uncertainty assumption is largely determined by the mathematical complexity of such models. However, the environment in which investment decisions are made is never that simple and is usually characterized by more than one uncertainty source. The inclusion of the second uncertainty source, as shown by OTT and THOMPSON (1996, p. 1), "… tends to mitigate the impacts of the uncertainty on completed project value". Ignoring the second uncertainty source may thus result in underestimating project's value, causing "… long-term projects to require larger declines in value before discontinuation of investment should occur" and hence higher suspension costs (IBID.).

In our model, we thus seek to account for this fact by incorporating one uncertainty on the input side and one on the output side. Although considering only two uncertainties remains a significant reduction of the complexity that firms face under real-world conditions, it nevertheless helps to reflect the different origins of uncertainties, as well as their reciprocal effects. By assuming two uncertainties, we also aim to address the hybrid nature of the bioenergy market, which is situated at the intersection of the energy and food markets.

The second question posed in this chapter (Q2) is motivated by the observations of the ambiguous investment trigger response to increasing uncertainty given the convexity of the profit function (e.g. OTT and THOMPSON, 1996; HARTMAN, 1972; CABALLERO, 1991; MAOZ, 2008). These observations seem to contradict the key conclusion of the ROA (e.g. DIXIT and PINDYCK, 1994), which states that the threshold price at which it is optimal to invest always increases with increasing uncertainty (i.e. volatility) of the project returns.

In our model, the convexity of profits in output price stems from the possibility to temporarily suspend production if business conditions worsen. The option to suspend implies that for investors facing high uncertainty in bad states (given by, e.g. too low output prices), the possibility to temporarily pause production would mean the possibility to significantly reduce the variable costs, limiting the size of losses to the fixed and maintenance costs. By contrast, in good states, the resumption or continuation of production would allow taking benefits of improved conditions. This suggests that a sufficiently high managerial flexibility may induce an ambiguous effect on investment incentives.

For the effect of the profit function curvature is mathematically proved (by *Jensen's inequality*), we aim to demonstrate that the ambiguous effect of uncertainty on investments is not alone due to the convexity of the profit function. We hypothesize that only in the simultaneous presence of a sufficiently high ratio of variable-to-fixed production costs and longer time-to-build the convexity of the profit function may decisively weaken the generally negative effect of uncertainty on investment activities (Q3). This hypothesis relies on intuition that firms, able to temporarily suspend production in bad states, can avoid the more losses the higher the share of their variable costs relatively to fixed costs. This effect may be accelerated by the existence of time-to-build, because the value of a project is not affected by uncertainties' dynamics during the time lag. Although the effect of the time-to-build is unquestionable in the literature on path dependence in agriculture (e.g. BALMANN, 1999; YESUF and BLUFFSTONE, 2009), it is hardly accounted for in agricultural investment analysis (e.g. SHYJAN, 2007). The present work aims thus to explicitly investigate the role of these investment specifics in investment decisions under uncertainty.

To approach the formulated objectives, we employ a *stochastic dynamic partial equilibrium model*, representing the interplay of the energy, bioenergy and food markets in a closed economy. The effect of changing uncertainties on the input and output markets on bioenergy investments is examined using stochastic simulations in the framework of the ROA. The foremost *methodological* objective of the present work is to address the generality of the standard conclusion of the investment theory about the negative uncertainty-investment relationship, which has been doubted by a number of studies[25]. For this purpose, we seek to provide a detailed investigation of the role of agricultural investment specifics of in determining this relationship. Although the study is designed as a theoretical investigation, the developed investment model reflects real business conditions, assuming parameter values reported for crop-based bioenergy production in the EU.

[25] See Chapter 2, Section 2.4.1 and the following sections of this chapter.

3.1.3 Organization of the chapter

The remainder of Chapter 3 is organized as follows. Section 3.2 provides an overview of the literature, dealing with uncertain real investments from different theoretical positions. It focuses on the real options approach to uncertain investments, while pointing up the role of project specifics in determining the optimal investment plans. Section 3.3 develops a real option-based investment model to analyze the role of these specifics in bioenergy investments under multiple uncertainties. Model's assumptions and scenarios under consideration are presented then in detail. Subsequently, we introduce parameters and their value utilized for initialization of the model. The methodologies employed for solving the investment model are introduced in Section 3.4. The simulation results for different scenarios are summarized and discussed in Section 3.5. Section 3.6 provides a summary of the chapter and identifies questions to be addressed by further research.

3.2 Real options perspective and the role of investment specifics

Literature on investment analysis of firms is enormous. Many authors have provided thorough surveys of its development, facets and theoretical extensions (e.g. Nickell, 1978; Crotty, 1992; Reilly and Brown, 2011). In the realm of the new investment theory, Dixit and Pindyck (1994), Brennan and Schwarz (1985) and Trigeorgis (1995 and 2005) have provided a work of reference on the theoretical and applied studies. For this reason, we abstain from reviewing the numerous related studies. In its place, we explore how the real options-based literature deals with the managerial flexibility, time-to-build and projects' period costs as special features of uncertain irreversible investments.

Variable and fixed costs

In contrast to other investment approaches, the ROA is paradigmatically concerned with *irreversible* investments. Investments are defined as irreversible when their costs cannot be recovered through disinvestments or if a disinvestment is impeded by the asset fixity or specificity of its use (cf. Chavas, 1994; Johnson and Pasour, 1981; Edwards, 1959). Such projects are typically characterized by high fixed expenditures that are totally or largely sunk. As discussed in the previous sections, the presence of sunk costs together with uncertainty and flexibility constitutes the precondition for the application of the real option approach. This presumption has important implications for project valuation. First, for uncertain investments that are irreversible yet can be postponed, the NPV investment rule becomes grossly incorrect (cf. Pindyck, 1991, p. 1109).[26] Second, as shown by

[26] Due to the decisive impact of the cost structure on investments under uncertainty, irreversibility – in Pindyck's view - not only invalidates the NPV investment criterion but also

PINDYCK (1991 and 1988) and other ROA-based studies (e.g. BRENNAN and SCHWARTZ, 1985; MCDONALD and SIEGEL, 1985 and 1986; MAJD and PINDYCK, 1987), irreversible investments with high sunk costs are especially sensitive to uncertainties. Consequently, the trade-off between the value of waiting and its cost may change, depending on the period cost structure.

This can be illustrated using analogy to the impact of fixed and variable cost shares in determining the *break-even point* of a certain production process. The break-even point determines the output amount at which the revenues cover all production costs (cf., e.g. SCHWEIZER and TROßMANN, 1998), that is, that point on the profit function at which the contribution margin of a product equals its fixed cost.[27] The effect of the variable and fixed-cost components on the revenues might be ambitious, depending on the economic conditions. A decrease in variable costs would imply an increasing contribution margin, leading to reduction in the output amount needed to cover production costs (which is identical with a lower break-even point). However, this can prove disadvantageous when either sales or sale price sharply decline, because – due to relative high fixed expenses – the break-even point would be higher and the safety margin would thus be lower. The lower share of variable costs would make the firm more sensitive to bad news, as its losses would be higher compared to firms with relatively low fixed costs. Vice versa, if sales increase, the revenues increase faster compared to the firms with high fixed costs. Consequently, firms with relatively high variable costs might be less vulnerable to unfavorable conditions, although under favorable conditions they will enjoy lower yet more stable net income.

This effect bears close similarity to the effect of the high ratio of the period variable-to-fixed costs on the optimal investment decision, as can be observed in the study by BAR-ILAN and STRANGE (1996). A striking assumption of their ROA-based study is that the marginal variable cost is 40 times higher than the annualized fixed cost. Although the authors do not investigate the role of this distinct assumption, the latter allows important conclusions. In their study of uncertain irreversible time-lagged projects that can be temporarily abandoned, the authors observe an ambiguous investment threshold behavior at increasing uncertainty, which they ascribe to the lag between investments and their pay-offs. However, the significantly high period variable cost suggests that under unfavorable conditions, the possibility to temporarily suspend production allows economizing on a high share of production costs and hence limiting firms' losses. In good states, there would be no corresponding upward limit for firms' profits, although the

"undermines the theoretical foundation of standard neoclassical investment models" (cf. PINDYCK, 1991, p. 1110).

[27] Alternatively, the break-even point can be calculated as the output price necessary at a given level of production to cover all accrued costs.

profits would be more moderate compared to a situation with a lower variable-to-fixed cost ratio. The cost structure of an investment project is thus likely to be a factor that may profoundly influence the optimal investment rule.

This intuition is further supported by the findings of SCHMIT et al. (2009). Their study on crops-based ethanol investments generally confirms the positive uncertainty-threshold relationship, showing that optimal investment "…price triggers drop with increases in firm size given decreased unit capital investment costs" (IBID., p. 1446). This finding is consonant with conclusions derived by PEDERSON and ZOU (2009), empirically analyzing investments in crop-based ethanol production under assumption of the option to expand the scale of operations. PEDERSON and ZOU conclude that increasing volatility of the output price may favor decision to expand production scale. In their view, this effect is only possible if the swings in prices on the input side are sufficiently low to enable increasing expected profitability; otherwise the optimal decision would be to postpone or reject the project. The outcomes of these two studies indicate the likely important role that the variable-to-fixed cost relation may play in bioenergy investment plans, which (as shown in Table 3.1) are characterized by the period variable cost clearly exceeding the annualized fixed cost.[28]

Flexibility

Flexibility is, along with uncertainty and irreversibility, one of the constitutive presumptions of the ROA. While the degree of project's irreversibility may reduce or exacerbate the level of revenues' uncertainty, it is primarily the flexibility of decisions about whether or when to carry out an uncertain project that creates *real options* as firms' response to contingencies. In the real options literature, flexibility of managerial decisions is understood primarily as the possibility to postpone investments until uncertainty is resolved and the level of profits exceeds a certain critical value (e.g. DIXIT and PINDYCK, 1994, p. 29; TRIGEORGIS, 1996). Another

[28] A factor that may significantly determine the effect of the cost structure itself is the investment horizon. While in the short run, flexible and committed resources with corresponding variable and fixed expenses can be easily distinguished, in the long run the fixed cost can also be directly related to the production, since it changes in direct relation to the output amount. This means that in the long run, all costs can be considered as variable costs (cf. COOPER and KAPLAN, 1988). The cost structure may thus be determined differently for the same investment project, depending on the time frame under consideration. This can be further complicated by the fact that costs for committed or flexible resources can also vary in their responses to changes in production volume. Within the fixed costs, for instance, DIXIT and PINDYCK (1994, p. 383) distinguish between stock fixed costs (lump-sum costs needed to start up an activity) and flow fixed costs (which accrue as a given rate of flow over a certain time step). Costs of flexible resources – namely, variable costs – may also behave differently and fluctuate in relation to other factors such as used capacity or commitments with suppliers (cf. COOPER and KAPLAN, 1988, p. 4).

kind of flexibility is warranted by the ability to take corrective actions during the project's lifetime; for instance, through variations of the output amount within the capacity limits or the abandonment or temporary suspension of unprofitable production. For example, HUCHZERMEIER and LOCH (2001) analyze R&D projects with uncertain and time-lagged costs and revenues, assuming that project managers can use the option to abandon or respond to uncertainties by variation of product quality. For the latter option, the authors conclude that the value of flexibility would be reduced, leading to lower investment thresholds. The authors point out that this effect can only be observed within the convex region of the increasing convex-concave pay-offs function. The findings of TEISBERG'S (1994) study back up this conclusion from the backward perspective. In the case of utility power plant investments, Teisberg observes that uncertainty reduction due to cost recover policies simultaneously lowers projects sensitivity to available flexibility, thus reducing investment incentives.

BAR-ILAN and STRANGE (1996) also emphasize the role of the profit function curvature. In their study of uncertain irreversible time-lagged investments, the project can be temporarily abandoned.[29] This option - which makes profits a convex function of uncertain output price - allows the firm to limit its losses by avoiding some variable production costs, while there is no corresponding upward profit limit in states with favorable business conditions (IBID., p. 611). The authors observe that the effect of uncertainty on investment incentives is not necessary negative for such projects. The studies by AGUERREVERE (2003) and MAOZ (2008) – in which the profit function convexity is rendered through variation of output in response to output price changes – arrive at similar conclusions.

In particular, AGUERREVERE (2003) analyzes incremental time-lagged investments in non-storable commodities (electricity) under conditions of competition and uncertain output price. He concludes that without such output adjustments, the net effect of uncertainty on investments is always negative. By contrast, the possibility to respond to contingencies by varying the output amount might incite further investments, even in the presence of unused production capacities. The

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[29] In the ROA-literature, the option to suspend is alternatively dealt with as the switching option. For instance, MCDONALD and SIEGEL (1985) and BRENNAN and SCHWARTZ (1985) study the options to temporarily shut down (or "mothball") production as an option on the option to restart production. In turn, the option to resume production contains the option to suspend. Their results suggest that in the presence of switching (and other compound) options, investment decisions are determined not by one but rather two thresholds: the exercising one option creates an asset with payoffs, containing the option of switching again. An important implication of this view is the resulting asymmetry in the values of both options. This asymmetry may contribute to an ambiguous trigger response to increasing volatility, depending on the occurrence of favorable and unfavorable business conditions and project characteristics.

longer the investment lags (which are assumed to vary between 6 and 10 years) the higher the optimal capacity might be. Other than AGUERREVERE (2003), MAOZ'S (2008) study of continuous time investments under uncertainty explicitly assumes that the profit function convexity is caused by the strictly positive marginal productivity of labor. This assumption implies that a flexible adjustment in the output amount in bad states would affects the curvature of the profit function directly and not via the cost-economizing effect of, e.g. production suspension. Despite this difference, MAOZ (2008) confirms the ambiguous investment threshold behavior at increased uncertainty.

At this point, it is necessary to do justice to DIXIT and PINDYCK (1994), the primer on real options. In Chapter 6.3 of their book, Dixit and Pindyck also highlight the importance of the curvature of the profit function for irreversible investments. In the extension of their general investment model, the authors consider investment projects with uncertain output price, constant input costs and some operational flexibility due to instantaneous input factor variations. DIXIT and PINDYCK (1994) show that instantaneous variability in operations, which do not incur any irreversible commitments, makes the profit function convex in price. The reason is that without such operational flexibility the output is constant and the revenues and profits change linearly with output price. By contrast, when an instantaneous input variation is possible, the profit increases faster with an increasing price and decreases slower when the price falls (IBID., p. 197). In the profit function, this effect is expressed by the power of the price being greater than one.

As a consequence of the profit function convexity, an additional effect on investment decision arises. DIXIT and PINDYCK use a risk-adjusted discount rate (which is equally consistent with the risk-neutral valuation) to show this effect in a greater detail[30]. Risk adjustment takes into account the convenience yield. Although the convenience yield, assumed to be exogenous, is independent of uncertainty, its marginal value decreases with increasing uncertainty (cf. IBID., p. 198).[31] This again lowers the profitability threshold required to carry out an investment and thus increases incentives to invest[32]. In technical terms, DIXIT and PINDYCK explain this

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30 Risk adjustment through reduction of the interest rate by a convenience or dividend yield is often also required to justify the assumption of the GBM process for stochastic variables (cf. COX et al., 1985). This is primarily the case if an analytical solution for the growth rate of a stochastic parameter holds interest (cf. MAUNG and FOSTER, 2002, p. 234; COX et al., 1985; GIBSON and SCHWQARTZ, 1990).

31 The assumption of a constant convenience yield is important, because if convenience yield is also stochastic (e.g. due to dependence on the stochastic prices or the interest rate), the stochastic process would rather follow a mean-reversion than a GBM (cf. CASASSUS and COLLIN-DUFRESNE, 2005, p. 2283).

32 The authors observe the same effect for a certain output price, but an uncertain interest rate (cf. IBID., p. 49).

effect as a combined implication of Jensen's inequality and convexity of profit function in an uncertain parameter, meaning that with increasing variance of the output price, the expected value of a convex function also increases.[33]

In view of this theoretical observation, it might appear surprising that the positive or at least ambiguous effect of uncertainty on investment incentives is treated marginally in the investment literature. The reason partly lies in the strong assumptions made by Dixit and Pindyck, requiring – along with a Cobb-Douglas production function and mean-preserving volatility spreads – operational flexibility and convenience yield. While the non-linearity of production function and the constant uncertainty distribution can be seen as technical devices that ease focusing on the variables of interest, flexibility through instantaneous factor variation relaxes the assumption of irreversibility and hence counteracts uncertainty to some extent. Studies focusing on the impact of irreversibility and related high sunk costs in highly uncertain investment projects may thus deliberately disregard the effect of additional managerial flexibility. Also convenience yields, which increase firms' "ability to avoid disruptions of the production process or the ability to meet unexpected demand for the final good" (ALQUIST and KILIAN, 2010, Section 5.5), contribute to uncertainty reduction. However, in many commodity markets, the ability to adjust production to unexpected changes in business conditions by using inventories is either impossible (e.g. for energy or livestock) or very limited (as for food and other perishable produce), whereby no convenience yield occurs (cf., e.g. MAUNG and FOSTER, 2002, p. 227). The instantaneous adjustment of factors, which is responsible for profit function convexity in DIXIT'S and PINDYCK'S (1994) model, is hardly feasible at all. Although the authors repeatedly underscore the significance of profit convexity on the uncertainty-investment relationship (cf. IBID., p 49, 197 and 364) the restrictive nature of their model's central assumptions marginalize this effect as rather theoretical.

Finally, as vividly shown by Dixit and Pindyck, the volatility of stochastic parameter has always two effects: it increases the expected value of the project, while also producing incentives to wait. The net effect of uncertainty on investments is thus dependent on the relation between the potential benefits from flexibility and its opportunity costs. Thus, the question that still needs to be answered is what factors may profoundly determine this net effect. Although they do not provide an exhaustive answer to this question, Dixit and Pindyck nonetheless offer a important search direction by pointing out the crucial role of profit function curvature in strategic investment plans.

[33] This effect can also be illustrated by the Ito's Lemma, where an additional term in the expected growth rate of the profit flow reduces the marginal value of convenience yields, leading a lower threshold price (cf. DIXIT and PINDYCK, 1994, p. 199).

Time-to-build

Unlike financial investments, most investments in physical assets require a certain time to build production facilities and produce the first marketable output. According to the International Monetary Fund (cf. KOEVA, 2000), the average time-to-build across the industries is two years, while for non-durable goods such as energy or food it may be even longer, namely up to eight years. Such non-negligible periods of waiting for the first revenues betoken their relevance in capital budgeting. The ROA-based studies which do not consider the effect of the time-to-build (e.g. ODENING et al., 2005; PIETOLA and WANG, 2000) usually conclude that an increase in uncertainty would unavoidably create the value of holding the option to delay and hence raise the threshold price of investment. By contrast, an explicit consideration of time-to-build may influence the trade-off between making strategic commitments and exploiting the option to wait (cf. PACHECO-DE-ALMEIDA and ZEMSKY, 2003, p. 166). Indeed, as reported by a number of ROA-based studies (e.g. HUCHZEMEIER and LOCH, 2001; MAOZ, 2008; TEISBERG, 1994; BAR-ILAN and STRANGE, 1996), project's lead time affects the optimal investment rule.

In line with the most ROA-based models, Bar-Ilan and Strange argue that in the presence of a time lag, increasing uncertainty means a higher variance of investment returns and consequently higher option value. On the other hand, the opportunity costs of waiting (which solely depend on the future prices, but not on the prices during the lag) also increase with increasing uncertainty, which may incite investments. The authors thus conclude that a sufficiently long time-to-build increases the likelihood of extreme profits and may not only weaken, but also reverse the generally depressing effect of contingencies on investment incentives.

The findings by BAR-ILAN and STRANGE (1996) are the point of departure for MAOZ' (2008) investigation of uncertainty-flexibility effect in time-lagged investments. Maoz observers that uncertainty negatively affects investments for short lengths of time-to-build, whereas sufficiently long lags engender an inverse U-shape relationship between the uncertainty and the optimal threshold price. Maoz further demonstrates that the longer the time-to-build, the wider the range of a positive uncertainty-investment relationship and the lower the level of uncertainty from which the critical price decreases. Both studies explain this effect in Bernanke's terms of the balance between the *good* and *bad news* (cf. MAOZ, 2008, p. 1; BAR-ILAN and STRANGE, 1996, p. 611). According to BERNANKE (1983), the optimal investment timing is affected primarily by the bad news. However, in the presence of time-to-build, it is not possible to receive the profits from good news immediately, whereby good news becomes more relevant for investors than in the case with no time-to-build.

Other than Bar-Ilan and Strange, Maoz depicts the concurrent presence of time-to-build and convex profit function in the output price as the necessary condition for the positive effect of volatility on investment. The relevance of the simultaneous effect of the lead time and project's flexibility can also be presumed in the previously mentioned studies by TEISBERG (1994) and HUCHZEMEIER and LOCH (2001), showing that a longer time-to-build tends to lessen the proclivity to delay investments and thus the value of holding this option. The study by MARTINS and DA SILVA (2005) – dealing with exit and entry options – endorses this finding. The authors numerically demonstrate that for time-lagged sequential investments, an option's time value may not be very significant, implying that the gap between the NPV and ROA triggers becomes smaller. The authors also conclude that sequential investments strengthen the effect that the time-to-build has on investments decisions, especially at high uncertainty.

The observed effects of the time lag, high variable costs and the ability of management to flexibly respond to uncertainty provide scattered but supportive evidence of the potentially important role of these specifics in determining the optimal investment policy. In view of the non-negligible empirical values of the time-to-build and the relative variable costs in agricultural investments, presented in Table 3.1, they certainly substantiate the need to reconsider the uncertainty-threshold relationship in agricultural context. The comparison of the alternative theoretical perspectives on the uncertainty-flexibility relationship in cost-intensive irreversible projects additionally supports our hypothesis that the structure of the period costs and the time-to-build – taken separately or together – can affect projects' irreversibility and uncertainty properties and thus the optimal investment schedule. Assuming the managerial skills to respond to changing conditions, these project features may offer a useful tool of risk management and thus deserve an explicit investigation. In the following section, we will assess the relevance of these specifics for strategic irreversible decisions of bioenergy producers.

3.3 INVESTMENT MODEL

3.3.1 General assumptions and scenarios

To approach the formulated objectives, we develop a dynamic stochastic partial equilibrium model of crop-based bioenergy investments in the closed-economy case. The model encompasses the interrelated energy market, bioenergy and food markets. It is assumed that the bioenergy and food markets are relatively small compared to the energy market, implying that the latter is not affected by activities on the other two markets. The energy market is proxied by a multiple of the exogenous and stochastic world price of crude oil (in the following referred to as energy price). The food market is represented by all kinds of field crops that can be used for both food and bioenergy production. This generalization also allows the assumption of constant production technologies on the food and bioenergy markets. The demand for these crops is assumed to be stochastic and its supply exogenous and limited by the available agricultural area.

On the bioenergy market, there is an *aggregated* risk-neutral[34] bioenergy producer that represents the total number of bioenergy producers within an economy. Bioenergy production is based upon using agricultural crops as the only substrate. For ease of exposition, we consider the crops price as the only variable cost component. Bioenergy plants are subject to depreciation, which makes reinvestments necessary to keep production capacity constant. In the short term, this capacity is limited, although in the long run it can be increased by additional investments. Investment outlays $Inv_{(t)}$ are irreversible and variable. Returns-to-scale are assumed to be constant, implying that investment outlays and production are proportional. The direct energy use and the irreversibility in thermodynamic terms – i.e. as an increase of entropy – associated with bioenergy production are not considered in the present work.

The *central assumption* of the investment model is that bioenergy production can be temporarily suspended if the expected output price falls below the period production cost. The option to suspend reflects the ability of bioenergy producers to adjust the scale of operations to changing market conditions. It is further assumed that such production stoppage incurs *no additional* cost, whereby the losses during the suspension are limited to the period fixed costs. There are also no policy support programs for bioenergy sector, implying that the bioenergy price is directly determined by the world energy price. At the end of the period $t=0$, there is an initial investment based upon the expected energy price and expected food demand in the next period. Bioenergy production starts in the period $t=1$. An investment triggered in t is supposed to generate revenues, not immediately but rather at time $t + \Delta t \cdot l$, where Δt represents the discrete time step length and the integer l stands for the number of time steps needed for the implementation of the investment project. The product of both terms, $\Delta t \cdot l$, indicates the project's *time-to-build*, namely the period between an investment decision and its effectiveness. In the base scenario, only one time-to-build length of one period is considered. Further scenarios will be introduced by variation of the length of time-to-build, the initial variable-to-fixed cost ratio, food demand elasticity and an explicit consideration of the case of no suspension. Different

[34] The assumption of risk-neutrality is a necessary precondition for the application of the real options approach (for a more detailed discussion on this assumption, see Chapter 2, Section 2.4.2). This simplification surely prevents from taking full account of the true risk attitude of investors, although it is not prejudicial to our model focusing on an aggregate investor.

policy regimes and their impact on the optimal investment policy will be analyzed separately in Chapter 5.

3.3.2 Food market

For the purpose of the model, the food crops production is seen as aggregated and limited by its maximum capacity (determined, e.g. by the amount of arable land). The total food crops supply $Q^{S}_{(t)c}$ is thus exogenous and constant. Crops demand $Q^{D}_{(t)c}$ comprises two parts, namely crops demand for biomass (used as input for bioenergy production) $Q^{D}_{(t)b}$ and crops demand for other uses $Q^{D}_{(t)f}$ (mainly for food production):

$$Q^{D}_{(t)c} = Q^{D}_{(t)b} + Q^{D}_{(t)f}\ . \quad (3.1)$$

The amount of crops demanded for food production is determined by the food demand parameter and the crop price:

$$Q^{D}_{(t)f} = \frac{\varphi_{(t)}}{p_{(t)c}{}^{-\eta}} \quad (3.2)$$

where $\varphi_{(t)}$ is demand parameter and η demand elasticity and $p_{(t)c}$ the market-clearing crops (i.e. food) price.

The demand parameter $\varphi_{(t)}$ follows a time-discrete version of GBM as the underlying stochastic process:

$$\varphi_{(t)} = \hat{\varphi}_{\ (t+\Delta t)} = \ \varphi_{(t-\Delta t)} \cdot exp\left[(\mu_{\varphi} - \frac{\sigma_{\varphi}^{2}}{2}) \cdot \Delta t + \sigma_{\varphi} \cdot \varepsilon_{(t)\varphi} \cdot \sqrt{\Delta t}\right]. \quad (3.3)$$

with $\hat{\varphi}$ as expected demand parameter, a drift rate μ_{φ}, volatility σ_{φ}, a normally distributed random number $\varepsilon_{(t)\varphi}$ and a time step length Δt.[35] The GBM is a process that describes the probability distribution of the future value of stochastic variables. The GBM assumes that over a longer period, the relative (thus geometric) logarithmic changes (i.e. motions) in the value of the stochastic variable are normally distributed. The future changes of such variables are determined by present conditions alone and are independent of past values of these variables; namely, they follow a random walk. The present conditions consist of the drift, which is the expected change of the variable and random shocks added to (or

[35] Although the GBM is a continuous-time continuous-variable process, it can be modeled time-discretely, particularly if a numerical solution is preferred. For this aim, we replace derivatives with finite differences and use discrete equidistant time steps. Such discretization is a technical simplification and as such surely offers a target surface for criticism. However, since we assume that investments are made once a period, corresponding to the input yield rate, the discrete-time version of the GBM does not entail a loss of valuable solutions (cf., e.g., BALMANN and MUßHOFF, 2002; FEIL et al., 2013; ODENING et al., 2007). Besides, our model allows variations of time step length, which makes consideration of sufficiently small time steps possible.

subtracted from) the drift. The standard normal variable $\varepsilon_{(t)\varphi}$ randomizes the volatility while ensuring that during a certain period the shock represented by the term $\sigma_\varphi \cdot \varepsilon_{(t)\varphi} \cdot \sqrt{\Delta t}$ will lie within the standard deviation. Such dynamics imply that after an investment decision is made, the food crop price will solely depend on the behavior of the demand parameter $\varphi_{(t)}$.

3.3.3 Energy market

For the energy market, we assume that the exogenous stochastic energy price $p_{(t)e}$ also follows a time-discrete version of the GBM:

$$p_{(t)e} = p_{(t-\Delta t)e} \cdot exp\left[(\mu_e - \frac{\sigma_e^2}{2}) \cdot \Delta t + \sigma_e \cdot \varepsilon_{(t)e} \cdot \sqrt{\Delta t}\right]. \tag{3.4}$$

Due to its relative size, the energy market is not influenced by the bioenergy or food production. However, vice versa, the impact might be significant. If an increase in energy price leads to a higher per hectare profit from bioenergy production than from food production, the rededication of the limited agricultural land towards bioenergy production would increase. For consumers, any price increase on the energy market would induce an increase in spending for food and energy. This correlation is likely to tighten in view of the policy goal to increase the share of renewables in the energy mix.

To reflect the linkage between the energy, bioenergy and food markets arising, for instance, due to the income effect, we introduce a correlation between the both stochastic processes. This correlation is expressed by variation of the normally distributed random number $\varepsilon_{(t)}$, which scales the standard deviation of a random shock in the GBM process. For this aim, we decompose the random number $\varepsilon_{(t)}$ in a variable specific component $z'_{(t)}$ and a non-specific component $z_{(t)}$:

$$\varepsilon_{(t)\varphi} = \alpha z_{(t)} + (1-\alpha) z'_{(t)\varphi} \tag{3.5}$$

$$\varepsilon_{(t)e} = \alpha z_{(t)} + (1-\alpha) z'_{(t)e} \tag{3.6}$$

with the correlation parameter α.

A correlation parameter $\alpha = 1$ would yield the same random numbers (or the same withe noises) for both stochastic variables. In the case of $\alpha = 0$, there is no correlation between the evolutions of food and energy demand. Within the range from zero to one, the correlation can be varied.

3.3.4 Bioenergy market

The bioenergy market is assumed to be considerably smaller than the global energy market, whereby the latter is not influenced by investment decisions of the bioenergy sector. Bioenergy demand is unlimited and the bioenergy sector is able to absorb all available food crops by adjusting its production decisions.

By substituting equation (3.2) into (3.1) and taking into account the identity of demand and supply, the crops supply for bioenergy sector can be presented as the residual of the total crops supply and the crops demand for food:

$$Q_{(t)b}^{D} = Q_{(t)c}^{S} - \frac{\varphi_{(t)}}{p_{(t)c}{}^{-\eta}}. \tag{3.7}$$

However, this is only possible if the bioenergy sector has no production constraints. Since such constraints exist, three situations for a sector's crops demand in each period can be distinguished. In the first one, the sector does not demand any crop if the expected crop price $p_{(t)c}$ is higher than the expected energy price $p_{(t)e}$. Second, if the crop price equals the energy price and the current production capacity $q_{(t)b}^{\max}$ is not reached, the amount of crops demanded by the bioenergy sector is the difference of the total crop supply and the crop demanded for food. And finally, if the crop price is lower than the energy price, the bioenergy sector can adjust its production up to the production capacity. The amount of bioenergy produced in a given period $q_{(t)b}$ subsequently equals the amount of crops demanded by the sector $Q_{(t)b}^{D}$, measured in terms of the crop's energetic value[36]:

$$q_{(t)b} = Q_{(t)b}^{D} = \begin{cases} MIN\left[Q_{(t)c}^{S} - \frac{\varphi_{(t)}}{p_{(t)c}{}^{-\eta}}\ ,\ q_{(t)b}^{max}\right], if \quad p_{(t)e} \geq p_{(t)c} \\ 0 \qquad otherwise. \end{cases} \tag{3.8}$$

The bioenergy production is thus determined by its maximum capacity and the available amount of crops. As equation (3.8) shows, bioenergy is only produced if the expected contribution margin – namely, the difference between the expected energy and crop prices – is not negative.

Since bioenergy production competes for crops with food production, crop price is determined by crop demand on the food and bioenergy markets and the energy price development:

$$p_{(t)c} = \begin{cases} \left(\frac{\varphi_{(t)}}{Q_{(t)c}^{S}}\right)^{-\frac{1}{\eta}}, if\ p_{(t)e} < p_{(t)c} \\ MIN\left[\left(\frac{\varphi_{(t)}}{Q_{(t)c}^{S} - q_{(t)b}^{max}}\right)^{-\frac{1}{\eta}};\ p_{(t)e}\right]\ otherwise. \end{cases} \tag{3.9}$$

In equation (3.9), energy price $p_{(t)e}$ is the shadow price of the energetic use of crop. It indicates the maximum price that an investor would be willing to pay to extend the current limited production capacity by one unit. Since an instantaneous capacity increase is not possible for a time-lagged investment, the

[36] For conversion of units, see Tables A3.1 and A3.2 in Appendix.

bioenergy sector can influence the crop price by running production up to its limits. Consequently, the crop price in a given period is defined as the minimum of its shadow price and the crop price at which bioenergy production is run at its current capacity. Equation (3.9) also indicates that after the production capacity has been determined, the crop price will only depend on the behavior of the stochastic demand parameter $\varphi_{(t)}$ and the energy price $p_{(t)e}$.

3.3.5 Investment decision

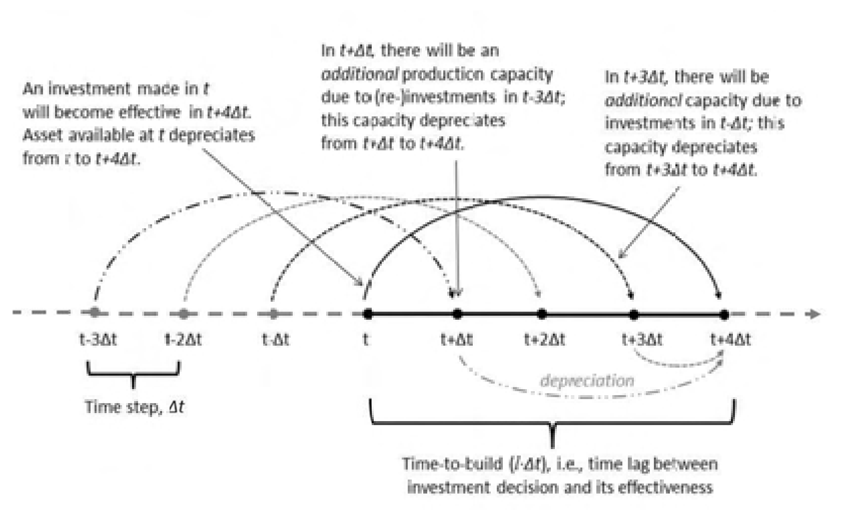
Bioenergy plants are assumed to depreciate geometrically at the rate λ, whereby for each period their productivity declines to $(1-\lambda)^{\Delta t}$ of the previous period's production capacity. To maintain or increase the production level, investments and reinvestments are necessary. If the sector does not invest or reinvest, the asset's productivity declines over time and the total output of the bioenergy sector also declines, resulting in a limited lifetime of the investment project. The term $(1-\lambda)^{\Delta t}$ can, thus, be seen as survival probability of the bioenergy sector. Due to the depreciation, the sector's production capacity at a given time point is determined by the sum of the remaining asset productivity and investments made in the previous period. Under explicit consideration of the time-to-build, the production capacity available in *t* is calculated as following:

$$q_{(t)b}^{max} = q_{(t-\Delta t\cdot l)b}^{max} \cdot (1-\lambda)^{\Delta t\cdot l} + \frac{Inv_{(t-\Delta t\cdot l)}}{inv} \tag{3.10}$$

where inv denotes the unit investment cost.

For *Δt*=1 and *l*=1, this calculation of the available production capacity is straightforward. However, with increasing time-to-build, namely if *l* >*Δt*, the capacity available at a certain time point will also be determined by the previous investments, which become effective during the delay of the current investment. Figure 3.1 illustrates the dynamic structure of asset's productive capacity for a time-lagged irreversible investment triggered in *t* and effective in *t* + *l·Δt* for *l*=4 and *Δt*=1. Since the sector has the possibility to invest in an asset or its fraction in every time period *Δt*, the total assets capacity at *t+4Δt* will be the sum of the initial capacity at *t*, $q_{(t)b}^{max}$, and all additional capacities gained due to investments in each time step and respectively adjusted for their depreciation. For instance, in the time period *t+Δt,* the investment made in *t-3Δt* becomes effective. The net capacity increase due to this investment will be adjusted for depreciation during the time from *t+Δt* to *t+4Δt*. Vice versa, investments that can be triggered in *t+Δt, t+2Δt, t+3Δt* and *t+4Δt* are irrelevant for calculation of the total asset capacity at *t+4Δt*, because due to time-to-build they will become effective not before *t+5Δt, t+6Δt, t+7Δt* and *t+8Δt* respectively.

Figure 3.1: Production capacity change in time-lagged investments for *l*=4 and *Δt*=1



In a general form, the total asset's capacity available in *t+ l·Δt,* $q^{max}_{(t+l\cdot\Delta t)b}$, will be the sum of the depreciated asset in *t* and the depreciated values of the additional assets, which will become effective in *t+Δt, t+2Δt …, t+(l-1)·Δt* due to investments undertaken correspondingly in *t-(l-1)·Δt, t-(l-2)·Δt,…t-Δt:*

$$q^{max}_{(t+l\cdot\Delta t)b} = q^{max}_{(t)b} \cdot (1-\lambda)^{l\cdot\Delta t} + \frac{Inv_{(t-(l-1)\cdot\Delta t)}}{inv} \cdot (1-\lambda)^{(l-1)\cdot\Delta t} + \frac{Inv_{(t-(l-2)\cdot\Delta t)}}{inv} \cdot (1-\lambda)^{(l-2)\cdot\Delta t} + \dots + \frac{Inv_{(t-\Delta t)}}{inv} \cdot (1-\lambda)^{\Delta t} = q^{max}_{(t)b} \cdot (1-\lambda)^{l\cdot\Delta t} + \sum_{i=1}^{l-1} \frac{Inv_{(t-(l-i)\cdot\Delta t)}}{inv} \cdot (1-\lambda)^{(l-i)\cdot\Delta t}, \quad (3.11)$$

with index variable i = 1, …, l-1.

In equation (3.11), the term $\frac{Inv_{(t-(l-1)\cdot\Delta t)}}{inv}$ represents the additional asset capacity, which becomes effective in *t+Δt* due to investments in *t-(l-1)·Δt*, $\frac{Inv_{(t-(l-2)\cdot\Delta t)}}{inv}$ the additional asset capacity, which becomes effective in *t+2Δt* due to investments in *t-(l-2)·Δt,…* and $\frac{Inv_{(t-\Delta t)}}{inv}$ the additional asset capacity, which becomes effective in *t+(l-1)·Δt* due to investments in *t-Δt*.

As investment outlays are assumed to be totally irreversible, any downward adjustments in the production capacity (disinvestments) are not possible.

Consequently, investments $Inv_{(t)}$ are only made if the expected energy price is higher than the expected equilibrium investment trigger p^*:

$$Inv_{(t)} = \begin{cases} MAX\left[0;\ (Q^S_{(t)c} - \frac{\varphi_{(t)}}{(p_{(t)e} - p^*)^{-\eta}} - q^{max}_{(t)b} \cdot (1-\lambda)^{\Delta t}) \cdot inv\right],\ if\ p_{(t)e} > p^* \\ 0,\ otherwise. \end{cases} \tag{3.12}$$

where the term $\frac{\varphi_{(t)}}{(p_{(t)e} - p^*)^{-\eta}}$ denotes the expected crop demand by the food sector.

As mentioned at the outset of the model, the bioenergy sector is considered as an aggregate comprising many competing producers. In a perfectly competitive environment, market entry by new firms prevents the revenues of active producers from exceeding a certain level. Due to high sunk costs, these producers may be willing to accept operative losses and maintain their production until at least a part of fixed cost is covered. On the *aggregated* level, to prevent losses in a long run, the sector will choose an equilibrium investment trigger at which the expected cash flows cover all production costs. Triggers below the equilibrium threshold price would provide inferior solutions and triggers above – given they allow exercising the investment option – may entail temporary profits, although they would not fulfil the essential equilibrium condition for competitive markets, namely the zero-profit rule. Therefore, when choosing an equilibrium investment trigger *p**, the bioenergy sector aims to meet the zero-profit condition[37] in terms of the expected NPV of the cash flows at the end of the investment's lifetime.[38] Formally, the sector's goal can be defined as follows:

$$E\left[NPV_{(p^*)}\right] = E\left[\sum_{t=0}^{T} CF_{(t)}(1+r)^{-t} + RV_T\right] \equiv 0 \tag{3.13}$$

with

$$RV_T = q_T^{max} \cdot (1+r)^{-T} \tag{3.14}$$

[37] This condition requires that the obtained net present values of expected profits of the bioenergy sector are zero or sufficiently close to zero. Table A3.1 in Appendix summarizes the NPV of expected profits gained for the base scenario with five different lengths of the time-to-build. The obtained values are not exactly zero but sufficiently small. The increase in both the positive and negative net present values – which can be stated especially for the increased volatility on the output market – indicates the technical difficulty in numerically approximating the zero profit condition in the presence of high uncertainty and the asymmetric effect of suspension on the input and output markets. Regarding the assumed infinite time horizon (approximated by *T*=200 years), the resulting profits and losses are nevertheless still sufficiently low.

[38] As shown by DIXIT and PINDYCK (1994), when assuming an infinite lifetime of options, an investment trigger for irreversible projects under competition is the same as for exclusive options.

where RV_T denotes the residual value of production that arises if production capacity at (T) is higher than zero, r the interest rate and $CF_{(t)}$ the cash flow in a given period (t).

The cash flow $CF_{(t)}$ is the difference of the total contribution margin in a given period $CM_{(t)}$ and the investment amount made in the same period:

$$CF_{(t)} = CM_{(t)} - Inv_{(t)}. \tag{3.15}$$

Taking into account equations (3.12) and (3.15), equation (3.13) shows that the expected NPV of investment project depends on the equilibrium investment trigger.

3.3.6 Initialization of the model

The model is solved by utilizing stochastic simulation experiments in combination with a genetic algorithm technique.[39] The calculations are based upon an interest rate *r = 6 %* and a depreciation rate *λ = 5 %*. The interest rate is approximated based upon the data for average returns of stocks listed on the New York Stock Exchange since 1926 (6.4 %) (cf. SIEGEL, 1992, p. 28) and average returns of log-term bonds traded on the German Federal Stock Exchange since 1961 (6.2 %) (cf. DEUTSCHE BUNDESBANK, 2012; DAI-FACTBOOK, 2011). The depreciation rate was calculated using the data on average depreciation times for agricultural assets in Germany (BSTBL, 1996, I, p. 1416). The demand elasticity η is *-0.7*, implying a relatively elastic demand response to price changes. This value is based upon the studies estimating the price elasticity of food demand – particularly for cereals – in the USA (ANDREYEVA et al., 2010) and the European Union (TIFFIN et al., 2011). The initial energy price, $p_{e(t=0)}$, is assumed to exceed the initial crop price, $p_{c(t=0)}$, by an amount equal to the annualized fixed cost of investment, enabling the sector to make investments in the earlier periods. Table 3.2 provides an overview of the model parameter values.

Table 3.2: Overview of baseline parameter values

Global energy market	Bioenergy market	Food market
$p_{e\,(t=0)} = p_{c(t=0)} + fc$	r=6%, λ=5%	Q_c^S =100 billion kWh
$\sigma_{(e)}$={0%, 5%, 10%, 15%, 20%, 25%, 30%}	l=1, Δt=1 year	η=-0.7, μ_φ=0
μ_e=0	T=200 years	$\sigma(\varphi)$= {0%, 5%, 10%, 15%, 20%}
α=0.5	*No suspension, maintenance, or reactivation costs*	Δt=1 year, $VC/FC_{(t=0)}$=2

[39] The source code for stochastic simulation experiments is provided in Appendix, Table A3.3.

Investors are assumed to optimize their decisions over the period of T =200, which is an approximation of an infinite time horizon. Using discrete steps of 5 %, we consider the volatilities up to 30 % on the output market, σ€ and up to 20 % on the input market, σ(φ). These volatility ranges cover the real data for the world crude oil price volatility (ca. 20-25 %) and crop price volatility (13-15 %). These volatility values are estimated based upon the U.S. Energy Information Administration (EIA, 2010) data for crude oil prices for 1990-2010 and the DESTATIS (2013) data for crop and wheat prices for 1990-2010. The estimated volatilities correspond to the values for farm products and different energy sources calculated by REGNIER (2007). The total amount of crop supply is stipulated to be exogenous and limited to 100 billion kWh, corresponding to 22,779,043 t of crops per year. This number is very close to the total wheat yield in Germany (22,409,000 t) reported for 2012 (cf. DESTATIS, 2013).[40]

The initial food demand parameter, $\varphi_{t=0}$, is defined in relation to the total amount of crop supply and can be varied. It is calculated as follows:

$$\varphi_{t=0} = Q_c^S \cdot ((r + \lambda) \cdot m)^{-\eta}, \tag{3.16}$$

where m is a multiple by which the initial crop price exceeds the sum of the capital and depreciation costs, i.e. the ratio of variable-to-fixed costs. For the base scenario, we assume $m=2$.

The drift rate of stochastic variables is ignored (that is, μ_e and μ_φ are zero) to reduce complexity of the model and better disentangle the impact of the volatility on investment incentives. To justify this simplification, we recall that within the real options framework stochastic parameters grow at the risk-neutral discount rate.[41] As shown by DIXIT and PINDYCK (1994, p. 197), risk-neutral valuation is equivalent with the discounting at a rate adjusted for convenience yields or dividends. Provided that the underlying stochastic process is a GBM process, such adjustment in discount rate renders unnecessary an explicit consideration of the drift (cf. also MAUNG and FOSTER, 2002, p. 227; COX et al., 1985). The model is developed with the purpose of numerically showing the impact of multiple uncertainties – represented by the stochastic food demand and stochastic energy price – and of the possibility to temporarily suspend production on the investment rule of bioenergy sector. We also aim to analyze the role of time-to-build and high variable costs in a sector's investment decision. For our base scenario, we assume a time-to-build of one year. As already discussed in Section 3.1.1. (cf. Table 3.1), this issue corresponds to the lowest time-to-build value for crop-based bioenergy production as reported for the German bioenergy market. To study

[40] DESTATIS (2013), Field crops – Areas under cultivation, yields per hectare, quantities harvested.

[41] For further details on the assumption of risk-neutrality, see Chapter 2, Section 2.4.2.

the impact of the time-to-build on the optimal investment rule, we will introduce variations in its length (between 0, 1, 2, 3 and 4 time steps). The adjustment of the investment and production decision for different values of time-to-build is unproblematic and already captured by equations (3.11) and (3.12).

Under real business conditions, a temporary production suspension entails positive suspension, maintenance and reactivation costs. For the purpose of the present investigation with the focus on the role of investment specifics, these costs are set to zero. There are at least two reasons why we can and should do so. First, other than investments, suspension takes place immediately, so that suspension is not affected by the length of time-to-build. Introduction of positive suspension costs would thus not allow identifying and measuring the effect of the time-to-build, which is one of our central objectives. Second, the theoretical effect of additional cost can be interpreted as the change in the relation of variable-to-fixed costs. This cost ratio is incorporated in our analysis and observed for every parameter combination under consideration. Of course, these observations do not replace a thorough analysis of the impact of costs associated with suspension; nonetheless, ignoring of these costs appears to be a useful simplification for the sake of our investigation.

Some possible consequences of different suspension costs on the investment rule should nevertheless be briefly addressed. Positive suspension, maintenance and reactivation costs would mean an increase in the total production costs. These three kinds of costs have different shares in variable and fixed-cost components, whereby they do not influence management decisions in the same way. If the reactivation cost is higher than the maintenance cost, the reactivation threshold price will have to exceed the variable cost sufficiently to resume production. In this case, the value of flexibility will appreciate as a reaction to increasing expected output prices, for instance. When the volatility remains constant, an increase in the maintenance cost would lead to a higher fixed cost during suspension periods, thus requiring a higher price at which firms would invest. This would be in line with the standard wisdom of the real options theory, as a higher fixed cost reduces the variable-to-fixed cost ratio, whereby the loss-reducing effect of temporary suspension would be weakened. As a result, the amplifying effect of the time-to-build length will not be unfolded and the difference between the investment triggers for different values of time-to-build would be smaller. These are just two of many possible implications concerning the investment decision if suspension costs are taken into account. Their consequences should not be downplayed, but rather they should motivate further research.

3.4 THE METHODOLOGY

This section explains the choice of the real options-based simulations as the underlying methodology for solving our investment model. Since the ROA was exhaustively introduced in Chapter 2, this section focusses on how this approach is combined with the approximation technique of genetic algorithms into a procedure of simulation experiments.

3.4.1 Real options-based stochastic simulations

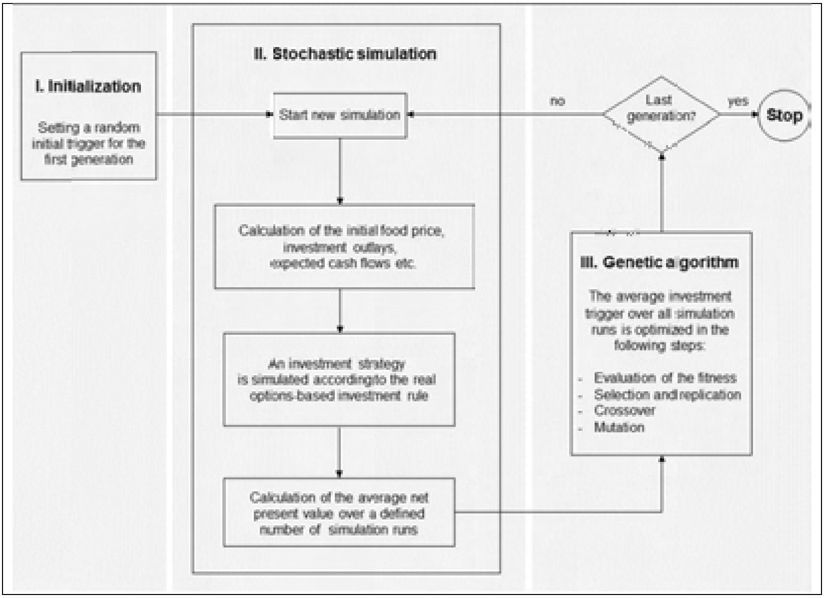
The issue of uncertainty in agricultural investments has been approached differently in the economic literature, using a variety of methodological tools such as a game theoretical approach (TADROS and CASLER, 1969; MCINERNEY, 1967), dynamic programing (TAYLOR, 1993; DUFFY and TAYLOR, 1994; MOSCHINI and HENNESSY, 2001) or stochastic simulations (ODENING et al., 2007; MUßHOFF and HIRSCHAUER, 2008; FEIL et al., 2013). The choice of an appropriate methodology for our model was guided by two aspects, the first being. The first one is the fact that crop-based bioenergy investments are characterized by uncertain returns and high sunk costs. Investments outlays of such projects cannot be fully recovered in the case of plant's sale, so that bioenergy investment decisions are largely irreversible. However, the uncertainty of irreversible investments can be reduced to some degree by the operational flexibility of firms (e.g. by delaying the investment due to the waiting for new information), which may limit the downside risk of losses and concurrently capture the upside potential associated with different choices. Of course, it is not always possible to delay investment or reinvestments, especially in a highly competitive environment, but in most cases investors can postpone the implementation of their decisions. Even if delays involve costs, the benefits from reducing uncertainty by waiting for additional information may outbalance the costs (cf. DIXIT and PINDYCK, 1994, p. 9).

Uncertainty, irreversibility and managerial flexibility – which characterize bioenergy and many other agricultural investments – are also preconditions for the application of the new investment theory to assess uncertain projects. As stated earlier in Section 3.1.2, the examination of these characteristics – uncertainty and different degrees of managerial flexibility (along with specific features of irreversible agricultural projects) – and their effect on investment incentives constitutes our particular research interest. The ROA thus offers an appropriate methodological framework for the aim of our analysis.

The second aspect in choosing an appropriate methodology is the dynamic nature of the investment model. Both time-to-build and the possibility of temporary production suspension bring about – similarly to the financial option of the American type – the notion that the expected option value in the next period affects the calculation of the expected project value. Solving such dynamic time interdependent investment decisions analytically is not possible. A further complexity in our model is added by the assumption of two stochastic processses – one on the input and one on the output market – which simultaneously influence investment decisions of the bioenergy sector. An analytical solution of their overlapping and interdependent impact is impracticable (cf. MUßHOFF and HIRSCHAUER, 2004). For this reason, we resort to stochastic simulations in combination with a genetic algorithm as an approximation technique to *numerically* identify the equilibrium investment trigger of the bioenergy sector. In the context of agricultural investments, the combination of numerical simulation experiments with genetic algorithms in the real options-based framework has already been applied by, e.g. BALMANN and HAPPE (2001), BALMANN and MUßHOFF (2002), ODENING et al. (2007) and FEIL et al. (2013).

The descriptive flow chart provided by Figure 3.2 shows how these three methodological tools are combined into a numerical approach for our model.[42]

Figure 3.2: Descriptive flow chart of the applied methodology



[42] A detailed flow chart of simulation experiments is provided by Figure A3.1 in the Appendix.

The simulation experiments are initialized by assigning a random initial investment trigger to the first investment strategy (which is referred to as the first *generation*). In the next step, a predefined number of alternative investment strategies are simulated over the total time period (see Section 3.4.2). In the third step, the average investment trigger over all simulation runs is optimized by the genetic algorithm technique in search for a solution that best fulfills the equilibrium condition (cf. equation (3.12)). The fittest trigger is subsequently fed into the simulation model and the simulations are repeated until the number of generations is completed.

As noted earlier, our investment model meets the necessary precondition for the application of the ROA, namely the simultaneous presence of uncertainty in returns, irreversibility (at least partially) of investment outlays and flexibility in investment timing. In our model, we even extend the scope of managerial flexibility as we not only consider the possibility to delay an initial investment, but also the possibility to suspend production after the initial investment has been made. However, this additional flexibility opposed by multiple uncertainties on the input and output side and a time-to-build in investment proceeds.

3.4.2 Genetic algorithms

The investment triggers calculated in the real options-based stochastic simulation are optimized in repeated iterations using the genetic algorithms technique (GA) as an approximation tool. A genetic algorithm is a heuristic optimization and search technique developed in analogy to the natural evolution processes such as selection, inheritance, mutation and recombination (cf. GOLDBERG, 1989). It was invented in the 1960s by John Holland, who provided formal theoretical rules for its application in different fields[43]. The principle of the problem solving with a GA is described as the global searching through a vast number of possible parameter combinations for best solutions fulfilling a certain optimality criterion[44] (cf. MITCHELL, 1998, p. 4; SCHMITT, 2001, p. 4; VOSE, 1999, p. 21). Expressed in GA terminology, this is a massively parallel search among numerous sets of possible genetic sequences (i.e. bit strings representing candidate solutions to a problem) for highly fit organisms able to survive and reproduce in a given environment (cf. HOLLAND, 1992, p. 9). Unlike other meta-heuristic techniques (e.g. tabu search or sequential quadratic programing), the search within the possible solutions is guided towards a steady improvement by the biological principle of a survival of the fittest (DOWSLAND, 1996, p. 550).

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[43] Numerous examples are given in MITCHELL (1998), p. 15-17.

[44] This can be expressed in terms of a satisfactory fitness level (defined e.g. in the profit function of an equilibrium condition) or simply as reaching the maximum number of generations.

There is a growing interest in the agricultural literature (e.g. PARMAR et al., 1996; KUOA et al., 2000; ODENING et al., 2007; GRAUBNER et al., 2012; FEIL et al., 2013) in using the GA as a discrete method or a part of the methodology. Indeed, the concept of genetic algorithm bears a number of advantages; for instance, it is easy to understand and can be used as modular flexible building blocks for hybrid applications, it supports optimization problems with many objectives or scenarios with large – up to infinitive – sets of possible solutions and allows for exploring alternative solutions. In models aiming at predicting behavior influenced simultaneously by many factors and those assuming stochastic processes or other changing conditions – as in our case – these advantages are particularly serviceable.

Of course, there are also potential applications where this method may not perform robustly. For instance, this is the case if the number of candidate solutions (i.e. the search space) is relatively small, whereby the algorithm can search too exhaustively, converging on a local rather than on a global optimum (cf. MITCHELL, 1998, p. 156). On the other hand, if the fitness function leads to a range of extreme realizations[45], a GA will not be misdirected by such noise, as they improve the fitness of possible solutions over many generations. The choice of an appropriate heuristic procedure for a given problem is thus conditioned by many factors such as encoding complexity, the size of the search space and the properties of the fitness landscape.

In this study, we apply this technique to search for a single value, namely the equilibrium investment trigger of the bioenergy sector. For this aim, each possible investment strategy is specified as a string of genes on one or more genotypes (or genomes). In our model, every genome is represented by one value, namely the investment's trigger. We set the maximum population of genomes $G=10$, which are directly independent. Every genome can be interpreted as the variation of investment strategy of the sector. This means that the investment trigger of a single strategy is represented by one genome within the genome population. The number of iterations can vary depending on the problem at hand: for our analysis, 5,000 iterations are applied.

The initial population of triggers is generated randomly, covering the range of possible solutions. To bring new genetic varieties into the genomes population, genetic operators such as *selection* and *replication*, *crossover*[46] and *mutation* are applied in this fixed sequence. This procedure is designed to gradually adjust the obtained solutions to the model's requirements (e.g. market equilibrium). Before

[45] The range of all possible genotypes and their fitness is also referred to as the *adaptive landscape* (cf. WRIGHT, 1931) or *fitness landscape* (cf. MITCHELL, 1998; GAVRILETS, 2004).

[46] In the literature on genetic algorithms, *crossover* is also referred to as *recombination* (cf., e.g., HOLLAND, 1992, p. 4; MITCHELL, 1998, p. 3).

the operators are applied to each successive generation of genomes, the *fitness* of every genome – i.e. the capability of the genome to solve the given problem – is tested. In our application, the fitness value is derived from the average expected NPV of every strategy, stochastically simulated in 5,000 runs. The closer the average NPV is to zero, the fitter is the corresponding genome. The fittest solutions, as valuated by the fitness function, determine a selection of genetic material to be reproduced in the following generation. The rate of survival for *selection* and *replication* operator is defined here to be five of the better adapted genomes, while the next three genomes are replaced with a defined probability by the same amount of the fittest genomes from the last simulation series. The least two successful genomes are replaced by the two most fit genomes.

New genetic varieties are further obtained by the crossover of parts of coded strings between two genomes. Every pair of genomes is chosen randomly with a certain probability and split at a random (yet the same for both genomes) digit. The split sub-strings are then exchanged, which leads to a new pair of genomes. To avoid a permanent fixation of a population on an inferior genotype and hence prevent the loss of genetic information (i.e. combinations of coded strings) that was sorted out in previous generations, a further operator – mutation – is used. In mutation, each solution from previous operators is multiplied with a predefined small likelihood of a random number, enabling new variations in string pattern. The generation of new genomes in the preset sequence is repeated until the fixed number of iterations has been reached.

3.5 SIMULATION RESULTS AND MAIN FINDINGS

The results obtained in the real options-based stochastic simulations support our hypothesis that the net effect of uncertainty on investment incentives can be decisively affected by investment specifics. The results demonstrate that the positive relationship between the price volatility and the investment threshold price – as known from the standard real options theory and financial markets – does not necessarily hold for investments characterized by the possibility to flexibly adjust production scale, gestation period and relatively high variable costs. This is true in the presence of both single and multiple volatilities and is especially pronounced at high volatility ends.

3.5.1 The effect of two uncertainties

Table 3.3 summarizes the investment threshold prices obtained for varying volatility values on the energy and food markets for three different values of the correlation between the both stochastic processes. The results were gained for the realistic values of the average ratio of annual variable-to-fixed costs (*VC/FC*=2) and the time-to-build of one year (cf. Table 3.1). For notational convenience, time-to-build is denoted here and below by *TL* rather than the term $\Delta t \cdot l$ introduced in Section 3.3.1. For a better comparability of our results with the findings of studies summarized in Table 2.3 (Chapter 2), the absolute threshold price *p** – as introduced in equation (3.12) – is normalized to the periodic investment cost and denoted by *p′* in the following. The presented threshold price values thus reflect the corresponding *option multiple* (or *investment cost multiple*), showing by what factor the ROA-based threshold price exceeds the NPV-based one. In the following, we only refer to the normalized threshold price value.

Table 3.3: Investment threshold prices under variation of stochastic food demand and energy price and the correlation of both stochastic processes

[a] *α*=0

Energy price volatility, $\sigma_{(e)}$	Volatility of food demand parameter, $\sigma_{(\varphi)}$ 0%	5%	10%	15%	20%
0%	1.00	1.11	1.19	1.20	1.21
5%	1.15	1.19	1.23	1.23	1.22
10%	1.30	1.32	1.30	1.26	1.22
15%	1.41	1.42	1.33	1.27	1.19
20%	1.40	1.37	1.31	1.22	1.09
25%	1.27	1.29	1.20	1.07	1.00
30%	1.06	1.01	0.99	0.98	0.94

[b] *α*=0.5

	0%	5%	10%	15%	20%
0%	1.00	1.11	1.18	1.21	1.22
5%	1.15	1.16	1.20	1.21	1.21
10%	1.31	1.29	1.26	1.23	1.20
15%	1.40	1.41	1.35	1.28	1.19
20%	1.41	1.43	1.37	1.26	1.13
25%	1.29	1.31	1.29	1.18	1.06
30%	1.08	1.01	1.01	1.00	0.97

[c] *α*=1

	0%	5%	10%	15%	20%
0%	1.00	1.11	1.19	1.21	1.21
5%	1.16	1.20	1.22	1.23	1.20
10%	1.31	1.29	1.31	1.26	1.18
15%	1.43	1.42	1.36	1.31	1.16
20%	1.41	1.39	1.34	1.26	1.10
25%	1.27	1.26	1.25	1.15	1.05
30%	1.06	1.01	1.00	1.02	0.94

Table 3.3 shows that for relatively small volatility values (up to 10 %), the generally positive impact of increasing volatility on investment threshold price holds. In all other cases, the equilibrium investment threshold declines, reaching values below the periodic investment cost, i.e. values below one, at very high volatilities ($\sigma_{(e)}$=30 %). This result supports our hypothesis posed at the outset of the study that the ability to downsize losses by temporary production suspension may under certain conditions compensate the generally depressing effect of uncertainty, creating incentives to invest even at very high uncertainty levels. The temporary pausing of production in periods when the output price is too low or the variable costs are too high limits the firms' losses to the periodic fixed cost. Since the losses can be flexibly economized, high output price volatilities induce a chance for very high contribution margins and profits able to cover all investment costs in only a few periods. At very high volatilities, the threshold price of an investment may thus decline even below the investment cost. This effect can be stated in the presence of uncertainty on only one as well as both markets, while it is amplified by the presence of the second uncertainty source.

The comparison of the results for different degrees of the correlation of both stochastic processes reveals no significant difference. Obviously, the effect of stochasticity differences is neutralized by the food and energy price responses to uncertainty in place (see further). This outcome allows us to focus our analysis on the effects of other parameters. For further simulations, we thus primarily utilized the correlation parameter a=0.5.

3.5.2 The effect of time-to-build

Table 3.4 summarizes investment threshold prices for five different lengths of time-to-build, showing that the described effect of the possibility to suspend production can only be observed in the presence of the time-to-build.[47] If investments are realized immediately (Table 3.4[a]) – namely, if there is no delay between the time of investment and the time of cash flows realized from it – the generally negative impact of uncertainty on investment incentives holds true.[48]

[47] Because our model setting does not allow for a direct implementation of the case of no suspension, the simulation results for TL=0 and $\sigma_{(\varphi)}$=0% serve here as approximation of the scenario without the option to suspend (cf. also Table A3.6(a) in Appendix). In this case, the standard negative impact of uncertainty on investment incentives is not affected by the initial cost ratio.

[48] Note that investment multiples shown in Table 3.5[a] were calculated assuming a=0 to exclude the influence of the correlation of both stochastic processes. The results for a=0.5 are shown in Table A3.6[b] in the Appendix. As show in Table A3.6[b], the generally negative impact of uncertainty on investment incentives holds if the input market uncertainty is lower than 15 %. At higher values of uncertainty in food demand parameters, investment incentives may increase, reflecting the effect of volatility transmission.

The introduction of a time-to-build (*TL*>0) changes this correlation distinctly. Tables 3.4[b-c] show that the threshold (or trigger) price of investment may already decline for a relatively short duration of time-to-build (*TL*=1) if the volatilities on both markets are high. With a further increase in the values of time-to-build, the negative trigger response becomes more pronounced. For *TL*>1 (Table 3.4[d]-[f]), the investment threshold price clearly declines below one at high volatilities.

Table 3.4: Investment threshold prices for varying values of food demand and energy price volatilities, time-to-build and correlations of both stochastic processes

[a] *TL*=0, *a*=0

	Volatility of food demand parameter, $\sigma_{(\varphi)}$				
Energy price volatility, $\sigma_{(e)}$	0%	5%	10%	15%	20%
0%	1.00	1.08	1.14	1.19	1.22
5%	1.07	1.11	1.17	1.20	1.24
10%	1.12	1.16	1.20	1.24	1.30
15%	1.18	1.20	1.24	1.28	1.31
20%	1.21	1.25	1.27	1.33	1.36
25%	1.26	1.27	1.32	1.35	1.39
30%	1.30	1.33	1.36	1.38	1.42

[b] *TL*=1, *a*=0 (cf. Table 3.4[a])

[c] *TL*=1, *a*=0.5 (cf. Table 3.4[b])

[d] *TL*=2, *a*=0.5

	0%	5%	10%	15%	20%
0%	1.00	1.11	1.17	1.18	1.17
5%	1.15	1.15	1.19	1.18	1.16
10%	1.28	1.27	1.23	1.20	1.14
15%	1.32	1.33	1.26	1.17	1.08
20%	1.20	1.24	1.17	1.07	1.00
25%	0.88	0.97	0.97	0.88	0.85
30%	0.71	0.76	0.76	0.74	0.61

[e] *TL*=3, *a*=0.5

	0%	5%	10%	15%	20%
0%	1.00	1.10	1.15	1.16	1.14
5%	1.14	1.15	1.17	1.16	1.12
10%	1.26	1.24	1.21	1.14	1.07
15%	1.26	1.25	1.19	1.08	1.01
20%	1.09	1.08	1.02	0.93	0.84
25%	0.84	0.82	0.79	0.75	0.67
30%	0.65	0.61	0.60	0.56	0.53

[f] *TL*=4, *a*=0.5

	0%	5%	10%	15%	20%
0%	1.00	1.10	1.14	1.15	1.10
5%	1.13	1.15	1.15	1.14	1.10
10%	1.24	1.22	1.18	1.11	1.00
15%	1.18	1.19	1.14	1.02	0.94
20%	0.98	0.96	0.94	0.87	0.78
25%	0.79	0.74	0.67	0.65	0.61
30%	0.65	0.62	0.56	0.52	0.46

Figure 3.3 graphically depicts this effect, showing that in the presence of high uncertainty on the energy market ($\sigma_{(e)} \geq 20$ %), a relatively short time-to-build of one period may already induce at a non-monotonic relationship between the investment trigger and uncertainty level, similar to an inverse U-shape curve.

Figure 3.3: Investment thresholds under variation of stochastic food demand and energy price for *a*=0 and *a*=0.5 and varying lengths of time-to-build

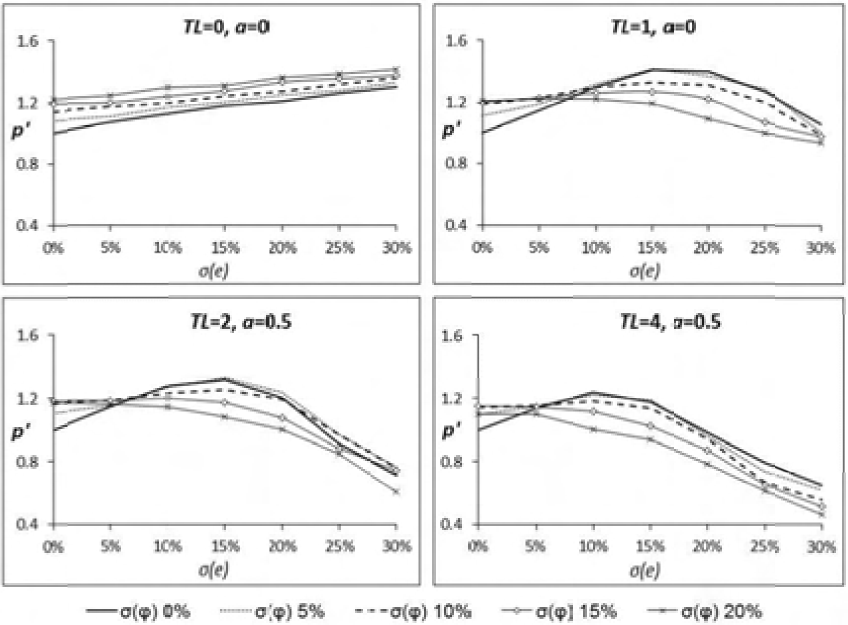


Figure 3.3 also illustrates that the higher the value of the time-to-build, the lower the energy price volatility at which the positive effect of uncertainty on the optimal investment threshold can be neutralized or overcompensated. Moreover, the presence of a further uncertainty source ($\sigma_{(\varphi)}$>0 %) additionally intensifies the positive uncertainty-investment relationship.

As discussed in the previous sections, DIXIT and PINDYCK (1994) do not explicitly deal with the effect of time-to-build on investment decisions. Nonetheless, their standard model allows the intuition that a faster realization of returns (that is a shorter time-to-build) would reduce the likelihood of extreme prices in the presence of high volatility. Lower expected price spikes mean a lower expected product price or marginal return, which makes a higher trigger price necessary to cover all investment outlays. Vice versa, a longer time-to-build should lead to a lower investment trigger. Our results clearly support this intuition. As seen from Figure 3.3, the negative correlation between the investment threshold price and uncertainty is the stronger the longer the time-to-build.

3.5.3 The effect of high variable costs

Nonetheless, it would be wrong to jump to the conclusion that the managerial flexibility and the presence of time-to-build alone are responsible for the positive uncertainty-trigger relationship. In the presented results for the base scenario, the initial ratio of variable-to-fixed cost is assumed to be $VC/FC_{(t=0)}$=2. Despite being typical for crop-based bioenergy projects (cp. Table 3.1), this cost ratio is relatively high. To analyze its impact on the investment decisions under uncertainty, we have carried out a set of simulation experiments for four further values of this cost ratio.

The comparison of the results provided in Table 3.5 allows some important conclusions. First, it shows that the introduction of a higher initial cost ratio strengthens the positive effect of the time-to-build on investment incentives at high volatility values, just as observed in the base scenario. For the relatively low volatility values (up to 10 %), an introduction of higher initial cost ratio leads rather to a stronger positive effect of uncertainty increase on the investment threshold price. With an increase of the initial cost ratio, this positive effect still holds, although it becomes weaker within the same volatility range. By contrast, at high uncertainty ends, the threshold price clearly responds negatively to increases in both the time lag and the cost ratio, even falling below the investment cost and hence the NPV-based trigger.

For a high cost ratio, $VC/FC_{(t=0)}$=8, the positive correlation between uncertainty and investment trigger could only be stated for very small volatilities on the energy market ($\sigma_{(e)} \leq 5$ %) and the time-to-build of one period. However, if the initial ratio of the variable-to-fixed cost is sufficiently small (e.g. $VC/FC_{(t=0)}$=0.5) – whereby the annualized fixed cost exceeds the variable cost – the threshold price responds steadily and positively to increases in the output price volatility, and up to the value $\sigma_{(e)} < 10$ % also to the increase in the volatility on the input market.

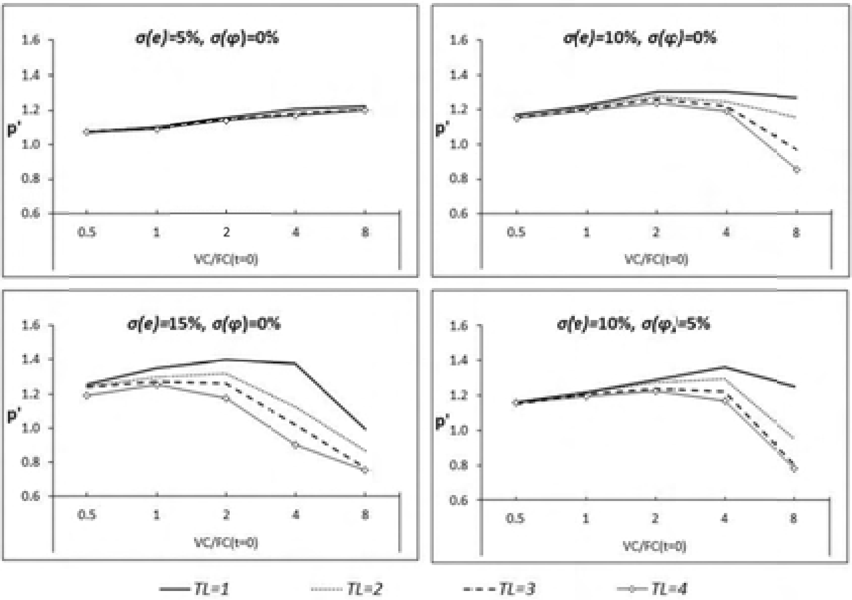
Table 3.5: Investment threshold prices for varying values of initial variable-to-fixed cost ratio and volatilities (*TL*=1, *α*=0.5)

Energy price volatility, $\sigma_{(e)}$	Initial ratio of variable-to-fixed costs, $VC/FC_{(t=0)}$	Volatility of food demand parameter, $\sigma_{(\varphi)}$				
		0%	5%	10%	15%	20%
0%	0.5	1.00	1.03	1.05	1.07	1.08
	1	1.00	1.06	1.10	1.13	1.15
	2	1.00	1.11	1.18	1.21	1.22
	4	1.00	1.20	1.26	1.26	1.18
	8	1.00	1.17	1.23	0.99	0.73
5%	0.5	1.07	1.07	1.08	1.09	1.10
	1	1.10	1.11	1.13	1.14	1.15
	2	1.15	1.16	1.20	1.21	1.20
	4	1.21	1.25	1.27	1.26	1.16
	8	1.19	1.27	1.21	0.97	0.67
10%	0.5	1.17	1.16	1.16	1.16	1.15
	1	1.23	1.22	1.21	1.21	1.19
	2	1.31	1.29	1.26	1.23	1.21
	4	1.30	1.39	1.29	1.22	1.11
	8	1.27	1.25	1.05	0.84	0.65
15%	0.5	1.26	1.25	1.25	1.23	1.23
	1	1.35	1.35	1.29	1.28	1.24
	2	1.40	1.41	1.35	1.28	1.19
	4	1.37	1.31	1.28	0.16	1.01
	8	0.99	0.92	0.78	0.70	0.58
20%	0.5	1.35	1.34	1.33	1.30	1.27
	1	1.44	1.43	1.39	1.33	1.26
	2	1.41	1.43	1.37	1.26	1.13
	4	1.17	1.17	1.11	1.01	0.90
	8	0.73	0.68	0.63	0.60	0.54
25%	0.5	1.42	1.41	1.38	1.36	1.31
	1	1.45	1.43	1.37	1.33	1.32
	2	1.29	1.31	1.29	1.18	1.06
	4	0.81	0.88	0.82	0.79	0.64
	8	0.70	0.65	0.59	0.54	0.49
30%	0.5	1.44	1.42	1.40	1.37	1.35
	1	1.32	1.32	1.34	1.27	1.24
	2	1.08	1.01	1.01	1.00	0.97
	4	0.63	0.67	0.63	0.50	0.49
	8	0.63	0.59	0.55	0.51	0.47

In this case, the costs that could potentially be economized on by temporary production suspension are relatively small, so that the generally negative effect of uncertainty on investment incentives cannot be neutralized or reversed, even at very high uncertainties. On the other side, for $\sigma_{(e)}\geq 10$ %, a one-sided increase in the volatility on the input market leads to a steady negative trigger response.

The simultaneous effect of the relative costs and the time-to-build is additionally visualized for selected volatility combinations in Figure 3.4.

Figure 3.4: Investment threshold price as a function of the initial variable-to-fixed cost ratio for different values of time-to-build and volatility combinations



Noticeably, the actual cost ratio of one at $\sigma_{(e)}=10$ % (Table 3.6[a]) marks the point at which the generally positive uncertainty-trigger correlation begins to weaken.[49] This observation is interesting as the standard real option theory presupposes very high fixed costs of an investment project. Although this presumption is not explicit on the relative size of the costs, the overemphasis of the role of the fixed cost implies that it is higher than the annual variable cost, whereby the ratio of variable-to-fixed costs is rather somewhat below one. For projects with a cost

[49] The endogenous values of the variable-to-fixed cost ratios are calculated for each genome as a ratio of the net present value of the bioenergy produced in each period and assessed at the period food price to the net present value of the period investment outlays. The values reported in Table 3.6 are average values of these ratios over the number of genomes.

ratio higher than one, it can thus be expected that under certain conditions the cost ratio may tip the balance in the uncertainty-investment relationship.

Table 3.6: Variable-to-fixed cost ratios for varying values of the initial cost ratio and different volatility combinations (*TL*=1, *α*=0.5)

[a] $VC/FC_{(t=0)}$=0.5

	Volatility of food demand parameter, $\sigma_{(\varphi)}$				
Energy price volatility, $\sigma_{(e)}$	0%	5%	10%	15%	20%
0%	0.5	0.5	0.5	0.5	0.5
5%	0.8	0.8	0.8	0.7	0.7
10%	*1.0*	*1.0*	*1.0*	*0.9*	*0.9*
15%	1.2	1.2	1.2	1.1	1.1
20%	1.4	1.3	1.3	1.3	1.3
25%	1.5	1.5	1.4	1.3	1.3
30%	1.6	1.5	1.5	1.5	1.4

[b] $VC/FC_{(t=0)}$=1

	0%	5%	10%	15%	20%
0%	1.0	1.0	1.0	1.0	1.0
5%	1.3	1.3	1.1	1.1	1.0
10%	1.6	1.6	1.4	1.3	1.2
15%	1.8	1.7	1.6	1.5	1.4
20%	2.1	1.9	1.8	1.7	1.6
25%	2.2	2.2	2.0	1.8	1.7
30%	2.4	2.2	2.0	1.9	1.8

[c] $VC/FC_{(t=0)}$=2

	0%	5%	10%	15%	20%
0%	2.0	2.0	1.9	1.8	1.8
5%	2.3	2.2	1.9	1.8	1.8
10%	2.6	2.5	2.2	2.0	1.9
15%	2.8	2.7	2.6	2.3	2.1
20%	3.0	2.8	2.7	2.6	2.3
25%	3.1	2.9	2.8	2.7	2.7
30%	3.3	3.4	3.0	2.9	2.8

[d] $VC/FC_{(t=0)}=4$

	0%	5%	10%	15%	20%
0%	4.0	3.7	3.5	3.4	3.3
5%	4.2	3.7	3.5	3.4	3.3
10%	4.4	4.1	3.8	3.7	3.5
15%	4.4	4.4	4.2	3.8	3.7
20%	4.6	4.4	4.1	4.5	3.9
25%	4.4	4.5	4.1	4.3	4.2
30%	4.5	4.1	4.1	4.0	4.0

[e] $VC/FC_{(t=0)}=8$

	0%	5%	10%	15%	20%
0%	8.0	7.3	6.9	6.7	6.6
5%	7.4	7.6	7.1	6.9	6.8
10%	7.3	7.6	7.5	7.0	7.1
15%	7.2	7.2	7.5	7.4	7.2
20%	7.2	7.6	7.4	7.9	7.4
25%	7.5	7.8	8.0	8.0	7.2
30%	7.9	8.4	8.3	7.8	7.6

Table 3.6 further shows that for different initial cost ratios, a volatility increase on the energy market induces an increase in the cost ratios, while they respond negatively to an increase in volatility on the food market. This negative response has two reasons: the calculation technique of the cost ratio and the asymmetry of the production suspension effect on the involved markets. In the periods of production suspension, the variable cost does not accrue so that the ratio of the variable-to-fixed cost is zero.[50] A frequent pausing of production may thus reduce the calculated cost ratio.

Other than on the input side, the expected upward price movements on the output side do not lead to production suspension: by contrast, they boost investment and production activities, leading to higher demand for inputs and thus higher variable costs of production. This effect is simultaneously translated into higher food prices. In turn, in the case of low output prices, production may be suspended, whereby the influence of the bioenergy market on the price on the factor market would be less pronounced.[51] Consequently, in the presence

[50] As mentioned earlier (section 3.3.6), the maintenance cost – which would accrue in the case of production suspension – is assumed to be zero.

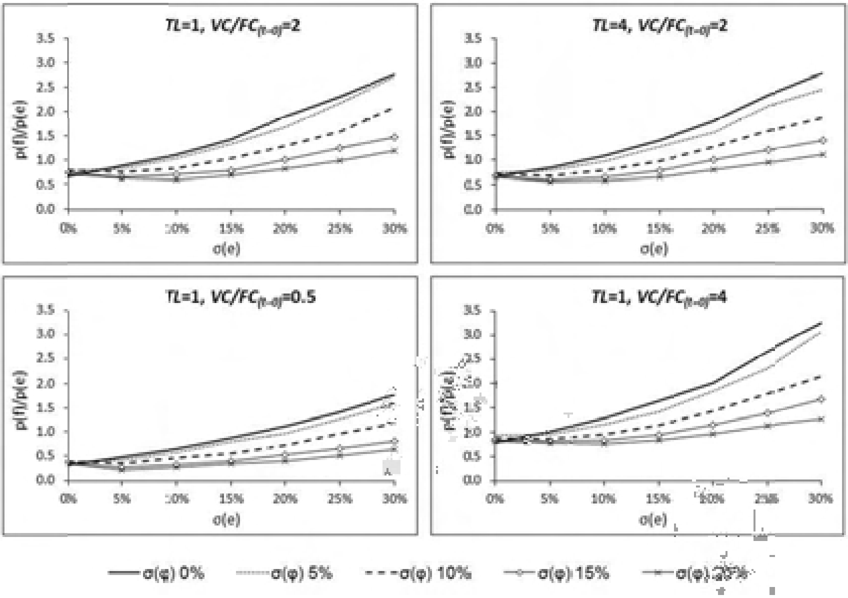
[51] In the periods of investment inactivity (owed, e.g. to a relatively low expected output price), the present value of the annualized fixed investment outlays would be zero. For calculation

of the option to suspend, the variable-to-fixed cost ratio responds differently to an increase in the volatility on the output and input markets.[52]

3.5.4 Food price behavior

The volatility and variable cost effects are reflected by the movements of the absolute and relative food prices. Figure 3.5 graphically illustrates how the food price relative to the energy price, $p_{(f)}/p_{(e)}$ – calculated as the average values over a project's lifetime – reacts to changes in uncertainties, time-to-build and the initial ratio of variable-to-fixed costs.[53]

Figure 3.5: Food price relative to energy price as a function of the energy price volatility for different values of *TL*, *VC/FC*$_{(t=0)}$ and $\sigma_{(\varphi)}$



It shows that as long as the volatility on the input side is higher than the volatility on the output side, the relative food price slightly decreases. In this case, bioenergy production would rather be temporarily suspended, whereby the absolute food price primarily reflects the demand and supply dynamics on the food market. In all other cases, an increase in the volatility on the output side leads

reasons, if this occurs in the present analysis, the ratio of the variable-to-fixed costs is set to one. This may further lower the calculated value of the average cost ratio over all genomes.

52 Variable-to-fixed cost ratios for varying volatilities and lengths of time-to-build are provided in Appendix, Table A3.5.

53 The corresponding values of the absolute food price are provided in Appendix, Table A3.7.

to a step-up in the relative food price, which may exceed the value of one. The higher the initial ratio of the variable-to-fixed cost, the lower the value of the energy price volatility at which the disproportionate rise in the food price relative to the energy price occurs.[54] However, if the volatility on the energy market is kept constant, a volatility increase on the input side dampens the rise in the relative food price, thus creating additional incentives to invest. This behavior of the relative food price corresponds to the results observed for investment threshold price (e.g. Tables 3.3 and 3.4) in response to changes in the volatilities. The reasons for the negative effect of the second uncertainty source on the food price are the same as for the investment threshold price, namely the possibility to pause bioenergy production and the assumption of exogenous energy price. While a rise in the energy price volatility affects the prices on the food market, the exogenous energy cannot be influenced by the price and volatility movements on the input (i.e. food) market.[55]

Any changes in uncertainty on the input market can thus only be reflected by the food price and (as a consequence) by decisions of bioenergy producers. A high relative food price (i.e. high input costs from the viewpoint of bioenergy producers) would lead to temporary production suspension, whereas a low relative food price would stimulate bioenergy production. Pausing production means that the bioenergy sector does not demand inputs and the food price in the periods of suspension is solely determined by the food demand and supply. If production is not suspended, bioenergy sector competes with the food consumers for crops, which results in lower food supply and higher food prices. The total effect of uncertainties and investment specifics on the relative food price in each time period is thus not only determined by the balance of advantageous and disadvantageous price movements on both markets, but also by the competing use of agricultural crops. However, the food price tends towards a clearly stronger positive response to increasing uncertainties on average than the exogenous energy price.

The standard deviation of the corresponding food prices (cf. Table 3.7) reveals a steady positive response to the volatility rise on both markets. Even if the food demand is certain ($\sigma_{(\varphi)}$=0 %), an increase in the volatility on the energy market leads (through the inputs demand by the bioenergy sector) to the standard deviation of the food price upwards. This suggests that the relative (and absolute)

[54] Here, it should be noted that due to the option to suspend, the average price of food (considered the only input factor of bioenergy production) does not necessarily coincide with the average variable cost of bioenergy and hence does not fully reflect the dynamics on the bioenergy market.

[55] The indirect income effect, which could apply here, is not considered in the model.

food price decreases are most likely expressions of reduced bioenergy production activities.

Regarding investment decisions, this means that the discussed project specifics do not lead to uncertainty reduction but rather to reduction of the negative consequences of uncertainty on investment incentives. Table 3.8 further shows that (as for the absolute and relative food price) the standard deviation of the food price is not dependent on the length of time-to-build. The reason is that the duration of the time-to-build is known and constant, so that it can be directly anticipated in terms of the annualized fixed cost when calculating profitability of bioenergy projects. As expected, the standard deviation is positively correlated with the initial ratio of variable-to-fixed costs.

Table 3.7: Standard deviation of the food price for varying volatility values, lengths of time-to-build and initial ratios of variable-to-fixed cost

[a] *TL*=1, *VC/FC*$_{(t=0)}$=2

	Volatility of food demand parameter, $\sigma_{(\varphi)}$				
Energy price volatility, $\sigma_{(e)}$	0%	5%	10%	15%	20%
0%	0.00	0.07	0.10	0.11	0.11
5%	0.05	0.10	0.13	0.14	0.14
10%	0.12	0.16	0.18	0.20	0.22
15%	0.19	0.23	0.25	0.26	0.27
20%	0.21	0.26	0.28	0.29	0.33
25%	0.22	0.29	0.32	0.32	0.32
30%	0.24	0.32	0.37	0.40	0.42

[b] *TL*=4, *VC/FC*$_{(t=0)}$=2

	0%	5%	10%	15%	20%
0%	0.00	0.07	0.11	0.12	0.13
5%	0.05	0.10	0.14	0.15	0.15
10%	0.11	0.15	0.19	0.19	0.20
15%	0.19	0.23	0.27	0.28	0.28
20%	0.20	0.25	0.26	0.29	0.29
25%	0.21	0.28	0.30	0.34	0.31
30%	0.22	0.30	0.36	0.38	0.39

[c] *TL*=1, *VC/FC*$_{(t=0)}$=0.5

	0%	5%	10%	15%	20%
0%	0.00	0.02	0.04	0.05	0.05
5%	0.03	0.04	0.06	0.07	0.07
10%	0.06	0.07	0.09	0.10	0.10
15%	0.08	0.09	0.13	0.13	0.13
20%	0.14	0.14	0.14	0.15	0.16
25%	0.14	0.15	0.15	0.16	0.17
30%	0.18	0.17	0.17	0.17	0.19

[d] *TL*=1, *VC/FC*$_{(t=0)}$=4

	0%	5%	10%	15%	20%
0%	0.00	0.09	0.12	0.12	0.13
5%	0.09	0.17	0.18	0.19	0.20
10%	0.21	0.26	0.30	0.32	0.34
15%	0.30	0.37	0.41	0.47	0.49
20%	0.36	0.44	0.46	0.55	0.58
25%	0.37	0.48	0.57	0.65	0.65
30%	0.44	0.54	0.66	0.68	0.70

Generally, it can be stated that under given assumptions a volatility increase on the energy market induces a non-negligible increase in agricultural (i.e. food) prices. The presence of the volatility on the input factor (i.e. food) market together with the possibility to flexibly adjust the scale of bioenergy production in response to unfavorable price movements on both markets tend to dampen the food price increase.

3.6 Summary of the Chapter

Substantial sunk investment outlays, uncertainty in returns and the ability to adjust the production schedule to some extent are inherent features of many agricultural projects. If these features exist simultaneously, the precondition for application of the ROA to investment valuations is met. Therefore, it is unsurprising that this approach found a widespread use in the agricultural investment research. Nonetheless, there are further very typical characteristics of agricultural investments, namely the high ratio of the periodic variable cost relative to the fixed cost (up to 8) and the significant length of time needed to generate first revenues (up to 5 years). Surprisingly, these features have received hardly any attention in the relevant literature. Accounting for them – as suggested by some few studies – may also have implications for the valuation of bioenergy projects, which usually possess all of the aforementioned specifics.

Following up this intuition, the present chapter aimed to study the role of these specifics in investment decisions under multiple uncertainties and assess their relevance for crop-based bioenergy investments. Using the real options framework in combination with a genetic algorithm technique, it was shown that, given a possibility to flexibly respond to increasing uncertainty by temporary production suspension, a realistically high cost ratio and a time-to-build may tip the balance in the net effect of uncertainty on investment incentives.

The novelty of the present work comprises pointing out that for the common model settings, considering only the volatility of the output price, the simultaneous presence of these three specifics is decisive for neutralizing or even reversing the generally depressing effect of uncertainty on investment activities. Importantly, this conclusion is not at odds with the main thrust of the financial and real options thinking, but rather points out that certain investment specifics may help managers to use uncertainty in their own favor. The presence of a second uncertainty source (stemming from the input market) was found to contribute to the effect of investment project specifics, as production suspension has an asymmetric impact on the input and output markets.

Although our analysis is conceptualized rather as a theoretical investigation, the empirically justified values of the utilized parameters suggest that our findings have straightforward implication for bioenergy and other projects with similar investment characteristics. In particular, it was shown that under realistic conditions of crop-based bioenergy production ($VC/FC \geq 2$ and $TL \geq 1$), the counter-intuitive investment threshold price response to increasing uncertainty occurs when the volatility on the output market exceeds 10 %, again reflecting the real-world volatility values on the energy market. The more general implication of our results is that ignoring the effect of project characteristics may lead to highly flawed investment plans and competitive disadvantages due to underestimated project values.

The results of the present numerical investigation emphasize the complexity of strategic investment decisions settled at the intersection of the energy and agricultural markets, which raises a number of further questions. For instance, it appears necessary to clarify whether the existence of the mentioned project specifics contributes to overinvestments observed in industries characterized by a long time-to-build or if these specifics rather provide firms with competitive advantages in highly uncertain markets. The empirical underpinning of the model parameters points to implications of the findings, including for the assessment of macroeconomic policies that target reducing uncertainty.

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CHAPTER 4

MACROECONOMIC IMPLICATIONS OF BIOENERGY PROMOTION

Chapter 4 deals with the welfare implications of crop-based bioenergy production under different policy regimes. Particular attention is given to the role of the ambiguous uncertainty-investment relationship observed in the previous chapter in the effectiveness of the applied bioenergy policies. The chapter starts with an overview of the broad range of the existent policy instruments implemented worldwide, pointing out recent dynamics on the national and global bioenergy markets. Subsequently, the objectives of the chapters and questions to be addressed by the welfare analysis are defined and motivated. Before introducing the policy scenarios of interest and the formal framework of the welfare calculation, the chapter outlines the history of the welfare concept and its different understandings. Moreover, it discusses the main criticism related to the term "welfare" and its particular meaning in bioenergy context. Finally, the chapter summarizes the results of the welfare analysis and identifies questions that may warrant further investigation.

4.1 INTRODUCTION

4.1.1 Bioenergy policy regimes in place

Bioenergy production is high on the political agenda worldwide, with bioenergy policies motivated by political, economic and ecological concerns, such as energy security, dependence on energy imports, energy cost control or climate change mitigation. Not least, supporting bioenergy production offers a chance to create income-generating opportunities, particularly in rural areas, and enhance economic growth. In many countries worldwide, policy makers are therefore supportive of bioenergy and other renewables. By the end of 2013, 33 countries had already introduced biofuel blend mandates, over 80 countries had enacted feed-in policies and 144 had defined national renewable energy targets (cf. REN21, 2014, p. 15, Tables 3, R16 and R18; RAJAGOPAL and ZILBERMAN, 2007). The type and composition of applied support instruments significantly varies across the countries, reflecting national targets, economic and geographic specifics (cf. Table A4.1 in Appendix).

As Table A4.1 (Appendix) shows, even the countries with a market leadership[56] in crop-based biofuel production (Brazil, the USA and the EU) still rely on additional payments and other support instruments such as the facilitation of market access. Despite having particularly advantageous natural production conditions and the internationally lowest production costs[57], Brazil supports sugar-based ethanol production by means of tax exemptions, sales prices regulation and domestic ethanol use mandate. In the USA, one of the widest ranges of support regimes is used to boost domestic production of corn-based ethanol and other renewables. The EU countries also offer a broad variety of support instruments. However, the relatively low shares of renewables in the energy mix of the EU countries (cf. Table A4.2) and the small production amount of crop-based biofuels (cf. Table A4.3) at present inevitably raise questions concerning the commensurability of the extensive and costly support regimes. Moreover, in an international comparison, considerable policy support to bioenergy industries and their ongoing growth stand opposed to the rather insignificant shares of the crop-based renewables in the national and global mix of final energy (Table 4.1).[58]

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[56] The largest part of the global bioethanol production (about 90 %) currently takes place in the United States and Brazil, while the European Union remains the largest biodiesel producer (53 %) (cf. IEA, 2013, pp. 88-93).

[57] Under these conditions, large-scale bioethanol production in Brazil can be often run cost-efficiently. For details on the costs of Brazilian bioethanol production and the sales prices, see VALDES (2011, pp. 10-15). International comparison of bioethanol production costs is provided by F. O. LICHT (2013).

[58] Cf. also IEA (2006 and 2014) and Figure 1.1 (Chapter 1).

Table 4.1: Renewable energy investments in 2013 by industry

Industry	Global new investments (billion USD) Developed countries	Developing countries	World	Relative change in new investments 2013/2012	2012/2011	Share in global final energy consumption	Jobs* (1000)
Solar power	74.8	38.9	113.7	-19%	-20%	1.2% (Solar, wind, biomass and geothermal power)	2,819
Wind	36	44	80	-0.4%	-1%		834
Biomass & waste	5.7	2.3	8	-7%	-28%		782
Geothermal power	2	0.5	2.5	25%	38%		184
Hydro (<50 MW)	0.5	4.6	5.1	-35%	-16%	3.8%	156
Biofuels	3.6	1.3	4.9	-2%	-26%	0.8%	1,453

Source: Own presentation based upon REN 21 (2014), pp. 63-67 and REN 21 (2013), p. 61.
Note: * Estimated direct and indirect jobs.

On the other side, as Table 4.1 shows, biofuel and other industries (e.g. biomass-based heat and power production) with currently very low shares of their produce in the energy mix appear to be important employers offering vast job opportunities. This fact underpins the particular interest of national policies in supporting these industries.

In recent years, the mid-term reviews of bioenergy policy effects, advances in the relevant research and declining technology costs in many bioenergy industries (cf. REN21, 2013, pp. 57-58; EC COM 2010/2020) have prompted revisions of the ambitious political targets. The most important adjustments are the cutbacks in subsidy amounts in the USA and Europe and the realignment of the mid-term targets (cf., e.g. REN21, 2014, Tables R12-R15). The undertaken adjustments primarily aim to commit renewable energy production not only to the competitiveness and energy supply security requirements, but also to *sustainability* standards (cf. also EC COM 2008/30; 2008/781 and national regulations). For instance, the German Renewable Energy Source Act (§1(1) EEG 2014) explicitly names ecological sustainability and the reduction of the macroeconomic costs of the energy supply among its main targets.

Nonetheless, when successfully providing economically and ecologically sustainable energy supply, renewable energy production – promoted or not – may benefit society. In reality, the orientation towards crop-based bioenergy and its political promotion can not only entail desired positive effects, but also unintended negative effects in terms of the indirect land use change (LEOPOLDINA, 2012; BANSE et al., 2008), economic path dependences (LOVIO et al., 2011), social costs (GORTER and JUST, 2010), investments in unused capacities (REISE et al., 2012) and other "green paradoxes" (SINN, 2008).

Probably the main challenge in terms of reaching the desired policy effects is given by the hybrid structure of the crop-based bioenergy market. Because this market is placed at the intersection of the energy and agricultural markets, all three markets are closely interrelated, so that even in the absence of policy support programs – as was shown in the preceding chapter – bioenergy production might have significant implications on the prices of agricultural produce. Due to this hybrid nature of crop-based energy, bioenergy policies are simultaneously environmental, energy and agricultural policies, which significantly hinders the predictability of the effectiveness of the policy regimes. A further challenge comprises the trivial fact that bioenergy targets and measures do not necessarily reflect actual needs of producers or ecological and social environments, but are primarily the result of political negotiations between the governing parties. In view of these facts, the economic and societal relevance of the crop-based bioenergy promotion should be questioned and assessed.

4.1.2 Objectives of the chapter

As discussed at the outset of the thesis (Chapter 1), most studies dealing with crop-based bioenergy primarily focus on the effect of policy regimes on the food and energy prices and the inter-market volatility transmission. This main interest is largely motivated by the steadily increasing concerns of food and energy security and thus it is justified. Nonetheless, by boosting bioenergy production, policy programs may create ambivalent or even incorrect incentives, e.g. when stimulating investment in unused production capacities. The resulting dynamics in the bioenergy sector would not only affect the food prices, but would also cause long-term redistribution effects on the macroeconomic level. Exploring the implications of bioenergy promotion appears requisite, particularly regarding the possible ambiguous strategic behavior of bioenergy producers under uncertain business conditions, as observed in the preceding chapter.

Following these considerations, the present analysis is designed to address the macroeconomic consequences of different bioenergy policy regimes. Being based upon the results of the stylized model of bioenergy production, our welfare analysis certainly cannot provide a detailed assessment of the real-world policy implications on bioenergy and other sectors. It therefore aims to spell out the reach of selected policy regimes and quantify the range of their implications for involved markets. In particular, the present chapter addresses the following questions:

(Q1) Are bioenergy investments conducive to economic welfare?

(Q2) Which sectors benefit most from the policy regime in place?

(Q3) Do bioenergy policies affect food prices?

The first question deals with the relationship between the growth of the bioenergy sector and possible gains in the economic welfare when different bioenergy support programs are applied. In the context of bioenergy production, this question has additional dimensions as it touches upon the subjects of welfare figures as descriptors of sustainable economic development and the growth imperative as the precondition for societal well-being. These issues will be addressed when discussing the neoclassical economic and alternative understanddings of the welfare concept. The qualitative relationship between the politically promoted bioenergy production and the macroeconomic surplus will be explored within the welfare analysis.

The second question is directed at quantifying and comparing the effect of policy regimes in terms of changes in consumer and producer rents and government budget. These figures are used to observe whether the applied policy instruments reach the desired effects and which sectors or economic actors are most (dis)advantaged by a certain policy regime. The last question focuses on the response of the relative food price to bioenergy sector activities under different policy regimes. Because the latter can be designed to reduce the fixed or variable cost of investments or guarantee a minimum output price (and hence to reduce market uncertainty), their effect on the food price may be significantly different.

Answering these questions can be supportive in managing investment projects under uncertainty, as well as calibrating policy instruments aimed to stimulate investments in sustainable energy. It also can shed light on the congruence of some policy goals, such as ensuring the food price stability, boosting crop-based bioenergy production and increasing societal well-being.

4.1.3 Structure of the chapter

Section 4.2 reviews different concepts of the economic welfare and its measurements and discusses its particular meaning in the bioenergy context. Section 4.3 defines scenarios for the present welfare analysis and provides the formal framework to calculate the macroeconomic effects of different bioenergy regimes. The results of the welfare analysis are presented and interpreted in Section 4.4, before the summary of the main findings and implications for successive research (Section 4.5) conclude the chapter.

4.2 WELFARE AS A MEASURE OF ECONOMY'S PERFORMANCE

4.2.1 Definitions of welfare

Etymologically, the term *welfare* is related to a sufficient supply of food, which can be interpreted as feeling certain that the satisfaction of basic needs is secure.[59] More generally, it refers to a state or condition of doing well.[60] Contemporary welfare economics is dominated by two views: the *neoclassical welfare approach* (cf. EDGEWORTH, 1881; MARSHALL, 1920 (1890); PIGOU, 1920) and the *new welfare economics* (as related to the work of, e.g. PARETO, 2014 (1906); HICKS, 1939; KALDOR, 1939). These two approaches correspond respectively to the cardinal and ordinal concepts of utility.

The *cardinal* (neoclassical) approach defines welfare in terms of material or pecuniary requisites of well-being, resulting solely from economic transactions (MARSHALL, 1920; BUCHANAN, 1987). Any improvement in the welfare (in terms of income or good distribution) is considered as utility (cf. KLEINEWEFERS, 2008, p. 42). Due to assumptions of exogenous and constant individual preferences, which are interpersonally comparable[61], a monotonically positive relationship between the personal and social welfare and diminishing marginal utility, this concept of social welfare can be quantitatively measured in monetary units or indexes, for instance.

The utility-based understanding of welfare is rooted in the classical school of economic thought of the 18th century. Being ideologically shaped not only by the industrial revolution but also by the age of enlightenment, classical utilitarianism considers the individual happiness of all persons as the ethical meaning of welfare. In its view, societal welfare does not relate to the well-being of a king or a nation but rather the wealth at least of the majority of all society members, whereby each individual decides what is best for him or her. The often-paraphrased quote by BENTHAM (1907 (1823)) about the "greatest happiness for the greatest number" is illustrative of this view. The total welfare of a society is considered as the sum of the individual hedonic utilities and it is correlated with the economic welfare. In Marshall's words, creating and increasing "man's welfare is also its (economy's) ultimate goal" (MARSHALL, 1920 (1890), p. 152). As conventionalized rational utility maximizers, individuals are thus strongly allowed by the neoclassical economics to maximize their happiness.

By contrast, ROBBINS (1934), HICKS (1939), PARETO (2014 (1906)) and others doubted that welfare can be quantitatively measured at all, because the perception of

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[59] ONLINE CENTURY DICTIONARY, http://www.global-language.com/CENTURY/.

[60] IBID.

[61] However, EDGEWORTH (1881) does not explicitly assume the interpersonal comparability of utility functions.

welfare is rather very individual. This measurability problem is bypassed by the *ordinal* approach, which simply ranks the utilities of persons or groups, rather than quantitatively measuring changes in their welfare. The ordinal welfare concept is characteristic of the post-neoclassical economics, which also incorporates social science understandings of economic activities and organization. This concept is usually applied if a measurement or comparison of personal perceptions of health (ABASOLO and TSUCHIYA, 2004), quality of life (DASGUPTA and WEALE, 1992), poverty (SEN, 1976) or the access to economic resources (FINSVEEN and OORSCHOT, 2008) cannot be assessed by a numerical scale. The ranking of individual utility or different states of a society is achieved by grouping bundles of goods that have the same utility. Different utility levels can subsequently be mapped as indifference curves and compared (cf. ARROW, 1963).

The distributional aspects of socioeconomic welfare are usually assessed by means of Pareto-efficiency. This principle states that a situation or social state can be considered as optimal if its improvement does not require making someone else worse off. The focus on the optimality of societal states, which does not require an interpersonal comparability of preferences, evades the neoclassical normative ethics of happiness with its cardinal hedonic scale. As a result, socially undesirable states, such as overexploiting of labor or natural resources, or even wars, may be assessed as Pareto-efficient or optimal. The social costs of such optimal states remain invisible. This fact suggests that a welfare assessment based upon the ordinal scale alone does not live up to the complex socioeconomic reality.

A number of further welfare concepts – such as capability approach, happiness economics, or the social welfare approach – have been developed at the intersection of the neoclassical and new welfare economics. In welfare assessments, the *capability approach* refers to the importance of personal freedom as the central precondition for individual choices and the ability to enjoy the realization of skills, preferences and wishes. This approach has been used in development economics to assess the effect of the resource access on the welfare or to provide a human development index, for instance. *Happiness economics* is based upon empirical data on individual happiness and less (or not at all) on statistical data on economic indicators. It is applied to study the individual perception of wealth often in addition to the neoclassical economic indicators of societal wellbeing. The *social welfare approach* places an explicit emphasis on the broad range of qualitative aspects of the societal welfare such as social life and cohesion, albeit combining qualitative assessment with quantitative measures. A comprehensive overview of these and further welfare understandings is provided by JUST et al. (2004), LITTLE (2002) and KUENNE (ed.) (2000).

The combined utilization of different welfare valuation devices has become conventional in practice. Social reports published by governments and other organizations (e.g. FAO or OECD) often provide qualitative judgments along with quantitative assessments to provide a more comprehensive valuation of the complex multidimensional socioeconomic reality. The trend in the contemporary understanding of welfare can thus be summarized as aiming to encompass both an individual perception of what is being and doing "well" and what is "fair" for an individual as a member of a society. The comparison of different welfare understandings suggests that while the assessment of the net effect of economic activities on society constitutes the common concern of different economic welfare concepts, their differences result rather from the definition of society. Nonetheless, although the advanced approaches to the welfare can be interpreted as a move away from a purely quantitative concept of the welfare, they still leave unanswered the basic question of what is actually *well* for a societal well-being: a numerical growth or qualitative improvements enabling sustainable development.

4.2.2 Welfare and bioenergy

As a quantitative measure of an economy's performance, welfare reflects economic surplus; namely, the growth of an economy over time. The system boundaries of the latter – given by competition and limited resources – define economic growth as being based upon efficiency and hence strong incentives. The inadequacy of this rough measurement is particularly plainly evident if applied to valuation of the bioenergy sector performance in terms of its contribution to the economic welfare.

Being defined as renewable energy (cf. IEA, 2012; EC COM 2006/105), bioenergy has to be *sustainable* energy (cf. also Introduction, Chapter 1.1). Sustainability criterion is associated with additional requirements to agricultural practices (e.g. compliance with ecological and animal welfare criteria, also with reference to water and fertilizer use, readjustment of tillage techniques etc.) and general economic principles (e.g. alternative organization forms, weakening of pecuniary incentives and efficiency goals). These requirements can be summed up as the claim for increasing sensitivity towards business environs. Consequently, in contrast to other sectors, the performance of the bioenergy sector also *has to* be assessed in terms of being responsive to social and ecological environments (cf. also the United Nations definitions of the green economy and sustainable development (UNCSD, 2012, p. 79)).

Such an assessment encounters certain practical problems. For instance, accounting for the social and ecological consequences of economic activities (i.e. for so-called *social costs*) is not always easy to express numerically, so that the valuation of sector's contribution to the sustainability goals would remain an ethical judgment to some extent. Moreover, accounting for social costs would necessarily lead to higher total production costs and hence the deliberate weakening of economic incentives in terms of lower profits (or other efficiency figures). Again, this is counter-directional to the valuation of the welfare surplus based upon imperatives of strong incentives.[62] An assessment of macroeconomic efficiency increases through bioenergy production thus appears to be a conflicting undertaking. A noteworthy ambiguity also arises from the fact that while the welfare calculations aim to assess efficiency increases of economic activities, bioenergy production is currently not driven by economic efficiency, but rather by political motives.[63]

Due to this largely political motivation of bioenergy production, the valuation of the economic performance of the bioenergy sector involves, along with an assessment of the societal merits of bioenergy production, an assessment of the policy regimes in place. This correlation becomes particularly apparent when recalling that not only bioenergy itself (per definition) claims to be sustainable and ecologically advantageous, but also the political instruments of its promotion are motivated by the same reasoning, namely to increase the share of sustainable and environmentally friendly energy in the energy mix (cf., e.g. EEG, 2014).[64]

The sustainability-efficiency trade-off is reflected by the fact that there is no study reporting a positive relationship between the political promotion of renewables and their contribution to societal welfare. Several studies have concluded that

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[62] Cf., e.g., Article 109 (2) of the German Constitutional Laws or Stability and Growth Pact (SGP) of the European Union which considers economic stability and growth as complementary development factors. The inherent trade-off between the economic efficiency and social benefits has been prominently pointed out by Rawls in his critique of utilitarian economics, "A Theory of Justice" (1971). Rawls (IBID., chapter 1) concludes that in the framework of classical utilitarianism, productivity gains necessarily lead to an increase of social disadvantages; namely, to higher social costs. LUHMANN (1999) considers such conduct of a system (including an economic one) as goal-rational and complexity-reducing. In his view, a system guided by strong – namely, goal-rational – incentives "makes itself free from the innumerable aspects of its environment; it sets boundaries and gains autonomy, but also exposes itself to the danger of ignoring those facts and changes of the environment that are crucial for its continued existence" (IBID., p. 199). Applied to economic systems, this means that goal-rationality (e.g., profit maximization by means of cost reduction) allows the economy to maintain its boundaries and preferred states but at the same time lowers its sensitivity to the critical environmental dependencies.

[63] DE GORTER and JUST (2009, p. 486) conclude in their study of U.S. corn and ethanol markets that under current market and policy conditions, framed by international trade, biofuel tax credit and price contingent farm subsidies, 50 % of "ethanol production occurs only because of price supports."

[64] EEG (2014), §1(1): "The purpose of this Act is to facilitate a sustainable development of energy supply, particularly for the sake of protecting our climate and the environment, to reduce the costs of energy supply to the national economy…".

policies such as tax credits for bioethanol producers (GARDNER, 2003; DE GORTER and JUST, 2009) or bioethanol import tariffs (MARTINEZ-GONZALEZ et al., 2007) lead to significant deadweight costs, i.e. hence welfare losses. LAPAN and MOSCHINI (2009) similarly conclude that although the welfare implications of financial (e.g. subsidies) and regulatory policies (such as a quantity-based biofuel mandate or bioenergy price floor) may differ quantitatively and regarding affected sectors, all bioenergy support programs result in the total social welfare loss. GARDNER and TYNER (2007) show that U.S. ethanol subsidy programs cause net social losses not only on the national level, but also on a global scale.

In line with these findings, DEVADOSS and BAYHAM (2010, p. 747) conclude that reductions in current subsidy payments to corn producers would not only reduce market distortions, but also improve production efficiency and augment welfare. A further study by de GORTER and JUST (2010, p. 26) attests that bioenergy policies are clearly inferior measures compared to the effectiveness of "…directly target environmental, energy and agricultural policy goals". The authors argue that "(t)axpayer costs of biofuel and renewable energy policies in general are very high, especially relative to their benefit (which can easily be negative and highly so)" (IBID.). In their view, the total welfare loss may be even higher if the "negative externalities related to vehicle miles traveled, local air pollution and CO2 emissions" encouraged by policy support payments are accounted for (IBID., p. 6).

Many studies seek to identify other than economic benefits of politically promoted renewable production. LANKOSKI and OLLIKAINEN (2008, p. 543) consider crop-based bioenergy per se as societal benefit since it "can replace fossil fuels in electricity production and thereby bring climate benefits to society" in terms of CO_2 emissions reduction. Similarly, LUNDGREN and MARKLUND (2013) advocate accounting for potentially positive effects from reductions in greenhouse gas emissions through facilitated renewable production as the welfare improving factors. By contrast, SEARCHINGER et al. (2008) and CHERUBINI et al. (2011) point out the notion that politically promoted crop-based bioenergy production leads rather to higher CO_2 emissions due to sindirect land use changes (ILUC), thus undoing the potential welfare gains through emissions reduction. Furthermore, the study by METCALF (2008, p. 90) dealing with bioethanol promotion via tax credits as the policy of reducing greenhouse gas emissions concludes that this policy instrument is "highly cost ineffective at best and counterproductive at worse" since its costs exceed the expected benefits of emissions savings by many times.

In view of the attested contradictory political expectation towards renewable energy being both economically efficient and environmentally sustainable, the bioenergy sector's contribution to social welfare seems to be based upon the goal conflict right from the beginning. This fact – along with the extant bioenergy support regimes – raises a number of questions that can be summed up and rephrased as the question of whether alternative energy requires alternative modes of economic organization or alternative welfare understandings or both. The above-discussed different current understandings of the welfare concept as a measure of economic performance typify the equivocal claim of this economic concept to act as a quantitative measurement of social benefits, while simultaneously acknowledging the impracticality of a full numerical capturing of social values. Accordingly, it appears natural to ask in what way could the welfare analysis of bioenergy production be informative, especially if bioenergy's contribution to sustainability goal is, despite being desirable and necessary by definition, not considered or only as a welfare-reducing factor. These considerations reinforce doubt about the practicability and accuracy of the welfare figures as descriptors of the performance of sustainable economic activities, necessitating an explicit investigation by further research.

The overview of the welfare concepts also evidences the modality of the welfare discourse as an expression of the predominant economic paradigm, implying that the reductionist numerical valuation of the economy's contribution to the societal well-being will prevail as long as quantification by itself is reckoned as an ultimate form of economic cognition. In the words of PIGOU (1920, Ch. 1), the welfare assessment will remain "restricted to that part of social welfare that can be brought directly or indirectly into relation with the measuring rod of money".

4.3 WELFARE ANALYSIS

As outlined above, the main purpose of our welfare analysis is to quantify the changes in the economic welfare caused by the introduction of a certain bioenergy policy. The analysis draws upon examples of current bioenergy policy regimes. Since our investigation is rather cursory and does not allow judgments related to social welfare, the use of the neoclassical welfare valuation technique appears sufficient and convenient.

4.3.1 Policy scenarios

The case of no bioenergy promotion, which underlies our stochastic dynamic partial equilibri-um investment model (Chapter 3), frames the reference scenario for the present welfare anal-ysis. The assumptions of the model – to recapitulate the central ones – involve the case of a closed economy producing bioenergy from agricultural crops and selling it on the energy market. The model assumes homogeneity of the produced and consumed bioenergy. The energy market is proxied by a multiple of the exogenous and stochastic energy price. The food market is represented by all field crops that can be used for both food and bioenergy production, allowing an assumption of constant production technologies on the food and bioenergy markets. The supply of these crops is limited by the available agricultural area. The food de-mand is uncertain and – as the energy price – is assumed to follow a time-discrete version of the geometric Brownian motion. The bioenergy market is presented by an aggregated risk-neutral bioenergy producer which uses agricultural crops as the only substrate. The crop price is therefore the only variable cost component. The bioenergy and food markets are assumed to be considerably smaller than the energy market and thus not able to influence the latter. Bio-energy demand is unlimited and the sector is able to absorb all available crops by adjusting its production decisions. Bioenergy plants depreciate over time, and reinvestments are needed to keep the production level constant or to increase it. Bioenergy investments are assumed to be totally irreversible and time-lagged; however, during the project, investors have the possibility to respond to worsening business conditions by pausing production at no additional costs.

In the absence of policy support programs, bioenergy price is determined directly by the sto-chastic exogenous energy price. The existence of the bioenergy support aiming to stabilize the output price for bioenergy (and thus to reduce its volatility) would change this direct price correlation. Other policy tools such as, e.g., fixed cost subsidies or bonuses for the use of some inputs would influence the fixed or variable costs of bioenergy production. The ratio of these costs may, as it was found out in our investment analysis, tip the balance in determining investment decisions of bioenergy producers at high uncertainty. The applied policy measures might thus fall short of the desired effect or entail high macroeconomic costs, if the ambiguous uncertainty-investment relationship is ignored.

These deliberations motivate us to study the effectiveness of the policy regimes in the particular context of ambiguous investment incentives of bioenergy producers. For our analysis we select the regimes of *the fixed-cost subsidy* and *the bioenergy price floor*. These regimes correspond to the two of three types of the renewable energy policies summarized in Table A4.1 (Appendix) and represent the most common support instruments in use worldwide. The fixed-cost subsidy belongs to the group of financial incentives, which support bioenergy projects by directly reducing investment of production expenditures. Subsidizing a certain share of the fixed investment outlays reduces a share of the sunk cost proportionally to the project size, but independently from the production amount. For our analysis, we will vary the amount of the fixed-cost subsidy from 10 % to 99 %. A politically defined price floor for bioenergy is a regulatory policy, aiming to facilitate the output market conditions for bioenergy producers. These regulatory regimes are also considered as price subsidies, transferring firms' risk to government (IEA et al., Joint Report, 2010, p. 12). They are usually combined with the guaranteed priority feed-in into the energy grid or biofuel obligations. Other than the clearly fixed sales price (also referred to as feed-in tariff), the price floor regime prescribes only the minimum sales price, allowing bioenergy producers to benefit from increases in the energy price.

To explore the implications of both regulatory regimes, the guaranteed minimum sales price will be varied within the range from 0.2 to 2 €. As shown in Chapter 3, in the absence of policy programs, the energy price in our model never has been below 0.2 €, whereby setting the minimum bioenergy price below this value would be irrational and correspond to the case of no policy support. The price floor of 0.5 and higher is rather unrealistic (cp. the composition of the German feed-in tariff system for biogas production provided in Appendix, Table A4.4) but useful for the theoretical analysis of the relationship between the scale of the price regulation and the welfare figures. Public financing as a further group of support instruments – although broadly applied and increasingly important – is not considered in our analysis.[65]

For the purpose of the present welfare analyses, the selected policy regimes will be applied to the base scenario of the investment model (cf. Chapter 3, Section 3.3.6) with the initial ratio of the variable-to-fixed cost ratio of two. The equilibrium threshold prices (i.e. option multiples) of bioenergy investments will be calculated for two selected volatility combinations that reflect their typical values $(\sigma_{(e)}, \sigma_{(\varphi)})$ = {(15 %, 5 %); (20 %, 10 %)} and three combinations of extreme volatility values $(\sigma_{(e)}, \sigma_{(\varphi)})$ = {(30 %, 20 %); (30 %, 0 %); (5 %, 0 %)}. The threshold prices obtained will subsequently be used to calculate the changes in the macroeconomic welfare and its components.

As shown in Section 4.1, in many countries worldwide bioenergy is currently produced primarily due to the advantageous promotion conditions. Focusing on the effects of the introduction of bioenergy support regimes compared to the case of no bioenergy support policies may thus appear behind schedule. However, this retrospective is necessary to assess the magnitude and the differences of the macroeconomic implications of policy scenarios given the ambiguous uncertainty-investment relationship. Besides, it offers a reverse perspective on the effect of possible full liberalization of the bioenergy market.

65 The reason is that accounting for the complex structure of loans, grants and other kinds of public stakes would require significant modifications in the investment model design, as well as in the framework of the present welfare analysis.

4.3.2 Welfare and its components

Absolute and relative welfare

In quantitative terms of neoclassical economics, social welfare is the sum of the rents or surpluses generated by the economic agents "consumers", "producers" and "government" over a certain time period (cf. JUST et al., 2004, chapter 8). Because our welfare analysis is based upon the results obtained in a partial equilibrium investment model, the absolute values of the welfare and its components would not be informative about the effectiveness of a policy regime. For this reason, we measure the welfare change (WF) associated with implementation of a bioenergy policy (in our case, the policy of the fixed-cost subsidy) relative to the production value (PV) of the bioenergy sector[66]:

$$R = WF/PV \tag{4.1}$$

with R denoting the relative welfare.

The production value is calculated as the product of the domestic market energy price (p_e) and the amount of bioenergy production (q_b) over the considered time period (T) discounted at the interest rate (r):

$$PV = \sum_{t=0}^{T} (p_{(t)e} \cdot q_{(t)b}) \cdot (1+\bar{r})^{-t}. \tag{4.2}$$

The *absolute* welfare (WF) is the sum of the absolute changes in the food consumer surplus (ΔCS_f), bioenergy producer surplus (ΔPS_b), crop producer surplus (ΔPS_c) and payments from government budget (GB), effectuated by the subsidy policy and discounted at the rate r over the same time period (T):

$$WF = \sum_{t=0}^{T} \left(\Delta SC_{f(t)} + \Delta PS_{b(t)} + \Delta PS_{c(t)} - GB_{(t)}\right) \cdot (1+r)^{-t}. \tag{4.3}$$

The interest rate r denotes the rate for the assumed time step $\Delta t = 1$; otherwise, it has to be adjusted as follows:

$$\bar{r} = (1+r)^{\Delta t} - 1 \tag{4.4}$$

The *relative welfare* (R) quantifies the relative value of monetary transfers within the economy resulting from activities in individual markets and policies in a

66 Other relative welfare figures within a similar framework (i.e. policy interventions, partial equilibrium and closed economy assumptions) are, for example, consumer and producer subsidy equivalents (cf. JOSLING, 1975; OECD, 2008, p. 1; TANGERMANN, 2005; HARVEY and HALL, 1989; KHAN, 2002). These measures are broadly used by the OECD, FAO and USDA to quantify the effect of government assistance to agriculture relative to the amount of consumed (or, respectively, produced) commodities valuated at their domestic prices. HESS and VON CRAMON-TAUBADEL (2008) also advocate the use of welfare figures set in relation to the production value of a certain sector. They found that although partial equilibrium models usually arrive at significantly higher estimates of welfare changes than general equilibrium frameworks, the relative welfare figures warrant a better comparison of economic performances of different counties.

given time span. For instance, the relative welfare of -0.2 would indicate that transfers from consumers, producers and taxpayers resulting from a certain government assistance to bioenergy market lead to a reduction of the total macroeconomic welfare by 20 % relative to the production value of the bioenergy sector.

Being calculated within a partial equilibrium model, the welfare figures reflect the assumption of constant, not affected by bioenergy policies, quantities and prices in all other economy's sectors beyond the model framework. The assumed closed-economy case where the energy market is much larger than the bioenergy and food markets implies that the economy has no influence on the world market, while on the national level any economic events on the bioenergy market or food market do not impact the domestic energy price. The single-input and single-output assumption along with the homogeneity of the produced and consumed energy allows to ignore any possible cross-commodity effects.

Food consumer surplus

The effect of a policy regime on food consumer surplus is defined as the absolute difference in consumer surplus compared to the case of no policy support regime. In both cases, the period food consumer surplus $CS_{f(t)}$ is calculated as the surface integral over the boundaries defined by the food demand and supply functions and the food price:

$$CS_{f(t)} = \int_{1}^{Q_{f(t)}} \left(\frac{\varphi_{(t)}}{Q_{f(t)}}\right)^{-\frac{1}{\eta}} dQ_{f(t)} - (Q_{f(t)} - 1) \cdot p_{c(t)}, \tag{4.5}$$

where $Q_{f(t)}$ denotes the period equilibrium amount of food. The reduction of this term by one $(Q_{f(t)} - 1)$ prevents that the value of the food consumer surplus tends towards infinity.

For $\eta \neq -1$, as in the present investment model, where η is assumed to be -0.7, equation (4.5) can be rewritten as follows:

$$CS_{f(t)} = \varphi_{(t)}^{-\frac{1}{\eta}} \cdot \left[\frac{1}{\frac{1}{\eta}+1} \cdot Q_{f(t)}^{\frac{1}{\eta}+1} - \frac{1}{\frac{1}{\eta}+1}\right] - (Q_{f(t)} - 1) \cdot p_{c(t)}. \tag{4.6}$$

For the value of the food demand elasticity of exactly -1, the rewritten equation (4.5) would yield:

$$CS_{f(t)} = \varphi_{(t)} \cdot \log Q_{f(t)} - (Q_{f(t)} - 1) \cdot p_{c(t)}. \tag{4.7}$$

Bioenergy producer surplus

Bioenergy producer surplus informs how the bioenergy sector (considered as an aggregated producer) benefits or loses from a certain policy regime, e.g.

when selling bioenergy at a market price higher (or lower) than the minimum acceptable price. Due to the assumption of the perfect competition among the bioenergy producers (cf. Section 3.3.5), the discounted equilibrium profit of the sector and hence its macroeconomic surplus have to approach the value of zero ($\Delta PS_{b(t)} \cong 0$). However, the stochastic simulation used in this study does not always allow reaching the exact value of zero. For this reason and to accurately assess the impact of policy regimes in each market, we will include the residual value of the bioenergy producer surplus into the welfare calculation.

Government budget

In welfare analysis, government budget stands for expenses associated with the redistribution of goods and services. In the present work, it is a measure of the annual monetary value of gross transfers from consumers and taxpayers to bioenergy producers owing to bioenergy promotion regimes. Its calculation depends on the kind of the support policy in place:

(i) bioenergy price floor (p_b^{MIN}):

$$GB_{(t)} = \begin{cases} \left(p_{e(t)} - p_{b(t)}^{MIN}\right) \cdot q_{b(t)}, & if\ p_{b(t)}^{MIN} > p_{e(t)} \\ 0 & otherwise; \end{cases} \tag{4.8}$$

(ii) fixed-cost subsidy (s):

$$GB_{(t)} = -(s \cdot Inv_{(t)}). \tag{4.9}$$

Crops producer surplus

Crops producer surplus $\Delta PS_{c(t)}$ indicates how producers of agricultural crops benefit or lose from supplying food consumers and bioenergy producers when the market price in the presence of a certain bioenergy policy regime (p_c^{pol}) differs from the price in the baseline scenario (p_c):

$$\Delta PS_{c(t)} = \Delta p_{c(t)} \cdot Q_{c(t)}^S = \left(p_{c(t)}^{pol} - p_{c(t)}\right) \cdot Q_{c(t)}^S \tag{4.10}$$

with Q_c^S denoting the total crop supply.

The described formal framework is utilized to assess the welfare implications of the crop-based bioenergy production under a financial and a regulative policy regime, introduced in Section 4.3.1.

Individual sectoral surpluses set in relation to the production value of the bioenergy sector (PV) reflect thus their policy-induced changes per unit of produced bioenergy valued at domestic energy prices. Production values for different scenarios are summarized in Table A4.10 in Appendix.

4.4 Results of the welfare analysis

For an easier interpretation of our welfare analysis, along with individual sectoral rents and the total relative welfare loss the results presented below also summarize some additional average figures for bioenergy sector such as the actually used production capacity ($q_{(b)}/q_{(b)max}$), the ratio of the variable-to-fixed cost (VC/FC), the ratio of the bioenergy to food production ($q_{(b)}/Q^{S}_{(f)}$) the input cost (food price) and its volatility. The figure for the relative surplus of bioenergy producers, $\Delta PS_{(b)}/PV$ – which should approximate the value of zero according to the investment model assumptions – is provided to demonstrate the robustness of the numerically gained results. The analysis was conducted, unless indicated otherwise, for $TL = 1$ and $VC/FC_{(t=0)} = 2$.

4.4.1 Fixed-cost subsidy

The welfare effect of the fixed-cost subsidy was studied for two different volatility combinations: $\sigma_{(e)=}$15 %, $\sigma_{(\varphi)}$=5 % (Table 4.2) and $\sigma_{(e)=}$20 %, $\sigma_{(\varphi)}$=10 % (Table 4.3). The results show that the investment threshold declines with an increase in the amount of the fixed-cost subsidy, indicating stronger investment incentives. High subsidies, acting as minimum prices, reduce the sunk cost of an investment and thus the required optimal threshold price that induces future revenues compensating for the investment outlays. Lower fixed costs imply that the actual ratio of variable-to-fixed costs increases. Together with the possibility to suspend production under unfavorable business conditions, reduced fixed costs appear to make investors particularly risk-friendly.[67]

[67] Dixit and Pindyck (1994, pp. 186 ff.) have shown that subsidies may create an incentive to temporary suspend production to downsize the losses. In doing so, producers "hibernate" the periods of unfavorable conditions and later – when the conditions recover improve – they restart their production and investment activities. Unfavorable conditions imply that the option to wait becomes more important than the option to invest and vice versa when conditions are favorable. The resulting asymmetry in values of both (compound) options may weaken the generally negative effect of uncertainty on investment incentives, depending on the occurrence of good and bad states.

Table 4.2: Welfare effects of fixed cost subsidy for $\sigma_{(e)}$=15 % and $\sigma_{(\varphi)}$=5 %

Scena-rio	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.41**						**0.2**	**57%**	**2.7**	**0.38**	**9%**
FC subsidy											
10%	1.27	-0.4%	-5.6%	7.2%	-2.0%	0.0%	0.2	56%	3.0	0.38	9%
20%	1.14	-0.8%	-9.5%	12.7%	-3.9%	0.0%	0.2	58%	3.4	0.38	10%
30%	0.90	-1.8%	-15.1%	20.3%	-6.3%	0.1%	0.2	62%	3.9	0.40	10%
40%	0.87	-2.8%	-20.1%	26.0%	-8.9%	0.2%	0.2	63%	4.3	0.39	10%
50%	0.70	-4.3%	-25.1%	32.5%	-11.7%	0.0%	0.2	61%	5.1	0.40	10%
60%	0.51	-6.0%	-30.4%	39.4%	-15.0%	0.1%	0.3	60%	6.3	0.41	10%
70%	0.32	-7.4%	-34.2%	45.3%	-18.6%	0.1%	0.3	59%	8.4	0.40	10%
80%	0.10	-10.6%	-38.6%	51.4%	-23.7%	0.2%	0.3	54%	12.8	0.41	10%
90%	-0.30	-14.1%	-41.7%	56.7%	-29.4%	0.2%	0.3	49%	21.6	0.41	10%
99%	-2.07	-30.3%	-44.1%	61.9%	-48.1%	0.0%	0.3	31%	198.2	0.42	11%

As seen from Table 4.3, increasing volatilities on the energy and food markets additionally strengthen the positive impact of subsidies on the investment incentives. These results support our conclusions derived in Chapter 3 concerning the depressing effect of high variable-to-fixed cost ratios on the threshold price of uncertain irreversible investment projects.

The extremely high (but not unrealistic[68]) values of fixed-cost subsidy allow an interesting observation: if more than 80 % of the fixed cost is compensated by subsidies, the threshold price may become negative. The reason is that bioenergy producers enabled to economize on both the variable cost (by means of the option to suspend) and a large share of the fixed cost (due to high subsidies), act as if there is no (or hardly any) competition and tend to speculate for high output prices. Under explicit consideration of the paid subsidy, the ratio of the variable- to fixed cost would yield about 200 for s=99 %, indicating a significant distortion in the relation of the cost components and a disproportionate effect of subsidies on the threshold price of investments.

68 For instance, in India, a capital subsidy of 90 % of the benchmark cost has been provided for setting up solar power projects since 2012 (MNRE, 2012, p. 8).

Table 4.3: Welfare effects of fixed cost subsidy for $\sigma_{(e)}$=20 % and $\sigma_{(\varphi)}$=10 %

Scenario	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^S_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.37**						**0.3**	**53%**	**2.7**	**0.36**	**16%**
FC subsidy											
10%	1.21	-0.4%	-2.9%	4.1%	-1.8%	0.2%	0.3	54%	3.0	0.39	16%
20%	1.05	-1.0%	-5.9%	8.5%	-3.9%	0.3%	0.3	55%	3.4	0.42	16%
30%	0.90	-2.3%	-10.4%	14.5%	-6.7%	0.3%	0.3	55%	3.6	0.36	17%
40%	0.72	-3.6%	-14.0%	19.4%	-9.0%	0.0%	0.3	57%	4.1	0.43	17%
50%	0.56	-5.2%	-18.2%	25.3%	-12.5%	0.2%	0.3	55%	5.1	0.40	16%
60%	0.34	-6.5%	-20.6%	29.3%	-15.4%	0.2%	0.4	55%	6.1	0.37	17%
70%	0.15	-8.1%	-22.2%	32.1%	-18.1%	0.2%	0.4	53%	7.9	0.37	16%
80%	-0.30	-12.1%	-26.5%	39.3%	-25.2%	0.3%	0.4	41%	12.0	0.40	16%
90%	-1.00	-16.6%	-27.5%	42.3%	-31.5%	0.2%	0.5	34%	23.9	0.41	16%
99%	-5.10	-33.1%	-29.4%	47.4%	-51.3%	0.1%	0.5	25%	190.8	0.41	17%

The effect of this distortion is reflected by the welfare figures. As Tables 4.2 and 4.3 show, the subsidy policy only benefits the crop producers. The total relative welfare, food consumer surplus and government budget strongly decrease with an increase in the amount of the fixed-cost subsidy, while the most pronounced losses are primarily borne by the food consumers. The results further demonstrate that increasing investment incentives do not necessarily mean a boost in production activities. By contrast, as the figures of the actual capacity show, subsidy-based bioenergy promotion stimulates investments in unused capacity. This observation is in line with findings by DE GORTER and JUST (2010, p. 26), showing that "[e]ighty percent of biodiesel capacity in both the United States and Germany currently lies idle in the face of both high consumption subsidies for biodiesel and high oil prices". The increase in underutilized capacities also explains the almost stable food price despite increasing subsidy amounts. The slight mark-up on the food price and its volatility in response to higher investment cost subsidies reflects a relative increase in demand for agricultural crops for bioenergy production ($q_{(b)}/Q^{S}_{(f)}$).

In the presence of higher uncertainties (Table 4.3), investment incentives also increase, resulting in an even higher share of unused production capacity and hence overinvestments. Although the total welfare loss and government spending are higher in this scenario, food consumers appear to be less disadvantaged by subsidies than in the case of lower uncertainties. By contrast, the surplus of the crops producers is smaller in this case. The comparison of the welfare components in both scenarios shows that while the decrease in the total welfare seems to largely correspond to the rise in government spending, the increase in the crop producer surplus reflects the decrease in the food consumer surplus. The food price does not respond to changes in volatilities if the initial ratio of the variable-to-fixed costs and time-to-build remain the same (cf. Tables 4.2 and 4.3 or rather Tables 4.4 and 4.5), although it increases with an increase in the initial ratio of the variable-to-fixed costs (cf., e.g. Tables 4.2 and 4.5).

Table 4.4: Welfare effects of fixed cost subsidy for $\sigma_{(e)}$=15 %, $\sigma_{(\varphi)}$=5 %, $VC/FC_{(t=0)}$=4

Scenario	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.31**						**0.2**	**52%**	**4.4**	**0.66**	**9%**
FC subsidy											
10%	1.23	-0.1%	-1.7%	2.2%	-1.2%	0.7%	0.2	52%	4.7	0.66	9%
20%	1.07	-0.4%	-4.9%	6.3%	-2.6%	0.7%	0.2	51%	5.4	0.69	9%
30%	0.95	-0.7%	-7.5%	9.6%	-4.0%	1.1%	0.2	53%	6.1	0.70	9%
40%	0.74	-1.5%	-12.0%	15.2%	-5.6%	0.9%	0.2	53%	6.7	0.66	9%
50%	0.53	-2.6%	-16.5%	20.8%	-7.8%	0.9%	0.2	51%	8.0	0.69	9%
60%	0.21	-3.8%	-20.7%	26.4%	-10.0%	0.4%	0.3	50%	9.7	0.67	9%
70%	0.00	-4.7%	-22.7%	29.3%	-12.2%	0.9%	0.3	47%	12.5	0.68	10%
80%	-0.31	-6.2%	-25.3%	33.0%	-15.2%	1.3%	0.2	45%	17.9	0.69	10%
90%	-0.95	-9.0%	-27.8%	36.9%	-19.4%	1.3%	0.3	39%	33.4	0.69	10%
99%	-3.12	-17.9%	-30.0%	41.0%	-30.2%	1.3%	0.3	28%	268.5	0.69	10%

A step-up in the initial ratio of the variable-to-fixed costs leads to higher investment incentives, which again confirms our findings from Chapter 3. Besides, as the comparison of Tables 4.2 and 4.4 and respectively Tables 4.3 and 4.5 reveals, in the presence of higher relative variable costs, the welfare loss, cuts in the food consumer surplus, government spending and gains in crop producer surplus are smaller. On the other hand, the usage of available production capacity also declines. However, if the volatility is low ($\sigma_{(e)}$=5 %, $\sigma_{(\varphi)}$=0 % and $VC/FC_{(t=0)}$=4, cf. Table A4.5 in Appendix), the employment of the installed production capacity is higher, although it not affected by the amount of subsidy. Although the loss in the total welfare is relatively low in this scenario, the trade-off between the change in the food consumer surplus and the surplus of crop producers becomes particularly strong, despite the food price being lower. By contrast, when the duration of the time-to-build is varied and the relative variable cost is kept constant, the welfare effect is different (cf. Tables 4.2 and 4.6).

Table 4.5: Welfare effects of fixed cost subsidy for $\sigma_{(e)}$=20 %, $\sigma_{(\varphi)}$=10 %, $VC/FC_{(t=0)}$=4

Scenario	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.11**						**0.3**	**51%**	**4.1**	**0.69**	**16%**
FC subsidy											
10%	0.97	-0.3%	-1.7%	2.4%	-1.3%	0.3%	0.3	51%	4.8	0.68	16%
20%	0.82	-0.7%	-3.9%	5.3%	-2.7%	0.6%	0.3	52%	5.2	0.65	16%
30%	0.60	-1.5%	-7.2%	9.6%	-4.4%	0.5%	0.3	50%	5.7	0.66	16%
40%	0.40	-1.9%	-8.9%	12.2%	-6.0%	0.8%	0.3	51%	6.8	0.68	16%
50%	0.16	-2.7%	-10.9%	15.1%	-7.8%	0.9%	0.4	49%	8.3	0.68	16%
60%	-0.16	-4.0%	-13.4%	18.8%	-10.3%	0.9%	0.4	43%	9.4	0.70	16%
70%	-0.55	-5.2%	-15.2%	22.7%	-12.8%	0.1%	0.4	37%	11.5	0.70	16%
80%	-1.34	-7.8%	-17.1%	25.3%	-16.5%	0.5%	0.4	33%	17.4	0.74	16%
90%	-2.12	-10.3%	-18.3%	28.6%	-20.9%	0.3%	0.4	31%	33.3	0.71	16%
99%	-5.21	-16.5%	-18.4%	30.2%	-28.5%	0.3%	0.4	25%	273.1	0.66	16%

Table 4.6: Welfare effects of fixed cost subsidy for $\sigma_{(e)}$=15 %, $\sigma_{(\varphi)}$=5 %, $VC/FC_{(t=0)}$=2, TL=4

Scenario	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.19**						**0.2**	**52%**	**2.0**	**0.37**	**9%**
FC subsidy											
10%	1.07	-0.7%	-4.9%	6.4%	-2.4%	0.2%	0.2	54%	2.3	0.37	9%
20%	0.94	-1.4%	-9.3%	12.2%	-4.8%	0.5%	0.2	54%	2.5	0.38	9%
30%	0.78	-3.5%	-16.2%	20.8%	-8.3%	0.1%	0.2	54%	2.7	0.38	9%
40%	0.62	-5.3%	-22.6%	29.0%	-11.9%	0.2%	0.2	55%	3.2	0.39	9%
50%	0.52	-6.4%	-25.2%	32.4%	-15.2%	1.7%	0.2	54%	3.7	0.39	9%
60%	0.22	-10.3%	-32.5%	42.6%	-20.5%	0.0%	0.3	52%	4.5	0.40	10%
70%	-0.05	-14.2%	-36.9%	49.4%	-26.7%	0.0%	0.3	47 %	5.8	0.41	10%
80%	-0.40	-17.6%	-38.7%	53.4%	-32.5%	0.3%	0.3	42%	8.9	0.41	10%
90%	-1.00	-23.5%	-40.9%	58.3%	-41.4%	0.6%	0.3	35%	16.1	0.40	11%
99%	-3.11	-43.2%	-44.4%	65.6%	-65.5%	1.1%	0.3	25%	130.4	0.41	11%

In this case, a higher value of the time-to-build not only increases investment incentives and overinvestments, but also the total welfare loss. By contrast, the consumer surplus and the crop producer surplus are not affected by the length of time-to-build, implying that the additional welfare loss is caused by higher government spending. The lower ratio of the variable-to-fixed costs along with the stable food price suggests that the option to suspend production is used more often than in the case of a shorter time-to-build.

Tables A4.6 and A4.7 (in Appendix) summarize results for two additional (extreme) volatility combinations, $\sigma_{(e)}$=30 % and $\sigma_{(\varphi)}$=0 % and $\sigma_{(e)}$=30 % and $\sigma_{(\varphi)}$=20 %. An important result is that in the presence of only one uncertainty (on the energy market), the food price is higher while government spendings and the use of installed production capacity are lower than in the case of positive uncertainties on the output and input markets. In the latter case (Table A4.7), higher subsidy levels (over 30 %) bring about a strongly decreasing relative share of crops available for food production (i.e. increasing $q_{(b)}/Q_f^S$) but not significant impact on the food price. Other than in the case of a single uncertainty (Table A4.6), the volatility of the food price may even slightly decrease at higher subsidy levels. The total welfare loss, the loss in the consumer surplus, and the gain in crop producer surplus are also lower compare to the case of a single uncertainty.

These observations are nontrivial for policies wishing to stimulate bioenergy production through instruments of uncertainty reduction, as they highlight that the presence of the positive volatility on the input market may actually be advantageous for bioenergy producers, food consumers and the economy overall. As was shown in Chapter 3, this effect is rooted in the asymmetric impact of different volatility sources on investment incentives of firms able to flexibly respond to changing business conditions.

4.4.2 Bioenergy price floor

The bioenergy price floor is a subtype of guaranteed feed-in tariffs, where only the minimum sales price is fixed, whereby the advantage of a possible increase in the energy price above the defined price floor can be fully exploited. This type of regulatory policy aims to facilitate the output market access for bioenergy producers. The results of the welfare analysis for the sales price regime are summarized in Tables 4.7 and 4.8. Table 4.7 demonstrates that – as in the case of the fixed-cost subsidy – the price floor reduces the depressing effect of uncertainty on investment incentives. An increase in volatilities on both markets (cf. Table 4.8) amplifies the positive effect of the price policy on bioenergy investments.

Table 4.7: Welfare effects of bioenergy price floor for $\sigma_{(e)}$=15 % and $\sigma_{(\varphi)}$=5 %

Scenario	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.41**						**0.2**	**57%**	**2.7**	**0.38**	**9%**
MIN p(b)											
0.2	***1.40***	***-0.2%***	***-1.2%***	***1.5%***	***-0.3%***	***-0.1%***	0.2	***69%***	***2.7***	***0.35***	9%
0.3	***1.30***	***-2.9%***	***-11.0%***	***13.2%***	***-5.3%***	***0.0%***	0.4	***88%***	***2.9***	***0.42***	10%
0.4	1.12	-16.8%	-50.7%	61.4%	-27.5%	0.0%	0.6	96%	3.3	0.49	10%
0.5	1.06	-28.5%	-79.8%	105.3%	-54.3%	0.0%	0.9	98%	4.0	0.57	10%
0.6	1.05	-37.9%	-99.2%	142.4%	-81.5%	0.1%	1.2	98%	4.8	0.67	11%
0.7	1.03	-46.9%	-117.6%	181.9%	-111.6%	0.2%	1.4	99%	5.6	0.73	12%
0.8	1.02	-55.0%	-131.5%	217.3%	-140.6%	0.2%	1.8	99%	6.4	0.80	13%
0.9	1.01	-60.3%	-141.1%	247.1%	-166.4%	0.3%	1.9	99%	7.3	0.91	13%
1.0	1.00	-68.2%	-154.0%	285.0%	-199.6%	0.2%	2.1	100%	8.2	0.98	14%
2.0	0.80	-113.8%	-225.0%	590.2%	-479.1%	0.1%	4.3	100%	17.2	1.98	17%

Table 4.8: Welfare effects of bioenergy price floor for $\sigma_{(e)}$=20% and $\sigma_{(\varphi)}$=10%

Scenario	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.37**						**0.3**	**53%**	**2.7**	**0.36**	**16%**
MIN p(b)											
0.2	***1.28***	***-1.3%***	***-3.5%***	***4.7%***	***-2.1%***	***-0.3%***	0.5	***82%***	***2.7***	***0.34***	17%
0.3	***1.16***	***-7.8%***	***-16.0%***	***21.7%***	***-13.2%***	***-0.2%***	1.0	***91%***	***3.0***	***0.41***	17%
0.4	1.12	-19.9%	-44.3%	60.0%	-35.8%	0.2%	1.4	93%	3.4	0.50	18%
0.5	1.11	-30.2%	-69.7%	99.6%	-61.0%	0.0%	1.8	95%	4.1	0.58	18%
0.6	1.10	-38.9%	-87.4%	136.4%	-88.5%	0.5%	2.2	96%	4.8	0.66	18%
0.7	1.07	-45.8%	-100.3%	167.4%	-113.1%	0.3%	2.6	97%	5.6	0.71	18%
0.8	1.02	-52.7%	-114.1%	202.6%	-141.5%	0.4%	3.0	97%	6.5	0.83	18%
0.9	0.98	-59.8%	-126.0%	236.1%	-170.6%	0.6%	3.4	98%	7.3	0.92	19%
1.0	0.95	-67.1%	-139.2%	272.5%	-200.6%	0.1%	3.9	98%	8.2	0.96	19%
2.0	0.01	-113.3%	-213.2%	584.3%	-484.2%	0.3%	7.0	99%	17.0	1.99	19%

The comparison of Tables 4.7 and 4.8 further shows that the loss in the food consumer surplus and the gains in the crop producer surplus, which increase with an introduction of a higher minimum bioenergy price, decrease at higher volatility values. However, if the price floor is relatively low, their impact on the welfare figures may differ. The minimum bioenergy price of 0.2 and 0.3 is lower than the average variable cost (i.e. food price) in the case of no policy regime. This means that the price of bioenergy would be primarily determined by the price of conventional energy, whereby the investment decision of bioenergy producers and its impact on the welfare figures would correspond to the scenario without policy support programs (cf. Table 4.9 and Table A4.8 for the price floor of 0.2).

In particular, a low price floor implies that bioenergy producers would more often postpone investment in the anticipation of a volatility-induced energy price increase. For this reason, the loss in the food consumer surplus and the gain in the crop producer surplus do not decrease (as for price floor of 0.4 and higher) but rather increase at higher volatility values.

Table 4.9: Welfare effects of bioenergy price floor for $\sigma_{(e)}$=5 % and $\sigma_{(\varphi)}$=0 %

Scenario	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.15**						**0.1**	**83%**	**2.3**	**0.28**	**2%**
MIN p(b)											
0.2	***1.15***	***0.0%***	***0.0%***	***0.0%***	***0.0%***	***0.0%***	0.1	***83%***	***2.3***	***0.28***	2%
0.3	***1.14***	***-0.1%***	***-3.9%***	***4.4%***	***-0.3%***	***-0.2%***	0.1	***88%***	***2.4***	***0.28***	2%
0.4	1.01	-11.4%	-72.9%	81.6%	-20.1%	0.0%	0.3	100%	2.7	0.33	3%
0.5	1.00	-22.6%	-102.0%	128.1%	-48.7%	0.0%	0.5	100%	3.6	0.41	4%
0.6	1.00	-31.3%	-118.8%	164.0%	-76.4%	0.0%	0.8	100%	4.5	0.50	6%
0.7	1.00	-40.7%	-134.7%	200.8%	-106.8%	0.0%	1.0	100%	5.4	0.60	7%
0.8	1.00	-47.1%	-144.8%	231.3%	-133.5%	0.0%	1.2	100%	6.3	0.70	8%
0.9	1.00	-54.2%	-155.7%	263.9%	-162.4%	0.0%	1.4	100%	7.2	0.79	9%
1.0	1.00	-61.3%	-166.6%	297.7%	-192.3%	0.0%	1.7	100%	8.1	0.89	10%
2.0	1.00	-108.5%	-236.3%	603.6%	-475.8%	0.0%	3.5	100%	17.2	1.89	15%

By contrast, a high guaranteed minimum sales price of bioenergy makes uncertainty increasingly irrelevant to investors. As evident from Tables 4.7, 4.8 and 4.9, the threshold price of investment approaches the threshold under certainty in most cases ($p'\approx1$).

The comparison of the results summarized in these three tables suggest that the increase in investment incentives (i.e. $p'<1$) is due to the positive volatility on the input market. By contrast, government spending not only increases in response to a higher floor price, but also to the rise in volatilities on both markets. Other than in the case of the fixed-cost subsidy, the bioenergy price floor stimulates the use of installed production capacities up to their full employment. However, the total welfare effect of this regulatory policy regime is negative and particularly strong for the higher guaranteed price floor.

Political promotion of bioenergy production by defining a minimum bioenergy sales price is a direct intervention into the market price mechanism. The resulting distortion in price formation is reflected by the variable cost relative to fixed costs and the food price. While the direct support through subsidy payments does not reveal any impact on the food price, the guaranteed minimum wholesale tariffs for bioenergy – as expected – significantly impair it. Only for a relatively low price floor (approximately equal to or lower than the initial energy or food price) may the food price decline[69] due to low investment activities of the bioenergy sector. The ratio of the variable-to-fixed cost (which strongly and positively responds to the increase in the level of a guaranteed sales price) reflects a rise in food prices induced by a step-up in the minimum bioenergy price. Moreover, unlike the investment subsidy policy, the price floor regime stimulates the use of installed bioenergy production capacity up to the full capacity employment. The relative amount of agricultural crops dedicated to bioenergy production ($q_{(b)}/Q_f^S$), the food price and its volatility respond clearly positively to the rise of the bioenergy price floor. However, as in the case of the fixed cost subsidy, at very high volatilities on both the input and output markets (Table A4.9) the food price volatility declines at a higher bioenergy price floor.

At the macroeconomic level, the comparison of the welfare implications of different bioenergy policies shows that the only positive effect of the supporting measures can be stated for the crop market. As the results show, the surplus in revenues of crop producers is generated regardless of whether the created bioenergy production capacities are used. The magnitude of this surplus is not least owed to the assumptions of partial equilibrium and a closed economy where bioenergy and food markets are significantly smaller than the energy market. Being able to absorb all bioenergy produced from agricultural crops, energy demand stimulates a disproportionate increase in demand for agricultural crops. Besides, as shown by, e.g., HESS and VON CRAMON-TAUBADEL (2008), policy assessments within a partial equilibrium framework, ignoring reciprocal effects of adjustments in the rest of the economy or the world, tend to produce higher estimates of welfare changes as within general equilibrium models. Nevertheless, even for low and moderate support to the bioenergy sector, crop producers appear to be the only economic actors benefitting from bioenergy policies. For agricultural sectors with a high share of leased arable land, this would mean

[69] However, the food price does not decline below its equilibrium value in the case of no bioenergy production.

that the land owners renting out their land for crops production are the ultimate winners of the bioenergy support policies.

The comparison of the welfare figures for the case of a single uncertainty (Tables 4.9 and A4.8) and multiple uncertainties (Table A4.9) reveals that the introduction of a second uncertainty source may significantly affect the assessment of a policy regime. While an increase in a single uncertainty leads to a higher welfare loss but lower gains in crop producer surplus, a positive uncertainty on the input market (Tables A4.8 and A4.9) may reduce the loss in the total welfare and in the food consumer surplus, albeit leading to even higher government spending and a higher crops producer surplus. This observation again emphasizes the important (and sometimes contra-intuitive) role of multiple uncertainties in assessments of uncertain irreversible investments characterized by the option to flexibly adjust production.

The central implication of the described welfare effects is that bioenergy policies aiming at stimulation of renewable energy production by means of uncertainty-reducing instruments might miss this goal and overestimate the required levels of an optimal support if their take no account of the effects of project specificity, allowing to partly hedge uncertainties.[70] Their consequences would be redundant budget expenses and the underestimation of both the welfare costs borne by food consumers and unintended transfers to crop producers (and hence land owners). This again would mean that the cuts in food consumer surplus, which lead to a reduction in real incomes, may lower public revenues (government's budget) in the next periods more than predicted. Furthermore the lost tax revenues – not considered in the present analysis – occurring when the bioenergy sector underutilized its production capacity may contribute to the welfare loss. As the result, additional deadweight costs, referred to as "rectangular deadweight cost" or "water" in tax costs (DE GORTER and JUST, 2009, p. 477), captured by no one may incur.

The complex simultaneous effects of politically supported crop-based bioenergy production on the involved markets do not allow identifying of a most effective policy. Depending on the main goal of different policy instruments (such as maximization of the bioenergy production, food price or supply stability, low welfare costs etc.), the assessment of the policy success might be highly varied. Given

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[70] FEIL and MUSSHOFF (2013) conclude similarly for the highly competitive diary sector alternatively supported by investment subsidies, price floors, and production ceilings. The authors show that dairy firms ignoring the cost-saving effect of their managerial flexibility (given by the option to partially reverse the already started projects) would tend to overestimate the optimal threshold prices. The required levels of an optimal policy support for such firms would consequently be overestimated as well (IBID., p. 15).

that the attainment of a certain level of produced crop-based bioenergy is the highest priority of bioenergy policies then the regulatory policy of a price floor might appear less problematic. Table 4.10 provides a comparison of the both considered policies for a fixed average bioenergy output of approximately 12 to 13 bn KW annually.[71] As evident from Table 4.10, for a given desired bioenergy output, the policy of a guaranteed minimum bioenergy price appears more efficient in terms of a clearly higher production capacity use, lower losses in the total welfare, consumer surplus and government budget.

Table 4.10: Comparison of bioenergy policies ($\sigma_{(e)}$=15 % and $\sigma_{(\varphi)}$=5 %)

Scenario	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$q_{(b)}$ (bn kW/t)	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.41**					**0.2**	**11.5**	**57%**	**2.7**	**0.38**	**9%**
FC subsidy											
10%	1.27	-0.4%	-5.6%	7.2%	-2.0%	0.2	11.5	59%	3.0	0.38	9%
20%	**1.14**	**-0.8%**	**-9.5%**	**12.7%**	**-3.9%**	**0.2**	**12.1**	**58%**	**3.4**	**0.38**	**10%**
30%	**0.90**	**-1.8%**	**-15.1%**	**20.3%**	**-6.3%**	**0.2**	**12.2**	**62%**	**3.9**	**0.40**	**10%**
40%	**0.87**	**-2.8%**	**-20.1%**	**26.0%**	**-8.9%**	**0.2**	**12.2**	**63%**	**4.3**	**0.39**	**10%**
50%	**0.70**	**-4.3%**	**-25.1%**	**32.5%**	**-11.7%**	**0.2**	**13.1**	**61%**	**5.1**	**0.40**	**10%**
60%	0.51	-6.0%	-30.4%	39.4%	-15.0%	0.3	13.5	60%	6.3	0.41	10%
MIN p(b), €											
0.2	**1.40**	**-0.2%**	**-1.2%**	**1.5%**	**-0.3%**	**0.2**	**12.6**	**69%**	**2.7**	**0.35**	**9%**
0.3	1.30	-2.9%	-11.0%	13.2%	-5.3%	0.4	21.3	88%	2.9	0.42	10%
0.4	1.12	-16.8%	-50.7%	61.4%	-27.5%	0.6	33.0	96%	3.3	0.49	10%
0.5	1.06	-28.5%	-79.8%	105.3%	-54.3%	0.9	41.7	98%	4.0	0.57	10%
0.6	1.05	-37.9%	-99.2%	142.4%	-81.5%	1.2	47.8	98%	4.8	0.67	11%
0.7	1.03	-46.9%	-117.6%	181.9%	-111.6%	1.4	52.8	99%	5.6	0.73	12%

Under the policy of the fixed cost subsidy, in contrast, the achievement of the same output amount of bioenergy would require subsidies up to 50 % of the investment cost and involve higher macroeconomic costs as well as a higher food price and its volatility.

4.5 SUMMARY OF THE CHAPTER

In economics, welfare is a descriptor of social benefits measured by assigning them quantitative or qualitative values of economic satisfaction. As such, it is designed to reflect what society as an aggre gate considers as good or utile. The various existent welfare concepts are concerned with the same question of the

[71] Further values of the average bioenergy output for different scenarios are provided in Table A4.11.

total outcome of various economic activities for the society. The difference between the concepts comprises the definition of the society. GREVE (2008, p. 51) highlights in this regard that "most analyses of welfare states deal with *public* welfare, fewer with welfare in *civil society*". From a utilitarian viewpoint, society is framed economically and comprises consumers, producers and the state. The alternative views are broader in the sense that they encompass also ethical, social and ecological aspects of a society and consider an economy as embedded in its manifold environments.

Defining the society and the relevant environments thus determines the key criteria for assessing economic performance. In the context of bioenergy, which has to be not only alternative and economically efficient but also sustainable (cf., e.g. United Nations' sustainability definition (UNCSD, 2012)), the relevant environment includes economic, ecological and social components. Within the reigning utilitarian welfare concept, sustainability-related welfare benefits of bioenergy production and promotion cannot be fully captured; besides, social and ecological sustainability can conflict with the purely economic efficiency goal. An assessment of the effectiveness of bioenergy policies can therefore be incomplete or incorrect if their conformance with the sustainability requirements as the central feature of renewable energy is not addressed. Further studies aiming to rethink the growth-oriented mainstream descriptors of societal benefits (and thus the standard mental models) would thus be of value.

The quantitative welfare analysis conducted in this chapter does not allow judgments related to the social and ecological sustainability requirements. Nonetheless, also regarding the economic figures, it doubts the effectiveness of the current policy regimes designed to stimulate bioenergy production from agricultural crops. In particular, the following points have been made.

- *Financial and regulatory instruments of bioenergy promotion shape investment incentives*.

These policies aiming at reducing uncertainty amplify the depressing effect of bioenergy projects specifics (high variable costs, time-to-build and managerial flexibility) at high uncertainties. The political promotion of agricultural bioenergy may therefore effectuate unnecessary public spending and undesired allocational consequences if the simultaneous and ambiguous effect of these specifics is ignored.

- *The effect of bioenergy policies vary at both the micro- and macroeconomic level.*

Fixed-cost subsidies stimulate investment incentives by reducing the sunk cost of investments, although they discourage production activities, while the regimes of the guaranteed output price increases both investment and production incentives. A significant part of subsidy payments can be redundant if bioenergy policies account for projects' specificity, which enables bioenergy producers to counteract the negative effects of uncertainties on their business.

- *Crop producers are the only beneficiaries of bioenergy policies.*

With bioenergy policies stimulating demand for agricultural crops, crop producers and eventually land owners appear to be the only winners of proactive support regimes. The costs of this support (in terms of a negative change in the corresponding sectoral rents) are borne by the tax payers and especially by food consumers. The resulting misallocation of the gains in the sectoral rents suggests an inefficient and erroneous policy of shaping economic incentives.

- *Bioenergy policies do not necessary increase the food price.*

Boosted demand for agricultural crops tightens the link between the energy and agricultural markets. The magnitude of the food price change is critically determined by the type of the energy policy. A fixed-cost subsidy does not influence the food price, while wholesale price policies strengthen the correlation between the energy and food prices so that the bioenergy price leads the food price.

- *Bioenergy promotion in the name of social welfare has rather a welfare-damaging effect.*

Under both support regimes, an increase in bioenergy investment activities results in welfare losses. A backward interpretation of the results – namely, comparing the welfare change from supported to liberalized bioenergy production – suggests that a reduction of policy support would economically benefit the society.

The observed effects of various bioenergy promotion programs suggest broad implications on agricultural structural change, especially concerning land use patterns, input choices and the scale of food production. To anticipate the evolution of agricultural structures and purposefully calibrate policy measures, further research on the role of investment specifics and the implications of overinvestments in a more realistic setting is required, including agricultural insurances, future contracts and other means of uncertainty reduction. Not least, our findings indicate that as long as the non-economic sustainability benefits and hence the efficiency-sustainability trade-off are not accounted for, welfare assessments of sustainability-driven policy instruments of bioenergy promotion hold little sense. Another option would be to reorient welfare analysis towards project specificity and away from the quantification of inherent trade-offs. Such a reorientation would not only be conductive to policies and scholastic analyses, but also to a broader public rethinking of expectations towards renewable energy.

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CHAPTER 5

SUMMARIZING DISCUSSION

5.1 OBJECTIVE OF THE WORK

Despite its still insignificant share in the global energy mix, the agriculturally-based bioenergy has attracted enormous research interest. The major reason for the unwaning interest in this field is the general awareness of the possible negative consequences of the food-fuel-conflict for the global food security. It is thus unsurprising that the main attention of the relevant research is given to the consequences of the bioenergy production from agricultural crops on the food price (cf. Table 1.1, Chapter 1). Since bioenergy production only takes place in most countries due to supportive policy regimes, this research focus as a rule simultaneously encompasses the analysis of bioenergy policies.

The purpose of the present dissertation was to direct attention to the fact that the context of crop-based bioenergy brings about some specifics that hold relevance for the economic analysis of bioenergy production from both the micro- and macroeconomic perspective. First, bioenergy not only has to be an alternative and economically efficient but also a sustainable energy source, complying with economic, ecological and social requirements (cf. UNCSD, 2012). Second, characteristic of investments in crop-based bioenergy are not only high sunk costs, but also high variable costs, a long time-to-build and the managerial capacity to respond to changes in production conditions.

Being quite distinct and of non-negligible magnitude, these specifics indicate the need to analyze the bioenergy sector not as a simple transmitter of price effects between the energy and food market, but rather as an active player at the intersection of the energy and food market. This particular position of the bioenergy sector between the two highly volatile markets envisions the importance of taking into account uncertainties stemming from both markets. It also suggests that activities within the bioenergy sector – especially if not only market-driven but also politically stimulated – would necessarily affect the interrelated markets and hence entail macroeconomic allocations. These considerations – multiple uncertainties, project's specifics and likely substantial effect on the economy's welfare – motivate the topical focus of the dissertation.

Methodologically, the present work is based upon the ROA, which is currently the most advanced technique for valuation of tangible irreversible investments under uncertainty. The ROA has become a popular tool for assessing investment behavior in agriculture. Its applications to agricultural problems invariably show that given high sunk costs and the flexibility in investment timing, uncertainty necessarily gives rise to the threshold prices of investments. However, these applications do not inform about the role of the distinctive features of crop-based bioenergy mentioned above. Drawing upon the finding of the general and agricultural investment literature, we have developed the hypothesis that in more realistic and thus complex model settings - including the project's time-to-build, multiple volatilities and the capacity to flexibly adjust production process to the changes conditions – the depressing impact of increasing uncertainty on investment incentives can be reduced or even overcompensated.

The main objective of the dissertation – i.e. investigating the micro- and macroeconomic implications of crop-based bioenergy investment specifics - is thus closely connected with the validation of the applied methodology. The research questions defined regarding this objective were answered using a stochastic dynamic partial equilibrium model of irreversible investments in crop-based bioenergy. Due to the explicit consideration of two volatility sources, the model was solved numerically, combining the options-based investment valuation with the genetic algorithms technique.

5.2 MAIN FINDING AND THEIR IMPLICATIONS

Although the present work is conceptualized rather as a theoretical investigation, the simulation experiments have been carried out using realistic values for key model parameters. The use of empirical data should prove the relevance of the derived conclusions for crop-based bioenergy production and indicate the scope of possible implications. For the reader's convenience and a better comparability of our results with other studies, the obtained equilibrium threshold prices have been presented as multiples of ROA-based investment trigger relative to the NPV-based ones. Because the ROA explicitly considers the opportunity costs of an investment's postponing (cf. DIXIT and PINDYCK, 1994), the ROA-based triggers are assumed to exceed the NPV-based ones. A corollary of this assumption is that ROA applications have to arrive at investment cost multiples (i.e. option multiples) higher than one (cf. Table 2.5, Chapter 2). However, the results gained in our investment analysis show that under certain conditions characterristic of many agricultural investment projects, the equilibrium threshold price may decline below one, reflecting an increase in investment activities at higher uncertainty values. The reasons for this effect and its implications have been studied in three steps by answering the formulated research questions (RQ). In the following, the main findings of this investigation are summarized.

RQ I: Do multiple uncertainties reduce investment incentives of bioenergy producers?

The first research question follows up the evidence from the real options literature that the introduction of the second uncertainty source "…adds a factor which changes the investment decision rule" (OTT and THOMPSON, 1996, p. 2). The assessment of firms' strategic decisions under uncertainty is the main thrust of the ROA. Nonetheless, it is primarily the output price that is usually perceived as an uncertain parameter in the most ROA applications. While the existence of significant uncertainties on the input side is not unknown, ROA-based models are usually formulated with known costs.

In studying this effect in irreversible crop-based bioenergy projects characterized by the option to suspend production, we conducted stochastic simulation experiments for varying combinations of both volatilities and fixed values of the time-to-build and initial variable-to-fixed cost ratio. The obtained results show that for relatively small volatility values on both markets, the generally positive impact of increasing volatility on investment threshold price holds. In all other cases, the equilibrium investment threshold declines, sometimes reaching values below the periodic investment cost – i.e. values below one – at very high volatilities. This effect can be stated in the presence of uncertainty on only one as well as both markets, while it is amplified by the inclusion of the second uncertainty source. Accounting for the fact that provision of production factors is associated with uncertainties is likely to decisively influence the project value.

The implications of this finding for strategic investment decisions might be substantial. First, they indicate that ignoring uncertainty in cost components may results in a tendency towards overestimating investment threshold price and thus in an underestimated project value. Second, irreversible projects (especially long-term ones) would tend to be limitedly insensitive to opportunities arising from favorable dynamics on the input markets or require a larger decline in a project's value when assessing an optimal discontinuation strategy.

RQ II: Do specifics of crop-based bioenergy production affect the investment rule?

In answering the first research question we assumed a variable-to-fixed cost ratio of two and a length of time-to-build of one period, which are typical for crop-based investments. Since these values are quite distinct, we have studied their role in investment decisions of bioenergy producers (RQ II). For this purpose, simulation experiments have been carried out for additional values of the time-to-build and varying cost ratios.

The results demonstrate that these characteristics (especially the time-to-build and the available managerial flexibility), which are usually omitted from the account in ROA-applications,may positively affect investment incentives at high uncertainty. This effect was traced back to the role of the profit function convexity in the output price. The key property of this function type is the positive correlation between the variance of the output price and the expected value of profits (cf. CABALLERO, 1991; ABEL, 1983). In our model, convexity results from the assumed option to suspend and hence from the available managerial flexibility. Because the latter allows reducing the firm's possible losses in bad states, high output price volatilities induce a chance for high profits to cover all investment costs in only a few periods. At very high volatilities, the threshold price of an investment may thus decline even below the investment cost, reflecting speculations of bioenergy producers for extremely high output prices.

The results of our investment analysis have demonstrated that the benefits of managerial flexibility can be fully unfolded in highly uncertain projects with a sufficiently high ratio of variable-to-fixed production costs, a longer time-to-build and (at least one) high uncertainty. Under these conditions, the generally depressing effect of uncertainty on investment activities can be reduced or even overcompensated. Conversely, firms unable to flexibly respond to changes in business conditions would have no chance to benefit from their specifics at high uncertainty and hence they would reduce their investment activities, just as predicted by the standard investment theory.

The central implication of the observed positive uncertainty-investment relationship is that the ROA-based assessments of uncertain irreversible investments ignoring the effect of projects' specifics tend to overestimate the threshold price of investments. This implication informs the investment analysis of irreversible projects by demonstrating the crucial role that these specifics may play in assessing investment strategies under uncertainty. It also provides project managers with an insight into the possibilities to respond to uncertainty by taking advantage of projects' particularities.

A further important finding of our analysis is that investments in crop-based bioenergy do not necessarily lead – as concluded by most studies on the food-fuel-conflict – to a food price increase. By contrast, agricultural prices may even decline, especially if the factor market uncertainty is higher than uncertainty on the output market. This finding again stresses the importance of including all relevant uncertainties into the valuation of agriculturally-based (and other) investment projects, as well as their implications for other sectors.

RQ III: What are the macroeconomic implications of crop-based bioenergy production under alternative policies?

The macroeconomic implications of uncertain crop-based bioenergy investments characterized by high variable costs, long time-to-build and a certain degree of managerial flexibility were the subject of the third research question. Specifically, we have explored the effects of bioenergy production under two bioenergy support regimes aimed at reducing uncertainty, namely a financial (fixed-cost subsidy) and a regulatory (output price floor) policy. The results of our quantitative welfare analysis have shown that both policies clearly shape investment incentives, amplifying the observed depressing effect of bioenergy projects specifics on investment incentives at high uncertainties. This finding advises policy makers against playing down the role of these specifics; otherwise, bioenergy policies may miss their actual goals or effectuate undesired consequences.

The welfare analysis has demonstrated the differences in macroeconomic effectiveness of both policy regimes. While the fixed-cost subsidy stimulates investment activities by reducing the sunk cost of investments but lowers production incentives (low capacity usage), the minimum output price regime increases both investment and production incentives. However, under both regimes, an increase in bioenergy investment activities results in welfare losses. The costs of the bioenergy support (in terms of a negative change in the corresponding rents) have been shown to be borne by the tax payers and especially by food consumers. As both types of considered policy regimes stimulate demand for agricultural crops, crop producers (and eventually land owners) appear to be "the smiling third" and the only party benefitting from the proactive bioenergy policies. These findings question the effectiveness of the current policy regimes and thus have straightforward implications for policies makers. In particular, they suggest that a reduction of political support to bioenergy producers would benefit a society in terms of welfare figures.

Regarding the effect of bioenergy promotion on the food price – the major concern of the ongoing food-fuel debate – the analysis has demonstrated that the magnitude of the food price effect is critically dependent on the type of the energy policy in place. Fixed-cost subsidies have been shown to have no perceptible influence on the food price, while output price policies appear to clearly strengthen the correlation between the energy and food prices. This observation highlights the need for a careful and differentiated judgment of bioenergy promotion instruments not only in the relevant research and defining targeted policy instruments, but also in the broader public discourse on renewable energy.

5.3 Further research

The present work has contributed to the analysis of bioenergy investment projects in agriculture by illustrating the non-trivial consequence of taking into consideration distinct features of crop-based bioenergy production. The findings of our simulation experiments have been shown to not only have implications for firms investing in bioenergy and other industries with similar characteristics, but also for policy-makers aiming at promoting certain industries in accordance with the welfare and sustainability goals.

At the same time, the findings necessarily generate a number of questions for further inquiries. First and foremost, our findings, being based upon the results on a highly stylized investment model, need to be verified in a more realistic model setting. For instance, the latter might reflect positive maintenance and reactivation costs of production suspension. Such additional validation of numerically obtained results would also narrow the range of industries potentially affected by our theoretical observations. With reference to the uncertainty structure of investment projects and producers' ability to respond to uncertainties (i.e. the uncertainty-flexibility trade-off) a more realistic model framework should take into consideration risk insurances, future contracts and other instruments of uncertainty reduction.

Moreover, the fact that most real cost-intensive irreversible investment projects (e.g. shipbuilding and construction industries, R&D, infrastructure and many agricultural projects) are not realized immediately but rather in stages or require a substantial time-to-build (cf. KOEVA, 2000) suggests that the role of the time lag in the total uncertainty structure should be thoroughly elaborated. In this connection, it is interesting to investigate whether an explicit consideration of the time-to-build in combination with the cost structure and available managerial flexibility might assist in explaining investments in unused capacities often observed in large-scale sequential projects.

The finding of the ambiguous effect of uncertainty on investment incentives appears to hold particular relevance in highly competitive markets. Specifically, it suggests that producers acting on the assumption of a steady positive correlation between the level of uncertainty and the threshold price of investments might tend to overestimate their optimal investment thresholds and hence arrive at competitive disadvantages. The empirical evidence and significance of this theoretical effect have to be proved.

Finally, the results of our study advise further bioenergy research to broaden its focus by addressing the closely related issues of resource and food security, resource and capacity utilization, structural adjustments and the compliance of the bioenergy production with sustainability requirements. These concerns ultimately lead to the probably main challenge of the future economic research, which is a necessity to rethink the growth-oriented concepts of societal benefits.

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APPENDIX

APPENDIX TO CHAPTER 3

Table A3.1: Conversion of energy units

	1 kJ	1 kcal	1 kWh	1 m³ natural gas
1 kJ	1	0,2388	0,000278	0,000032
1 kcal	4,1868	1	0,001163	0,00013
1 kWh	3.600	860	1	0,113
1 kg crude oil equivalent	41.868	10.000	11,63	1,319
1 m³ natural gas	31.736	7.580	8,816	1

Source: FNR (2010, p. 4).

Note: kJ – kilojoule, kcal – large calorie; kWh – kilowatt hour, m³ – cubic meter.

Table A3.2: Average calorific value of corn

Input source	High heating value MJ/kg	Middle heating value MJ/kg	Low heating value MJ/kg
Corn grain dry[a]	18.8	-	-
Corn stover[b]	17.7	-	16.5
Corn stalks[b]	15.8	-	14.8
Corn meal[b]	16.0	-	-
Grain crops[c] (average over all energy crops)	14.1	-	-
Grain crops[c] (grains only)	-	14.0	-
Fodder grass[c]	-	13.6	-

Sources: [a] SCHNEIDER and SPRAQUE (1995, p. 496); [a] MILLER (1958, p. 639); [a] PATZEK (2004, p. 90); [b] DOMALSKI et al. (1987, pp. 16-17 and p. 93); [c] FNR (2007).

Table A3.3: Source code for stochastic simulation experiments (VBA Excel)

Source code	Comments
Sub experiment() **Dim Cell As Range** Sheets("Parameter").Select Range("A4:A5").Select For Each Cell In Selection Cell.Select Range(Cell, ActiveCell.Offset(0, 8)).Select Selection.Copy Sheets("Initialization").Select Range("B5:J5").Select ActiveSheet.Paste **initial_trigger** **Simulationruns** Sheets("Parameter").Select Cell.Select **Next Cell** End Sub	• *Sub* denotes (here and below) the beginning of a section code, following by its name (e.g., "experiment"). • *Dim* statement determines a variable (e.g., "Cell") as a range value. • *Sheets* refers to an Excel spreadsheet named as indicated in the parenthesis. • *Range (*e.g., Range"A4:A5") provides a cell reference in the corresponding spreadsheet. • The sub "*experiment*" defines the sub routines of simulation experiments (i.e., their structure and order) by first retrieving the sub *initial trigger* and then the sub *Simulationruns.* • *Next cell* defines the code structure as a loop.
Sub initial_trigger() Sheets("Testgenome").Select Range("Z4:AI4").Select Selection.Copy Sheets("Testround").Select Range("C9:L9").Select ActiveSheet.PasteEnd Sub	• The sub *initial_trigger* introduces a range of initial threshold prices (i.e. triggers) into the model by copying their values from the spreadsheet *Testgenome* and pasting into the defined cells in the spreadsheet *Testround.*
Sub Simulationruns() **Dim i As Integer** Sheets("Testgenome").Select Range("C65536").End(xlUp).Select ActiveCell.Offset(1, 0).Select For i = 1 To 20 Step 1 **Generation** Next i End Sub	• The sub *Simulationruns* defines the number of simulation iterations, i.e. how many times the complete simulation run should be repeated in order to approximate an objective function. • Dim statement declares the variable *i* to hold an integer value (e.g., 20). • The sub *Simulationruns* refers to the sub *Generation.*
Sub Generation() Sheets("Testround").Select Range("C7:L8").Select Application.CutCopyMode = False Selection.ClearContents Application.CutCopyMode = False Range("C12:AR10011").Select Application.CutCopyMode = False Selection.ClearContents Range("C11:AR11").Select Selection.Copy Range("C12:AR12").Select	• The sub *Generation* determines the procedure of one simulation run and allocates the space for saving simulation results.

Sheets("Testround").Select **Application.Run "Simulation"** Range("A7:A8").Select Selection.Copy Range("C7:L8").Select ActiveSheet.Paste Application.CutCopyMode = False Sheets("Testround").Select Range("C9:AR9").Select Selection.Copy Sheets("Testgenome").Select Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _ :=False, Transpose:=False ActiveCell.Offset(1, 0).Select Sheets("GA").Select Application.CutCopyMode = False **Application.Run "GA"** End Sub	• The command *Application.Run "Simulation"* retrieves the loop function defined by the Sub *Simulation*. • The values of investment thresholds calculated in each simulation run are transmitted to the sub *GA* in order to create new "genetic" variations of thresholds'values.
Sub GA() Sheets("GA").Select Range("B11:C20").Select Selection.Copy ***'Fitness*** Range("E11").Select Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _ False, Transpose:=False Application.CutCopyMode = False Range("D10:F20").Select Selection.Sort Key1:=Range("D11"), Order1:=xlAscending, Key2:=Range("F11" _), Order2:=xlAscending, Header:=xlGuess, OrderCustom:=1, MatchCase:= _ False, Orientation:=xlTopToBottom ***'Selection*** Range("H10:H20").Select Selection.Copy Range("J10").Select Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _ False, Transpose:=False ***'Rekombination + Mutation*** Range("K5").Select Selection.Copy Range("K11:K20").Select ActiveSheet.Paste Range("K11:K20").Select Selection.Copy Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _ False, Transpose:=False Application.CutCopyMode = False Range("I10:K20").Select	• The sub *GA* defines the structure and the order of the applied genetic algorithm.

Selection.Sort Key1:=Range("I11"), Order1:=xlAscending, Key2:=Range("K11" _), Order2:=xlDescending, Header:=xlGuess, OrderCustom:=1, MatchCase:= _ False, Orientation:=xlTopToBottom ***' Migration*** Range("S5").Select Application.CutCopyMode = False Selection.Copy Range("S11:S20").Select ActiveSheet.Paste Selection.Copy Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _ False, Transpose:=False Range("Q11:Q20").Select Selection.Copy Range("T11:T20").Select Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _ False, Transpose:=False Range("S11:T20").Select Selection.Sort Key1:=Range("S11"), Or- der1:=xlDescending, Header:=xlGuess _ , OrderCustom:=1, MatchCase:=False, Orientation:=xlTopToBottom Range("V11:V20").Select Selection.Copy Range("Y11").Select Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _ False, Transpose:=False Range("X11:Y20").Select Selection.Sort Key1:=Range("X11"), Or- der1:=xlAscending, Key2:=Range("Y11" _), Order2:=xlAscending, Header:=xlGuess, OrderCustom:=1, MatchCase:= _ False, Orientation:=xlTopToBottom Range("Y11:Y20").Select Selection.Copy **Sheets("Testround").Select** Range("C9").Select Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _ False, Transpose:=True End Sub	• The command *Sheets("Testround").Select* inserts genetically modified variables (threshold prices) into the spreadsheet *Testround* for the next simulation run.
Sub Simulation() Sheets("Testround").Select Range("C11:L11").Select Selection.Copy Range("C12").Select Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _ :=False, Transpose:=False	• The sub *Simulation* defines a loop function for a number of simulation runs.

For i = 1 To 10000 Step 1 Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _ False, Transpose:=False ActiveCell.Offset(1, 0).Range("A1").Select Next i End Sub	• The command *For i = 1 To 10000 Step 1* determines a loop function for 10.000 simulations of a certain investment scenario (this value can be customized).

Table A3.4: Net present values for varying volatility combinations and lengths of time-to-build (α=0.5, $VC/FC_{(t=0)}$=2)

[a] *TL*=0 (no time-to-build)

	Volatility of food demand parameter, $\sigma_{(\varphi)}$				
Energy price volatility, $\sigma_{(e)}$	0%	5%	10%	15%	20%
0%	0	-501	-1416	2673	3406
5%	583	-1300	-1837	1341	181
10%	-196	-1790	-316	5444	659
15%	5874	2292	3872	-6202	7416
20%	3682	8035	4809	8340	-5208
25%	1625	909	-3771	3610	4537
30%	-878	160	803	8666	5605

[b] *TL*=1

	0%	5%	10%	15%	20%
0%	0	689	2681	2620	431
5%	1001	478	650	5401	490
10%	-410	1829	1052	71	-5619
15%	-2342	10	4620	1012	1348
20%	978	-2041	-8164	8166	17744
25%	3543	-6619	6755	-1251	-4540
30%	86647	-63615	77964	13167	78027

[c] *TL*= 4

	0%	5%	10%	15%	20%
0%	0	188	237	581	695
5%	3	275	-395	1689	128
10%	392	20	137	-950	7143
15%	-683	1206	580	-595	2
20%	1327	-1324	-172	-1205	1676
25%	477	10167	-1575	592	6645
30%	1108	47574	14349	16686	2113

Table A3.5: Variable-to-fixed cost ratios for varying volatility combinations and lengths of time-to-build (α=0.5, $VC/FC_{(t=0)}$=2)

[a] *TL*=0 (no time-to-build)

Energy price volatility, $\sigma_{(e)}$	Volatility of food demand parameter, $\sigma_{(\varphi)}$ 0%	5%	10%	15%	20%
0%	2.0	2.1	2.0	2.0	2.0
5%	2.5	2.3	2.1	2.0	2.0
10%	2.7	2.7	2.5	2.3	2.1
15%	2.9	2.9	2.8	2.5	2.5
20%	3.3	3.1	3.1	2.6	2.8
25%	3.7	3.4	3.0	3.2	3.0
30%	3.7	3.5	3.2	3.3	3.3

[b] *TL*=1 (cf. Table 3.8[c])

[c] *TL*=2

	0%	5%	10%	15%	20%
0%	2.0	1.8	1.7	1.7	1.6
5%	2.2	2.0	1.8	1.7	1.7
10%	2.4	2.3	2.1	1.9	1.8
15%	2.5	2.5	2.2	2.3	2.0
20%	2.6	2.6	2.5	2.4	2.1
25%	2.5	2.5	2.6	2.1	2.4
30%	2.3	2.3	2.4	2.1	2.0

[d] *TL*=3

	0%	5%	10%	15%	20%
0%	2.0	1.6	1.6	1.5	1.5
5%	2.0	1.9	1.6	1.6	1.5
10%	2.3	2.2	1.9	1.7	1.5
15%	2.4	2.5	2.1	1.9	1.7
20%	2.4	2.4	2.2	2.0	1.7
25%	2.1	2.4	2.1	1.8	2.0
30%	2.0	2.3	1.9	1.9	1.8

[e] *TL*=4

	0%	5%	10%	15%	20%
0%	2.0	1.5	1.4	1.4	1.3
5%	1.9	1.7	1.5	1.4	1.3
10%	2.1	2.0	1.8	1.5	1.4
15%	2.1	2.0	2.0	1.8	1.5
20%	2.0	1.9	1.9	1.7	1.6
25%	1.9	1.7	1.7	1.5	1.6
30%	1.8	1.7	1.9	1.8	1.5

Table A3.6: Investment multiples for the case of no time-to-build (*TL*=0, *a*=0.5)

[a] $\sigma_{(\varphi)}$=0% and varying values of $VC/FC_{(t=0)}$

Energy price volatility, $\sigma_{(e)}$	Initial variable-to-fixed cost ratio, $VC/FC_{(t=0)}$				
	0.5	1	2	4	8
0%	1.00	1.00	1.00	1.00	1.00
5%	1.08	1.11	1.14	1.15	1.16
10%	1.17	1.23	1.27	1.26	1.27
15%	1.29	1.37	1.39	1.40	1.40
20%	1.46	1.47	1.49	1.49	1.49
25%	1.55	1.56	1.58	1.60	1.60
30%	1.67	1.68	1.71	1.71	1.71

[b] $VC/FC_{(t=0)}$=2 and varying values of $\sigma_{(\varphi)}$

Energy price volatility, $\sigma_{(e)}$	Volatility of food demand parameter, $\sigma_{(\varphi)}$				
	0%	5%	10%	15%	20%
0%	1.00	1.12	1.2	1.23	1.24
5%	1.14	1.19	1.21	1.24	1.24
10%	1.27	1.33	1.37	*1.28*	*1.28*
15%	1.39	1.48	1.51	*1.44*	*1.35*
20%	1.49	1.58	1.60	*1.54*	*1.45*
25%	1.58	1.71	1.77	*1.67*	*1.55*
30%	1.71	1.82	1.92	*1.78*	*1.69*

Table A3.7: Average food price for varying volatility values, lengths of time-to-build and initial ratios of variable-to-fixed cost

[a] *TL*=1, *VC/FC*$_{(t=0)}$=2

Energy price volatility, $\sigma_{(e)}$	Volatility of food demand parameter, $\sigma_{(\varphi)}$				
	0%	5%	10%	15%	20%
0%	0.22	0.29	0.27	0.26	0.23
5%	0.28	0.29	0.28	0.27	0.25
10%	0.32	0.35	0.31	0.28	0.26
15%	0.36	0.38	0.35	0.32	0.26
20%	0.41	0.40	0.36	0.31	0.30
25%	0.44	0.42	0.42	0.30	0.42
30%	0.41	0.33	0.41	0.29	0.34

[b] *TL*=4, *VC/FC*$_{(t=0)}$=2

	0%	5%	10%	15%	20%
0%	0.22	0.28	0.27	0.25	0.23
5%	0.27	0.29	0.28	0.24	0.23
10%	0.31	0.34	0.31	0.26	0.22
15%	0.36	0.37	0.34	0.30	0.25
20%	0.42	0.39	0.35	0.30	0.27
25%	0.46	0.41	0.40	0.28	0.39
30%	0.38	0.31	0.33	0.31	0.31

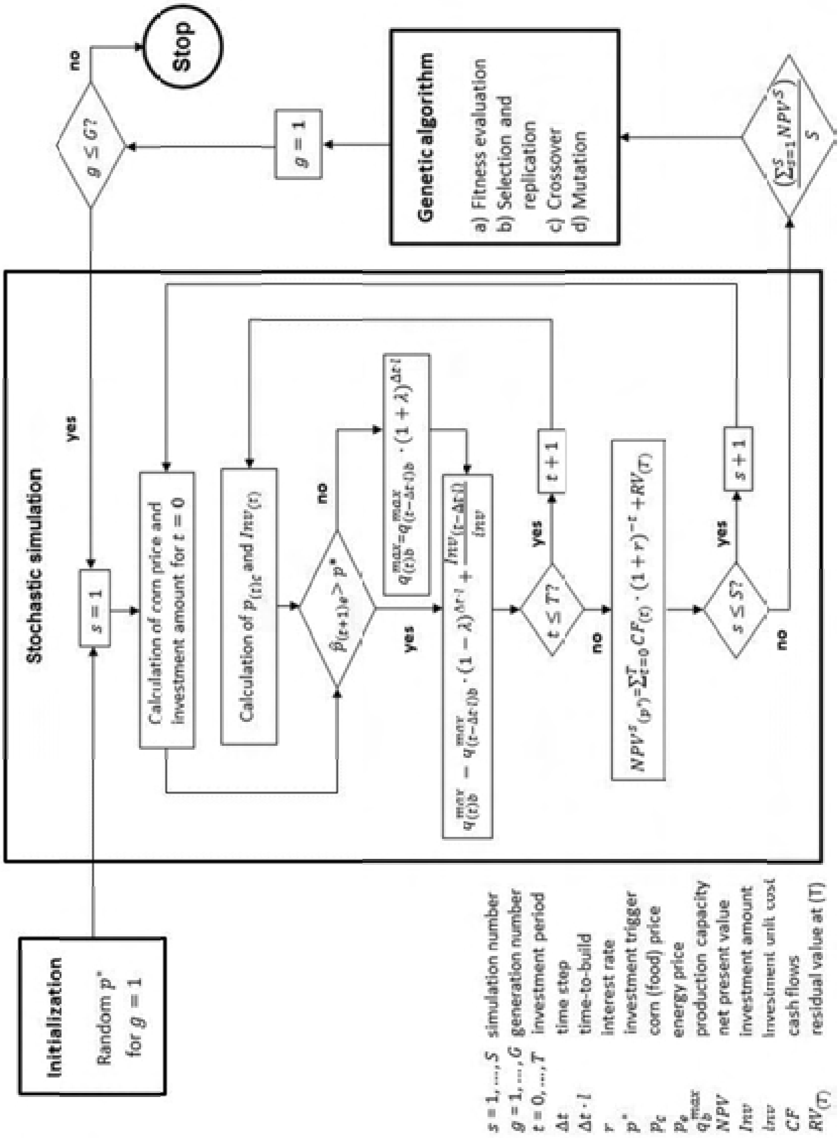
[c] *TL*= 1, *VC/FC*$_{(t=0)}$=0.5

	0%	5%	10%	15%	20%
0%	0.07	0.07	0.06	0.06	0.07
5%	0.09	0.09	0.09	0.09	0.09
10%	0.11	0.11	0.11	0.10	0.10
15%	0.14	0.14	0.14	0.13	0.12
20%	0.15	0.16	0.15	0.16	0.15
25%	0.16	0.13	0.13	0.12	0.12
30%	0.14	0.14	0.19	0.13	0.13

[d] *TL*= 1, *VC/FC*$_{(t=0)}$=4

	0%	5%	10%	15%	20%
0%	0.44	0.52	0.50	0.47	0.44
5%	0.54	0.52	0.49	0.47	0.45
10%	0.63	0.60	0.53	0.49	0.47
15%	0.66	0.66	0.64	0.52	0.45
20%	0.67	0.69	0.69	0.58	0.44
25%	0.69	0.91	0.48	0.48	0.43
30%	0.70	0.68	0.46	0.46	0.47

Figure A3.1: Flow chart of stochastic simulation experiments



Appendix to Chapter 4

Table A4.1: Renewable energy support policies in the EU 27, USA, and Brazil, 2013

Country	Renewable energy targets	Regulatory policy						Fiscal incentives				Public financing	
		Feed-in tariff (incl. premium payment)	Electric utility quota	Net metering	Biofuels obligation/mandate	Tendering	Tradable renewable energy certificates	Capital subsidy, grant, or rebate	Investment or production tax credits	Reductions in VAT, sales, energy, or other taxes	Energy production payment	Public investment, loans, or grants	Public competitive bidding
Austria	●	●			●		●	●	●			●	
Belgium	●		*	*	●	●	●	n*	●	●			
Bulgaria	●	●			●			●				●	
Cyprus	●	●		n	●	●		R					
Czech Republic	●	x			●		●	●	●	●			
Denmark	●	●		●	●	●	●	●	●	●		R	●
Estonia	●	●			●						●	●	
Finland	●	●			●		●	●		●	●		
France	R	R			●	R	●	●	R	●		●	●
Germany	●	R			●			●	●	●		●	
Greece	●	R		n	●			●	●	●		●	
Hungary	●	●			●			●		●		●	
Ireland	●	●			●	●	●						●
Italy	●	R	●	●	●	R	●	●	●	●		●	●
Latvia	●	●		n	●	●				●			●
Lithuania	●	R	●		●							●	
Luxembourg	●	●			●			●					
Netherlands	●	R		R	●		●	●	●	●	●	●	
Poland	●		●		●	R	●			●		●	●
Portugal	R	R	●		●	●		x	x	●		x	x
Romania	●		●		●		●					●	
Slovak Republic	●	R			●		●	●		●			
Slovenia	●	●				●	●	●	●	●		●	●
Spain	●			●	●			●	●			●	
Sweden	●		●		●		●	●	●	●		●	
United Kingdom	R	R	●		●		●	R		●	●	●	
Malta	●	●		●				●		●			
USA	R*	R*	R*	R*	R	R	*	●	x	●	●	R	●
Brazil	●			●	R	R			●	R		R	●

Source: Own compilation based on REN21 (2014, Table 3, pp. 89-91), and REN21 (2011, pp. 52-54=).

Note: ● – existing national, * – existing sub-national, n – new, R – revised, x – removed.

Table A4.2: Shares of final energy from renewables in the EU-27 and targets for 2020

Country	Baseline for 2005	Existing in 2009	Existing in 2012*	Target for 2020
Total (EU-27)	**8%**	**11.6%**	**14%**	**20%**
Sweden	45%	50%		50%
Latvia	35%	37%		42%
Austria	23%	29%		34%
Portugal	21%	25%	25%	31%
Denmark	17%	20%		30%
Finland	28%	30%		28%
Estonia	18%	23%		25%
Slovenia	16%	18%		25%
Romania	18%	22%		24%
France	11%	12%	7.9%	23%
Lithuania	15%	17%		23%
Spain	9%	13%	14%	20%
Germany	6%	9.7%	12%	18%
Greece	8%	7.9%		18%
Italy	5%	7.8%		17%
Bulgaria	9%	12%		16%
Ireland	3%	5.1%		16%
Poland	8%	9.4%		15%
United Kingdom	2%	2.9%		15%
Netherlands	3%	4.2%		14%
Slovak Republic	6%	10%		14%
Belgium	3%	3.8%		13%
Cyprus	4%	3.8%		13%
Czech Republic	7%	8.5%		13%
Hungary	5%	9.5%		13%
Luxembourg	1%	2.8%		11%
Malta	0%	0.7%		10%

Sources: EurObserv'ER (2011), REN21 (2013, pp. 13-14), and REN21 (2014, pp. 116-118).
Note: * Only available data are displayed.

Table A4.3: Biofuels production, top 10 countries and EU-27, 2010 and 2013 (billion liters)

Country	Fuel Ethanol		Biodiesel		Total	
	2010	2013	2010	2013	2010	2013
United States	49	50.3	1.2	4.8	50.2	55.1
Brazil	28	25.5	2.3	2.9	30.3	28.4
Germany	1.5	0.8	2.9	3.1	4.4	3.9
France	1.1	1.0	2.0	2.0	3.1	3.0
Argentina	0.1	0.5	2.1	2.3	2.3	2.7
China	2.1	2.0	0.2	0.2	2.3	2.2
Canada	1.4	1.8	0.2	0.2	1.6	2.0
Thailand	0.4	1.0	0.6	1.1	1.0	2.0
Poland	0.2	0.2	0.5	0.9	0.7	1.2
Spain	0.6	0.4	1.1	0.3	1.7	0.7
EU	**4.5**	**4.5**	**10**	**1.8**	**14.5**	**16.8**
World	**86**	**87.2**	**19**	**3.0**	**105**	**116.6**

Source: REN21 (2011, 2014).

Table A4.4: German feed-in tariff system for biogas production (2014), €ct/kWh

Tariff/Premium		Biogas plant size (kWel)			
		≤ 150	≤ 500	≤ 5.000	≤ 20.000
Basic feed-in price (start-up in 2012)		14.3	12.3	11	6
Premium for purely renewable agricultural substrates		6	6	4 5 (≤ 750)	-
Premium for use of manure		8	6-8	6-8	-
Premium for new techno-logies	Innovative processing (e.g. dry fermentation)	3 (≤ 700 Nm^3/h) 2 (≤ 1000 Nm^3/h) 1 (≤ 1400 Nm^3/h)			-
	Innovative plants, machinery	2.00	2.00	2.00	-
Premium for bio-waste fermentation		16		14	

Source: EEG (2014).

Table A4.5: Welfare effects of fixed cost subsidy for $\sigma_{(e)}$=5 %, $\sigma_{(\varphi)}$=0 %, $VC/FC_{(t=0)}$=4

Scena-rio	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.19**						**0.1**	**78%**	**4.2**	**0.54**	**2%**
FC subsidy											
10%	1.14	-0.1%	-5.6%	6.2%	-1.5%	0.8%	0.1	79%	4.7	0.55	2%
20%	1.02	-0.6%	-18.4%	20.4%	-3.2%	0.6%	0.1	79%	5.4	0.55	2%
30%	0.94	-1.0%	-26.8%	30.5%	-4.8%	0.1%	0.1	82%	6.3	0.56	2%
40%	0.91	-1.2%	-29.8%	34.9%	-6.5%	0.2%	0.1	80%	7.4	0.55	2%
50%	0.68	-2.9%	-47.8%	53.1%	-8.6%	0.4%	0.2	81%	8.8	0.56	3%
60%	0.53	-4.1%	-56.2%	62.7%	-10.7%	0.1%	0.2	79%	10.9	0.55	3%
70%	0.49	-4.3%	-58.0%	66.0%	-12.5%	0.2%	0.2	79%	14.7	0.56	3%
80%	0.48	-4.2%	-57.5%	67.4%	-14.2%	0.1%	0.2	79%	21.9	0.55	3%
90%	0.47	-4.2%	-59.2%	70.2%	-16.2%	0.9%	0.2	79%	43.7	0.54	3%
99%	0.46	-4.1%	-58.5%	71.4%	-17.8%	0.7%	0.2	79%	415.5	0.55	3%

Table A4.6: Welfare effects of fixed cost subsidy for $\sigma_{(e)}$=30% and $\sigma_{(\varphi)}$=0%

Scena-rio	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.08**						**0.1**	**30%**	**3.3**	**0.41**	**6%**
FC subsidy											
10%	0.95	-0.5%	-1.6%	2.3%	-1.5%	0.3%	0.1	33%	3.0	0.37	7%
20%	0.71	-2.0%	-4.8%	6.6%	-3.2%	-0.5%	0.1	32%	3.3	0.38	7%
30%	0.67	-2.5%	-5.6%	7.8%	-5.0%	1.0%	0.1	32%	3.9	0.37	7%
40%	0.29	-4.4%	-9.3%	13.2%	-8.0%	-0.2%	0.1	31%	4.2	0.37	7%
50%	-0.14	-6.3%	-11.5%	17.0%	-10.6%	-1.2%	0.1	30%	5.2	0.38	8%
60%	-0.49	-7.8%	-13.2%	19.9%	-13.8%	-0.8%	0.1	29%	6.3	0.38	8%
70%	-1.05	-10.4%	-14.8%	23.3%	-18.1%	-0.7%	0.1	27%	8.6	0.42	9%
80%	-1.46	-12.0%	-15.6%	25.0%	-22.1%	0.7%	0.1	25%	11.9	0.37	8%
90%	-3.45	-19.2%	-15.7%	27.5%	-31.0%	0.1%	0.1	13%	20.9	0.42	9%
99%	-5.22	-26.8%	-17.0%	29.6%	-40.9%	1.5%	0.1	10%	192.6	0.42	10%

Table A4.7: Welfare effects of fixed cost subsidy for $\sigma_{(e)}$=30% and $\sigma_{(\varphi)}$=20%

Scenario	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**0.97**						**0.2**	**53%**	**2.8**	**0.34**	**31%**
FC subsidy											
10%	0.85	0.0%	-0.3%	1.5%	-2.0%	0.8%	0.3	54%	3.0	0.30	32%
20%	0.65	-0.8%	-3.4%	5.2%	-4.1%	0.7%	0.3	53%	3.2	0.30	32%
30%	0.61	-2.2%	-5.3%	7.7%	-6.0%	0.6%	0.3	53%	3.5	0.29	32%
40%	0.47	-3.1%	-6.0%	11.0%	-8.3%	0.2%	0.4	53%	4.2	0.30	32%
50%	0.20	-4.5%	-8.0%	14.6%	-11.9%	0.6%	0.6	52%	5.0	0.28	31%
60%	-0.24	-5.6%	-8.9%	17.5%	-15.2%	1.1%	0.9	52%	6.1	0.25	29%
70%	-0.94	-8.2%	-10.2%	18.5%	-19.6%	1.2%	1.0	44%	7.7	0.29	29%
80%	-1.49	-12.4%	-13.0%	24.8%	-30.7%	1.3%	1.0	34%	11.8	0.29	29%
90%	-3.76	-20.5%	-14.0%	27.1%	-37.7%	1.1%	1.0	30%	19.4	0.28	29%
99%	-5.71	-24.3%	-13.5%	27.7%	-42.3%	3.8%	1.1	29%	196.8	0.29	29%

Table A4.8: Welfare effects of bioenergy price floor for $\sigma_{(e)}$=30% and $\sigma_{(\varphi)}$=0%

Scenario	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**1.08**						**0.1**	**30%**	**3.3**	**0.41**	**6%**
MIN p(b)											
0.2	***1.08***	***0.0%***	***0.0%***	***0.0%***	***0.0%***	***0.0%***	0.1	***30%***	***3.3***	***0.39***	6%
0.3	***0.89***	***-4.5%***	***-12.8%***	***14.6%***	***-5.3%***	***-0.9%***	0.1	***92%***	***3.7***	***0.34***	7%
0.4	0.86	-19.6%	-40.4%	47.3%	-26.6%	0.0%	0.3	99%	4.1	0.42	6%
0.5	0.89	-35.3%	-67.7%	87.2%	-54.9%	0.0%	0.6	99%	4.8	0.67	6%
0.6	0.85	-48.4%	-90.0%	126.2%	-84.7%	0.2%	0.8	100%	5.5	0.69	7%
0.7	0.85	-54.0%	-98.7%	151.5%	-107.4%	-0.4%	1.1	100%	6.2	0.75	8%
0.8	0.86	-62.3%	-111.6%	184.2%	-134.4%	-0.5%	1.3	100%	7.3	0.80	9%
0.9	0.88	-72.4%	-130.4%	223.9%	-165.9%	0.0%	1.5	100%	8.0	0.89	10%
1.0	0.88	-80.6%	-144.5%	262.0%	-198.1%	0.0%	1.7	100%	8.7	0.98	11%
2.0	0.91	-130.8%	-222.9%	579.7%	-487.3%	-0.4%	3.5	100%	17.5	1.96	15%

Table A4.9: Welfare effects of bioenergy price floor for $\sigma_{(e)}$=30% and $\sigma_{(\varphi)}$=20%

Scena-rio	p'	R	$\frac{\Delta CS_{(f)}}{PV}$	$\frac{\Delta PS_{(c)}}{PV}$	$\frac{GB}{PV}$	$\frac{\Delta PS_{(b)}}{PV}$	$\frac{q_{(b)}}{Q^s_{(f)}}$	$\frac{q_{(b)}}{q_{(b)max}}$	$\frac{VC}{FC}$	Food price	σ(food price)
No policy support	**0.97**						**0.2**	**53%**	**2.8**	**0.34**	**31%**
MIN p(b)											
0.2	0.97	-6.5%	-5.3%	9.1%	-11.4%	1.1%	2.9	94%	2.8	0.36	36%
0.3	0.93	-15.1%	-17.5%	31.5%	-29.6%	0.4%	4.2	95%	3.3	0.42	35%
0.4	0.92	-24.1%	-35.7%	64.3%	-53.2%	0.4%	5.0	96%	3.4	0.48	33%
0.5	0.89	-29.5%	-48.1%	90.7%	-72.7%	0.6%	6.3	96%	4.3	0.52	32%
0.6	0.84	-36.7%	-62.6%	127.6%	-102.0%	0.4%	6.9	96%	4.9	0.61	31%
0.7	0.70	-44.3%	-76.7%	157.8%	-125.8%	0.4%	7.8	96%	5.6	0.70	29%
0.8	0.51	-48.5%	-85.2%	187.3%	-151.1%	0.6%	9.1	97%	6.3	0.83	28%
0.9	0.37	-59.1%	-103.7%	236.4%	-193.2%	1.4%	10.2	97%	7.1	0.90	27%
1.0	0.18	-62.1%	-114.6%	264.6%	-212.3%	0.2%	10.8	97%	8.1	1.01	27%
2.0	-2.32	-112.7%	-193.6%	616.1%	-536.0%	0.9%	18.4	98%	16.8	2.29	24%

Table A4.10: Production value of the bioenergy sector (bn €)

[a] Fixed cost subsidy

	Scenario				
	TL=1, $VC/FC_{(t=0)}$=2		TL=1, $VC/FC_{(t=0)}$=4		TL=4, $VC/FC_{(t=0)}$=2
FC subsidy:	*σ(e)=15%, σ(φ)=5%*	*σ(e)=20%, σ(φ)=10%*	*σ(e)=15%, σ(φ)=5%*	*σ(e)=20%, σ(φ)=10%*	*σ(e)=15%, σ(φ)=5%*
0%	**104**	**139**	**166**	**244**	**86**
10%	111	141	168	265	88
20%	117	148	175	249	99
30%	134	161	178	272	101
40%	136	175	184	272	113
50%	138	184	199	270	119
60%	146	185	202	271	126
70%	156	186	210	285	137
80%	159	198	210	283	143
90%	166	206	225	281	148
99%	181	208	231	279	150

[b] Bioenergy price floor

	Scenario (TL=1, $VC/FC_{(t=0)}$=2)				
MIN p(b):	*σ(e)=15%, σ(φ)=5%*	*σ(e)=20%, σ(φ)=10%*	*σ(e)=30%, σ(φ)=0%*	*σ(e)=30%, σ(φ)=20%*	*σ(e)=5%, σ(φ)=0%*
-	**104**	**139**	**204**	**200**	**36**
0.2	104	152	205	203	36
0.3	107	153	229	235	39
0.4	156	203	250	247	108
0.5	218	242	267	276	182
0.6	251	278	296	277	236
0.7	277	290	308	347	275
0.8	306	308	344	350	305
0.9	326	328	346	358	327
1.0	342	353	366	374	344
2.0	429	425	418	457	425

Note: Production value is calculated according to equation 4.2.

Table A4.11: Average amount of bioenergy (bn kW/year)

[a] Fixed cost subsidy

FC subsidy:	Scenario					
	TL=1, $VC/FC_{(t=0)}$=2				TL=4, $VC/FC_{(t=0)}$=2	TL=1, $VC/FC_{(t=0)}$=4
	σ(e)=15%, σ(φ)=5%	*σ(e)=20%, σ(φ)=10%*	*σ(e)=30%, σ(φ)=0%*	*σ(e)=30%, σ(φ)=20%*	*σ(e)=15%, σ(φ)=5%*	*(e)=15%, σ(φ)=5%*
0%	**11.5**	**11.6**	**5.3**	**10.1**	**10.6**	**11.4**
10%	11.5	12.9	5.6	12.5	10.6	12.4
20%	***12.1***	13.3	4.8	12.7	11.7	11.4
30%	***12.2***	14.4	5.3	12.0	11.3	10.6
40%	***12.2***	15.0	5.9	15.0	12.2	12.5
50%	***13.1***	15.1	6.0	18.6	12.6	12.2
60%	13.5	16.0	6.1	24.6	14.1	12.8
70%	15.6	17.2	6.3	26.4	15.4	14.0
80%	14.7	19.3	6.5	26.0	15.7	13.0
90%	15.2	19.0	6.1	25.9	16.0	13.3
99%	16.9	17.9	6.1	25.8	15.7	14.1

[b] Bioenergy price floor

MIN p(b):	Scenario (TL=1, $VC/FC_{(t=0)}$=2)				
	σ(e)=15%, σ(φ)=5%	*σ(e)=20%, σ(φ)=10%*	*σ(e)=30%, σ(φ)=0%*	*σ(e)=30%, σ(φ)=20%*	*σ(e)=5%, σ(φ)=0%*
-	**11.5**	**11.6**	**5.3**	**10.1**	**10.4**
0.2	***12.6***	25.0	5.2	60.2	10.3
0.3	21.3	38.2	8.1	67.7	9.9
0.4	33.0	47.7	23.7	72.4	21.9
0.5	41.7	53.1	37.4	76.0	34.6
0.6	47.8	58.4	45.1	77.1	43.4
0.7	52.8	61.0	51.0	78.9	50.0
0.8	59.0	65.0	56.4	81.2	55.0
0.9	60.5	67.4	60.0	82.6	58.9
1	63.3	70.3	62.9	83.1	62.1
2	78.0	81.6	77.6	89.7	77.4

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Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbständig angefertigt und keine anderen als die angegebenen Hilfsmittel benutzt habe.

Lioudmila Chatalova Halle (Saale), den 31. August 2015

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