THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

An agent-based approach to supply side modeling of agricultural and power systems

EMMA JONSON

Department of Energy and Environment
Division of Physical Resource Theory
CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Energy and Environment
Division of Physical Resource Theory
CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 Göteborg
Sweden
www.chalmers.se
Tel. +46-(0)31 772 1000

Author email: emma.jonson@chalmers.se

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EMMA JONSON
Department of Energy and Environment, Chalmers University of Technology

Abstract

This thesis deals with the modeling of economic systems in the context of agricultural and power systems, and some aspects of the difference between the standard economics equilibrium approach and the agent-based approach. We model the supply side, where agents make decisions on what to produce or in what to invest. These decisions are based on predictions of future prices and other market conditions. In all settings time lags and limited foresight are important. Whereas standard economics is based on the idea of economic equilibrium, agent-based modeling describes dynamic systems based on the interaction of agents who do not necessarily possess perfect information and rationality.

This thesis consists of three parts. In papers I-III we present a model of interacting markets with cobweb characteristics, i.e. markets where prices are prone to oscillations due to a time lag between supply and demand decisions. We apply the model to land-use competition between food and bioenergy crops. We show how instability in one agricultural market, e.g. the bioenergy crops market, can be transferred to other agricultural markets, both on the supply side (by the limited availability of land) and on the demand side (by consumers choosing between different goods). Under certain circumstances the agent-based dynamics can be projected to a closed dynamics of aggregate quantities, which allows for the stability characteristics to be analytically approached. In paper IV we present a model of beef cattle dynamics based on decisions taken by boundedly rational farmers. We systematically examine the parameters determining the agents' expectations and decision mechanisms, and their impacts on the dynamics. In paper V we study a power system transition triggered by a carbon tax. We find that the level of carbon tax needed to reach a specific CO_2 mitigation target may be significantly higher in an agent-based model than in the corresponding optimization model.

In all papers we focus on mechanisms and model characteristics rather than on predictions.

Keywords: Agent-based modeling, non-equilibrium, Cobweb model, price fluctuations, stability, market interaction, agricultural land-use, power system transitions

List of publications

I. Liv Lundberg, Emma Jonson, Kristian Lindgren, David Bryngelsson and Vilhelm Verendel, "A cobweb model of land-use competition between food and bioenergy crops", *Journal of Economic Dynamics & Control*, **53:1-14**, (2015).

   KL had the idea. LL, EJ and KL performed the modeling with contributions from DB and VV. KL, LL and EJ analyzed the results with contributions from DB and VV. LL and EJ wrote the paper with contributions from KL.

II. Emma Jonson, Liv Lundberg and Kristian Lindgren, "Impacts on stability of interdependencies between markets in a cobweb model", *Advances in Artificial Economics*, **1:195-205**, (2015).

   EJ, LL and KL had the idea. EJ suggested modeling approach and LL implemented the model. EJ and LL analyzed the results and wrote the paper, both with contributions from KL.

III. Kristian Lindgren, Emma Jonson and Liv Lundberg, "Projection of a heterogenous agent-based production economy model to a closed dynamics of aggregate variables", *Advances in Complex Systems* **18.05n06**, (2015).

   KL had the idea and developed the model. KL, EJ and LL implemented the model and analyzed the results. KL wrote the paper with contributions from EJ and LL.

IV. Emma Jonson and Kristian Lindgren, "Cattle cycles and grain price volatility", *Working paper* (2015).

   EJ had the idea. EJ and KL developed the model and EJ implemented it. EJ analyzed the results with contributions from KL. EJ wrote the paper.

V. Emma Jonson, Liv Lundberg, Kristian Lindgren and Christian Azar, "Agent based models versus optimization models of the electricity system - exploring the dynamics of a large scale expansion of wind power", *Working paper* (2017).

   CA and KL had the first ideas, further developed with EJ and LL. EJ, LL, KL and CA developed several versions of the models. LL first implemented a static model not presented in this paper. EJ and KL implemented the ABM with contributions from LL. KL developed and implemented the optimization model. EJ, LL, KL and CA analyzed the results. EJ wrote the paper.

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Göteborg, April 2017
Emma Jonson

Contents

Chapter 1

Introduction

In a free market producers make decisions on what good to supply, when to do it and how much of it. Consider a farmer who grows crops. In the autumn he might choose to plant wheat. He decides what fertilizer to use and perhaps he invests in new equipment that will increase the yield. The following season the farmer sells his produce on the market and the aggregated quantity supplied and consumer demand determines the market price. The realized profit is therefore a function of not only the decisions made by the individual farmer, but also of the decisions made by other producers on the market, on the evolving consumer preferences, as well as on external shocks such as weather events. Expected profit is usually at least one of the factors taken into consideration when production decisions are being made. This means that agents are trying to form expectations about an outcome that in itself is a function of other agents' expectations. An economy is an evolving, complex, adaptive dynamic system (Leijonhufvud, 2006). This thesis includes five papers that take an agent-based approach to supply side modeling of agricultural and power systems. Agents are producers of a commodity that is sold on an open market. The production decision, or investment decision, is governed by agents' prediction of future market conditions.

When building his theory of human behavior, Simon (1957) proposed that agents in an economy have "bounded rationality". This means firstly that they do not have perfect information about the world around them. It is costly, or even impossible, to obtain the information needed to pursue optimal decision rules. Secondly, even if all information needed were at their fingertips they would not have the computational capacity to identify the course of action that would maximize their expected utility. Decision-makers may therefore aim for simply finding satisfactory solutions rather than optimal ones. In empirical studies it has been shown that people indeed tend to use simple heuristics, or rules of thumb, when making decisions under uncertainty (Kahneman and Tversky, 1973). In models of bounded rationality the process of choice is explicitly embedded (Rubinstein, 1998). In these models agents form expectations, and make decisions, based on observable quantities. Simple models with heterogeneous, boundedly rational agents can explain important observed stylized facts in financial time series, such as excess volatility, high trading volume, temporary bubbles and trend following, sudden crashes and mean reversion (Hommes, 2006). Specifying simple agent behavioral rules in a model, and letting these agents interact may lead to the emergence of important macro-social structures that are more than just the sum of the parts, see e.g. Epstein and Axtell (1996).

In contrast to this mindset, modern macroeconomics has adopted a general equilibrium framework (Leijonhufvud, 2006). This includes a rational agent approach, which means that the behavior of consumers, firms and investors can be described *as if* they behave rationally. Rational agents optimize expected utility and have beliefs that are perfectly consistent with realizations (Muth, 1961). Equilibrium modeling may be a useful tool for assessing in what direction a system is heading, although there are exceptions. The methodology is also valued for its simplicity since it lets human behavior be captured by simple mathematical functions, and allows for analytical examination.

However, the economy is not in equilibrium. Financial markets may have an optimum state but the system might never settle there. The optimum state can be very sensitive to small changes in the environment and therefore irrelevant to understanding what is going on (Bouchaud, 2008). There are many examples that indicate that economic actors do not have beliefs that are perfectly consistent with realizations. In year 2003 Sweden introduced green certificates, a support system intended to increase the share of electricity from renewable energy sources. One certificate represents generation of 1 MWh of electricity, and the producer of renewable electricity can sell the certificate on the open market where the price is determined by supply and demand. The buyers of the certificates are electricity retailers and other parties with quota obligations. In the last decade many suppliers have invested in wind power and the installed capacity has grown substantially. However, the hopes of making profitable investments did not become reality for most of the early investors. Between 2010 and 2015 the average Nordpool spot price of electricity decreased from around 500 to 200 SEK/MWh (Nordpool, 2017), mainly due to mild weather, high water inflow and the large expansion of wind power capacity itself (Kriström, 2016). At the same time the price of green certificates dropped from around 250 to 150 SEK/MWh (SKM, 2017). Revenues have not covered costs and many wind turbine owners face bankruptcy.

Agent-based modeling (ABM) is a more general way of studying economics, where equilibrium is a special case (Arthur, 2006). New phenomena may emerge that do not appear in steady state. ABMs are suited to handle real-world aspects such as asymmetric information, imperfect competition, strategic interaction, collective learning and the possibility of multiple equilibria (Tesfatsion, 2006). Agent interactions will sometimes give rise to equilibrium outcomes, and sometimes not. In some cases the simulated economy moves from one equilibrium to another.

Equilibrium is not necessarily equal to optimum. Tesfatsion (2006) notes that a system is in equilibrium if all influences acting on the system offset each other so that the system is in an unchanging condition. This definition does not include any conception of uniqueness, optimality, or stability with regard to external system disturbances. Conversely, the optimum is not necessarily an equilibrium state. Take for example integrated assessment models (IAM) which describe both economic and biophysical systems and the interactions between them. The majority of IAMs optimize the discounted utility for the world at large, given a damage function of environmental pollution. However, individual agents (e.g. decision makers acting in the best interest of their countries) may have incentives to defect from this state. In that case the world would end up in a sup-optimal Nash equilibrium (Brede and De Vries, 2013).

ABMs have recently been successfully used in several areas of economics, including financial markets, technology adoption, lock-in and transfer, business cycles in macroeconomics, labour networks, firm structure and larger scale agent-based macroeconomic models (Farmer et al., 2015; Stern, 2016).

1.1 Objective and scope

This thesis deals with the modeling of economic systems and the difference between the standard economics equilibrium approach and the agent-based approach. We model the supply side, where agents make decisions on what to produce or in what to invest. These decisions are based on predictions of future prices and other market conditions. In all settings time lags and limited foresight are important. Whereas standard economics is based on the idea of economic equilibrium, agent-based modeling describes dynamic systems based on the interaction of agents who do not necessarily possess perfect information and rationality. We focus on two limitations of equilibrium models: they do not say anything about the stability of the steady state, nor how a system transitions from one steady state to another.

In general terms the thesis deals with questions such as:

- Under what conditions does an ABM reach the stable state predicted by the corresponding equilibrium model?
- How does instability spread from one market to another?
- Under what circumstances is it possible to project an agent-based micro-dynamics to a closed form dynamics of aggregate variables?
- How will the qualitative results differ when modeling a power system transition with an ABM instead of an optimization model?

This thesis consists of five appended papers and an introduction to those. The papers can be grouped into three different parts:

I. In the first part (papers I-III) we present a model of interacting markets with cobweb characteristics, i.e. markets where prices are prone to fluctuations due to a time lag between supply and demand decisions. We apply the model to land-use competition between food and bioenergy crops. We investigate how instability in one agricultural market, e.g. the bioenergy crops market, can be transferred to other agricultural markets, both on the supply side (by the limited availability of land) and on the demand side (by consumers choosing between different goods). Agents' methods for forming expectations of the future, and the degree of inertia of the system, determine if the model dynamics is stable or not.

II. In the second part (paper IV) we study the emergence of cattle cycles, i.e. fluctuations of prices and quantities produced over time. We use a model of boundedly rational farmers and systematically examine the parameters determining the agents' expectations and decision mechanisms, and their impacts on the dynamics. In two model extensions we highlight the link between beef production and grain price volatility.

III. In the third part (paper V) we study a power system transition triggered by a carbon tax. We use both an optimization model and an agent-based model where agents are power companies making investment decisions. In the ABM we focus on the effect of limited foresight and perceived risk.

Chapter 2

Methods

This thesis focuses on methodology development, an improved understanding of mechanisms and model characteristics rather than on predictions. The first three papers have a highly theoretical character while the second two are somewhat more applied. In this chapter I describe the key methodological approaches that have been adopted.

2.1 Agent-based modeling

Agent-based modeling is a computational method that enables a researcher to create, analyze, and experiment with models composed of agents that interact within an environment (Gilbert, 2008). In these models individual entities (the agents) and their interactions are directly represented. The agents may be heterogeneous, and their decision rules are explicitly specified. The agents interact with each other which may trigger various kinds of adaptation and learning.

Agent-based models are valued for their ability to represent in a bottom-up way how individual behavior leads to the emergence of structures at the macro level that could not easily have been foreseen by simply studying a single agent. A typical example is swarm behavior, exhibited by e.g. insects, birds, quadrupeds and fish, where a group of agents move together without any central coordination. When each entity is modeled as following a few simple rules a swarm behavior emerges with complex motion and interaction that would have been hard to create otherwise (see e.g. Reynolds (1987)).

We use agent-based modeling in all five papers in this thesis. The agents in our models make their production decisions, or investment decisions, based on their expectations of future prices. They have either a "naive" prediction method, meaning that they assume current prices to hold in the future, or a more forward-looking strategy where they try to predict in what direction prices will move. All of our agents maximize expected profit. Agent-based models are well suited for also including other types of goal functions or decision rules. For example, in an interview study with Dutch power companies a frequently stated goal of the investment decision was to "not do worse than the competition" (Groot, 2013). This indicates that there is a tendency of imitation between power companies, in order to avoid doing worse investments that others. This is something that could be studied with agent-based modeling, but it is not within the scope of this thesis.

In the agent-based models of land-use competition, described in papers I-III, our agents are heterogeneous in the quality of land that they own and in their prediction method of future prices, whereas in the models described in papers IV and V they are homogenous. In all of our models the agents interact via the price signal they create by supplying their goods to the market. The agents react to this price signal by using it as a basis for prediction of future prices. In paper I agents may also update their prediction method based on their past success.

2.2 The cobweb model

The cobweb model is a central concept in papers I-III. A cobweb market has two main characteristics. Firstly, there is a time lag between supply decision and price formation. Secondly, the market is characterized by both supply and demand being elastic with respect to price. That means that suppliers increase production if the price is high, and decrease production if the price is low. In the same way, consumers increase their demand if prices are low, and increase demand if prices are high. The direction of causality goes both ways. If the quantity supplied to the market increases, the price decreases. This leads to a negative price expectations feedback. Due to the time lag suppliers must base their production decision on expectations of the future price of the good. If they expect a price higher (lower) than the fundamental price, the realized price will sink below (rise above) the fundamental price.

In "The Cobweb Theorem" Ezekiel (1938) offered an explanation to the cycles that had been observed in, e.g., the ratio of hog-corn prices (see Fig. 2.1). Corn has been considered the ideal feed for hogs in the US, and a hog was "nothing more than fifteen or twenty bushels of corn" (Holt and Craig, 2006). The rule on the farm thus became that as long as the price of twenty bushels of corn was less than the 200 pounds of various cuts that a hog could yield, it was profitable to feed corn to hogs. This created the hog-corn cycle. If the relative price of corn was low, farmers would breed more hogs. This behavior put upward pressure on the price of corn and once the hogs were delivered to the market their selling price would decrease. As the price ratio changed farmers would cut back on hog production; corn inventories would begin to accumulate; and the cycle would begin again.

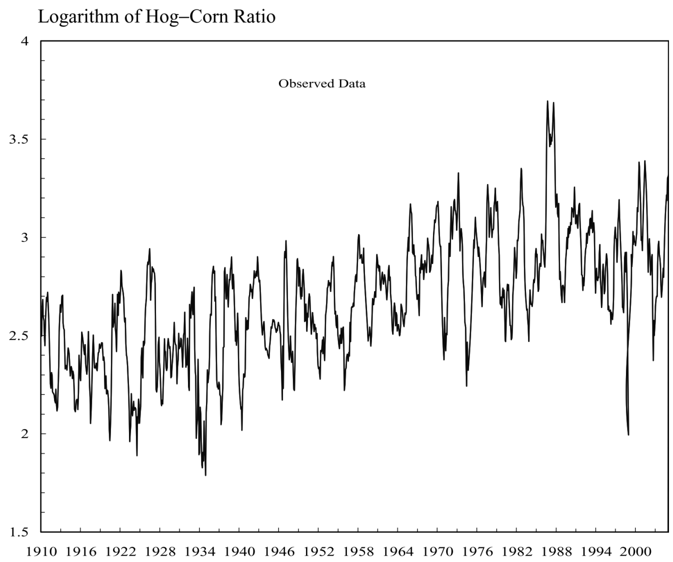

Figure 2.1: *U.S. hog-corn price ratio 1910-2006, illustrated by Holt and Craig (2006)*

The character of expectations and their effect on market dynamics in different circumstances have been extensively studied. Ezekiel assumed "naive" expectations, where future expected values are set equal to the latest observation of the corresponding variable. Nerlove (1958) suggested that farmers update their expectations over time in proportion to the latest prediction error. Prediction methods based on rules of thumb and past prices are often referred to as boundedly rational. In contrast to these, Muth (1961) proposed a rational expectation hypothesis, stating that decision-makers make efficient use of information, just as they do of other scarce resources. In modeling exercises this often translates into agents having full knowledge of future prices, less any random error term. As we might suspect, expectation formation is decisive for a model's stability. This explains why rational expectations models tend to ascribe the volatility of the economy to large outside shocks, while models with boundedly rational expectations attribute the volatility to the inherent features of the economy and/or relatively small outside shocks.

In controlled laboratory experiments Hommes et al. (2007) and Hommes (2011) found evidence that the rational expectations hypothesis is not an accurate description of realized prices in unstable cobweb-type commodity markets. Instead, they found that real agents use different simple heuristics, or rules of thumb, to predict future prices, and that a heterogeneous expectations model is crucial for explaining the market behavior.

A reason for agents using boundedly rational expectations could be that obtaining and processing information is costly. If the net benefit of obtaining and processing information is lower than the price of obtaining it, efficient use of information would actually be *not* to aquire it (Chavas, 2000). This was formalized by Brock and Hommes (1997) who presented a model of agents making a rational choice among prediction methods based on their past performance and the cost of using them.

If a cobweb-type market is unstable it is interesting to study how this instability affects other markets. In an agricultural setting, commodities may be interlinked on both the supply and demand sides since farmers can choose among different commodities to produce and once the products are on the market consumers may substitute between them. The supply side interaction of cobweb markets was studied by Dieci and Westerhoff (2009, 2010) who allowed producers to enter different markets. As exemplified by the authors, when a farmer decides to reduce his production of rye, he may alternatively expand his production of wheat. When cobweb markets interact in such a way, instability in any one market may destabilize the other one. There may even be cases when endogenous dynamics emerges although the markets in isolation would be stable. Connecting two simple markets that in isolation have linear supply and demand functions may produce long-run price fluctuations and even complex dynamics. The question of the stability of interlinked markets is investigated in papers I-III.

2.3 Equilibrium and optimization modeling

An economic equilibrium is a state where no actor has any incentive to change their actions or behavior. Prices and quantities of goods produced and consumed are consistent with the strategies and expectations of the agents acting on that market. It is common for models of both land-use and energy systems to assume that these conditions are met, which defines them as equilibrium models. An optimization model can be thought of conceptually as describing a world governed by a social planner who for instance maximizes social welfare.

If all agents in a model maximize expected profits, are well informed about internal and external factors affecting the market and the market is characterized by perfect competition without externalities, finding the equilibrium of the model can be done by transforming it into an optimization problem, where the objective function is the sum of consumer and producer surplus. Equilibrium modeling and optimization modeling can therefore in some cases both be used to solve the same problem, although it is important to remember that not all equilibria are optima, and not all optima are equilibria (as I already mentioned in Chapter 1). An example of this dubble approach possibility can be given in relation to the land-use model presented in papers I-III. Bryngelsson and Lindgren (2013b) showed that the model has a unique steady state, and that it can be found both by solving for the equilibrium and by maximizing the sum of consumer surplus and producer surplus.

There are two major types of models, common for the study of both agricultural and power markets, that use either market equilibrium or optimization as their general solution methodology: (i) macroeconomic models and (ii) partial equilibrium models (Knopf et al., 2013). Most of these models find intertemporal solutions through either a recursive dynamic solution methodology or with inter-temporal optimization. Macroeconomic models include computable general equilibrium (CGE) models which are solved recursively using market equilibrium conditions, and optimal growth models which are solved with optimization algorithms. Optimal growth models feature a representative agent with perfect foresight that maximizes lifetime consumption. Partial equilibrium models, the second type of model, only takes into consideration part of the market, e.g. the agricultural market or the energy market. Just as macroeconomic models, partial equilibrium models can be solved with either recursive dynamic equilibrium methods (e.g. GLOBIOM (Havlík et al., 2011), a model of the agricultural and forestry sector) or with intertemporal optimization (e.g. TIMES (Blesl et al., 2012) a partial equilibrium model of the energy sector). In paper V we present an intertemporal model of the power system that we solve by maximizing the sum of consumer and producer surplus.

As I mentioned, equilibrium modeling is a common approach when studying both agricultural markets and the energy market. In a review of 121 studies quantifying the impact of increased bioenergy demand on agricultural commodity prices 112 were either partial or general equilibrium studies (Persson, 2015). The energy modeling forum (EMF28) assesses the transformation of the European energy system with 13 modeling teams, all using different types of equilibrium models (Knopf et al., 2013).

2.4 Stability analysis

When dealing with dynamical systems it is often interesting to understand the stability of their trajectories. If a system is subject to a small perturbation, will it return to its initial state or diverge? The stability of our models is investigated in papers I-IV.

The stability of a dynamical model of an economy depends inter alia on the agents' prediction method and on the price elasticities of supply and demand. In a cobweb model with one single good the dynamics is unstable if agents use the "naive" prediction method and the demand curve is steeper than the supply curve. However, there are several factors that may stabilize the dynamics, such as different kinds of inertia as well as better informed agents. When several markets are interlinked, and agents are heterogeneous, the analysis becomes more complicated. If the agent-based micro-dynamics can be projected to a closed form dynamics of aggregate variables, like prices and quantities, the stability characteristics can be analytically approached by linearizing the system around the steady state. In paper III we discuss the model features that makes this kind of projection possible.

Chapter 3

Background

The models presented in this thesis are applied to land-use (papers I-III), beef production and the link between the beef and grain markets (paper IV) and finally power production (paper V). In this chapter I give a background to these fields.

3.1 Price volatility

Volatility in prices is of importance to both producers and consumers and is closely related to risk. In finance, volatility is measured as the standard deviation in returns of an investment. If an asset has high volatility in annual return, and this volatility is unpredictable, then the asset is risky. Most financial analysts start by observing past time series since it is reasonable to assume that portfolios with histories of high volatility also have the least predictable future performance (Brealey et al., 2011).

3.1.1 Price volatility in agricultural markets

Agricultural markets are prone to volatility. On the world cereal market, prices remained relatively stable for a few decades following the oil crises in the 70s, but took off again in vivid movements in 2007 (Fig. 3.1). In the cattle and hog sectors volatility has also long been observed, but with a more regular and long term cyclical behavior (Figs. 2.1 and 3.2).

The recent price movement in cereal has caused major concern due to the resulting welfare impacts on vulnerable poor. Episodes of high prices and extreme

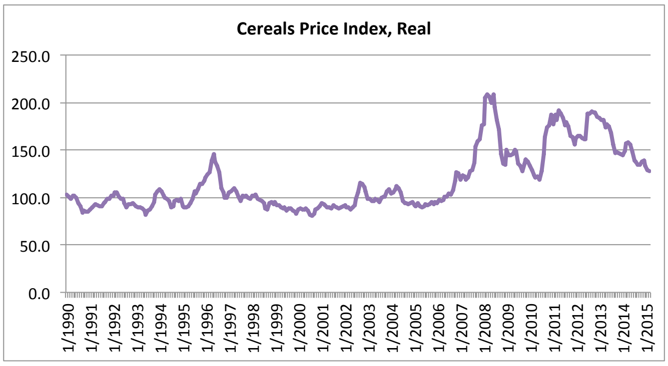

Figure 3.1: *Monthly food price indices (2002-2004=100).*
Data from http://www.fao.org/worldfoodsituation/foodpricesindex/en/, visited 2015.

volatility are a major threat to food security in developing countries. Their impact falls heaviest on the poor, who may spend well over 80% of their income on food (Prakash et al., 2011). Today, a number of developing countries such as Mali, Niger, Senegal, Burkina Faso and Lesotho, have diets with over 60% of calories coming from coarse grains and in countries with rice-based diets such as Bangladesh and Vietnam 70-80% of total food calories are derived from cereals. In the world as a whole, cereals account for 49% of the direct food consumption. Because of this, scholars have tried to understand the causes of the recent volatility.

The interest in the cattle and hog cycles has been more focused on understanding how biological lags naturally tend to create cycles in both stocks and prices. These cycles have been remarkably regular in their periodicity, over long time scales and in different regions of the world.

For natural reasons a large number of studies on food price volatility have been done since 2007/08 and a variety of factors have been identified to explain the recent fluctuations. Prices may of course be affected by simple singular events such as crop failure following extreme weather events or shock in demand from war or economic crises. But most of the important recent factors work in more intricate ways. We start with stocks, which are negatively correlated with cereal price. With very low elasticity of demand, a small shock in supply or demand may cause a large change in price, if stocks are low. This is what happened during the 2007/2008 food crisis since world grain stocks fell to very low levels by 2006 (Wright, 2012). A quickly increasing demand for bioenergy as fuel, coupled with a growing demand for meat in China and other countries, contributed

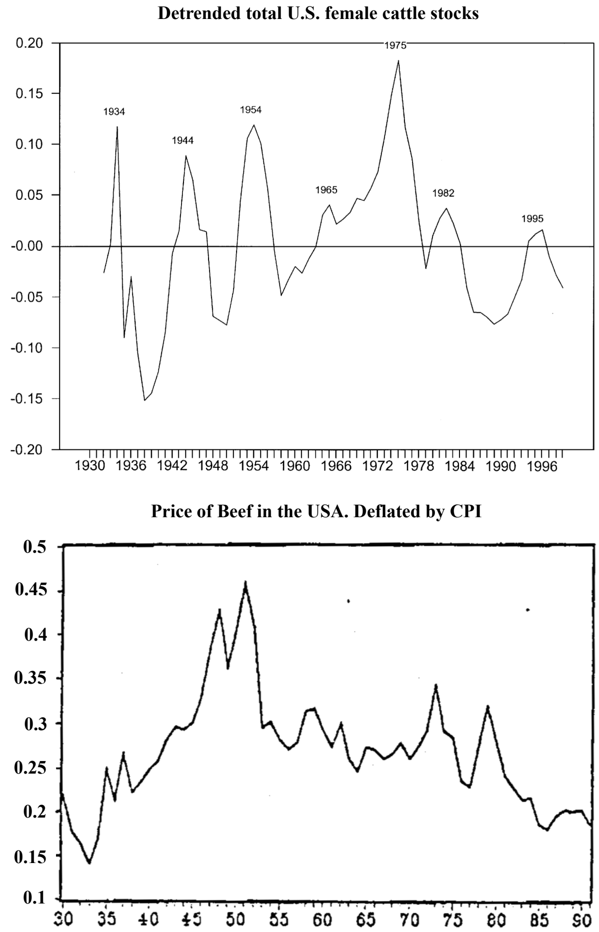

Figure 3.2: *Detrended total U.S. female cattle stocks (Aadland, 2004) and price of beef in the US, deflated by CPI (Mundlak et al., 1995). Both cattle stocks and prices fluctuate and show tendencies of a cyclical behavior.*

to the declining stocks. With jumping oil prices biofuel demand even exceeded mandates. Theoretically stock levels increase again as a result of price volatility, or at least as a result of *expected* volatility. If prices were believed to remain constant, there would be no incentive for competitive storekeeping given the cost of storing and the interest on capital. With increasing volatility and expected periods of elevated prices, keeping stocks once again becomes profitable. However, stocks themselves counteract the tendency of any price spike which may bring us back to a situation with low stocks. Another factor is speculation. When there is a highly liquid market for food commodities–i.e. when there is a large volume of trading opportunities–farmers benefit by having the choice not to bear the risk of selling their crops on the spot market. Instead they can hedge against the risk of a low spot market price through the futures market. Liquidity (defined as the number of contracts that have not yet been fulfilled through delivery) of commodities such as wheat, corn and soybeans began to increase around 2003/04. There was a short-lived decline in liquidity during the financial crisis, which began in the second half of 2008, but has since then recovered. Although the "efficient market" theory predicts that increasing the liquidity of markets also stabilizes prices, many scholars disagree. See e.g. Ghosh et al. (2012) who argue that trading volumes on the futures markets must be limited to stabilize food prices. Traders may be ever so well informed of market fundamentals but will still make the most rational investment by "anticipating what average opinion thinks average opinion to be", in the words of Keynes (1936). Bubbles could be initiated by a few irrational investors or a large-scale trader deliberately moving the market in a favorable direction. A final factor that I will mention here is policy interventions. An example is how a group of countries in 2007-2008, most notably India and Vietnam, restricted or even banned exports of rice causing the price to rise outside these countries (Slayton, 2009).

This account of events shows that fluctuations may emerge not only as a result of simple shocks in supply and demand, but also in more complicated ways where endogenous effects play an important role. In many cases the expectations of the economic actors are decisive. It is also clear that a specific agricultural sector cannot be studied in isolation, since market interactions transmit instability from one market to another, or even create instability where there otherwise would be none.

In the hog and cattle sectors there is another dimension to the dynamics: the dual nature of female animals as both a capital good (for their ability to produce offspring) and as a consumption good. Due to the lengthy biological lags, current breeding and consumption decisions have large effects on future stocks. These features have turned out to be important in explaining the observed cycles.

3.1.2 Price volatility in the power market

In the power markets there is volatility on two different time scales that are both of interest. On the shorter time scale there is price volatility over the course of the day. Demand is higher in the daytime than in the nighttime which usually leads to higher electricity prices in the day than at night. In power systems with a large share of solar and wind power, both which are intermittent and non-dispatchable, the power price may change quickly from hour to hour depending on the output of these technologies.

On the consumer side this volatility creates an incentive for demand response technology, e.g., dishwashers that remain idle until the electricity price is low. However, this would require a new type of metering system that measures end-consumption hour by hour and charges consumers in proportion to the hourly wholesale price. Small consumers' meters currently only record consumption with monthly resolution. On the supplier side price volatility is important for the level of activity on the intra-day market and on the balancing market. An increasingly important task for power system analysts is trying to predict the prices on these markets and choosing which of these markets to sell power on, hour by hour. In traditional hydropower and thermal systems, major changes in the production schedules set the day before delivery have been relatively rare. Acting on the balancing market can be an opportunity for flexible power plants that are able to quickly change output. Flexible generators are, for example, hydropower plants and combustion turbines that can be brought into service at very short notice. These types of power plants will probably be increasingly demanded in the future if variable renewable energy capacity continues to grow.

On a longer time scale there is a volatility in prices which affects the yearly profitability of power plants, or yearly returns on investments. Part of the explanation is that there is a tendency of investment cycles (IEA, 2016; Ranci and Cervigni, 2013). When profitability is low power companies halt investments which eventually leads to an increase in electricity prices. This triggers investments, and the cycle starts again.

3.2 World meat production

Meat production can be linked to both the average level and the volatility of grain prices. In paper IV we investigate cattle cycles and a possible link to grain price volatility. In this section I give an overview to world meat production, and more specifically to the cattle sector.

3.2.1 Overview

Pig, chicken and cattle dominate world meat production. Total production has been growing quickly (see Fig. 3.3a) and its volume is today four times as large as in the beginning of the sixties. The difference in growth is large, though, between the different meat types. Chicken has grown by a factor twelve, whereas cattle only has doubled. During the same period cereal production has grown by a factor three (see Fig. 3.3b), and the fraction consumed as feed has varied between 35-42%.

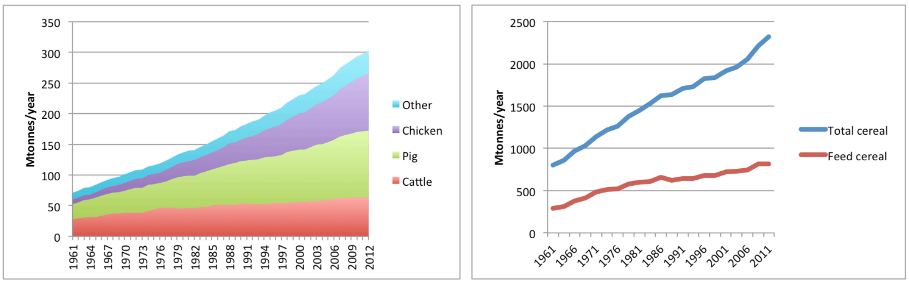

Figure 3.3: *(a) World meat production is dominated by pig, chicken and cattle. (b) A fraction of 35-42% of cereal production has been consumed as animal feed since the beginning of the sixties. Production of both meat and cereal has grown substantially in the last 50 years. (The figures are made with data from FAO Stat.)*

The pig sector is the largest contributor to global meat production. 61% of the pig production is specialized industrial farming where all of the feed is non-local (except in Sub-Saharan Africa where 25% of feed is local). Large-scale and market-oriented pig production systems have achieved a high level of uniformity in terms of animal genetics, feed and housing systems (MacLeod et al., 2013). 95% of the production takes place in East and Southeast Asia, Europe and the Americas. Industrial pigs are kept solely for meat production, i.e. there are no by-products with economic value.

Industrial chickens are either broilers (chickens reared for meat) or layers (chickens kept to produced eggs for human consumption). All of the feed used in industrial systems are non-local. Specialized layer systems contribute to only 6% of total poultry meat production, and this share is used for pet food or animal feed rather than for humans. Chicken systems, just as the industrial pig systems, are relatively homogenous and standardized compared to cattle. The chicken meat production is particularly high in Latin America and the Caribbean, North America, and East and Southeast Asia.

Cattle are reared in quite diverse systems ranging from grazing to mixed livestock-crop systems. The mixed systems dominate, with about 79% of beef production and 85% of dairy cattle systems. Beef production occurs both in dedicated beef herds without milk production (56% of beef production), and in dairy cattle herds (44% of beef production) where surplus calves are raised for beef and also culled cows are used for meat.

Cereal feed use for pig, chicken and cattle currently account for about 32% of world cereal production according to our estimation. The share is higher if residues are included (see e.g. Wirsenius et al. (2010)). Although chicken is a very efficient animal in terms of feed conversion ratio, it stands for the largest part of cereal demand by weight among the three animal types, if layer systems are included. This is due to the high volumes of chicken meat and egg production. (Feed conversion ratio is the efficiency with which the animal herd converts feed into tissue.) The numbers that we have based the cereal feed consumption on are given in sections 3.2.2 and 3.2.3.

From now until 2050 world aggregated demand for meat is projected to grow at only half the rate of the past 50 years, according to Alexandratos and Bruinsma (2012). The reason for this is slower population growth and lower growth of per capita consumption in the developing world. China and Brazil both increased their per capita meat consumption hugely starting in the 1970s and are unlikely to continue increasing their meat intake at the same rate. It is not believed that any other developing country will have the same kind of consumption explosion. India will probably increase its poultry consumption somewhat, but pig and cattle will face cultural constraints in much of South Asia. The growth in dairy products, on the other hand, is expected to show little decline.

In the last 50 years the feed use of cereals has been growing more slowly than the livestock production for three reasons. Firstly, the share of the poultry sector in the total meat production has been growing. Secondly, an increasing share of the cattle systems are found in developing countries which are less feed grain-intensive. Thirdly, there has been a shift towards more oilcake in the feed rations. However, it is believed that this gap in growth rates will be reduced in the future, partly due to developing countries increasingly shifting from grazing and backyard systems to grain-intensive industrial systems. All in all, Alexandratos and Bruinsma (2012), project the share of cereal being used for feed to be about the same in 2050 as today.

3.2.2 Demand for cereal as feed

Table 3.1 gives an overview of the three major animal types in the global meat sector (pig, chicken and cattle) and their contributions to cereal demand. The feed conversion ratio (FCF) is given as kg dry mass intake/kg live weight (LW) or carcass weight (CW) output. The FCR includes the feed consumed by mature breeding animals that are not growing, or are growing slowly. The ration composition and FCR refers to industrial systems in the cases of pig and chicken whereas for cattle they are global averages. The ration shares are based on mass on a dry matter basis. W.d.g. stands for wet distillers grain.

A difference between pig and chicken on the one hand and cattle on the other is that the industrial pig and chicken systems are fairy homogeneous throughout the world, whereas the cattle sector is very heterogeneous. The FCR of dairy cattle is not given since there are two co-products: meat and milk. As a reference though, the dairy system is around four times as efficient as the beef system in transforming feed into protein.

The feed row shows how much cereal is demanded by the different systems, and their shares of global cereal production. (Grains and cereal by-products are counted together.) Here the feed demand is given as the current total demand including non-industrial production.

The country lists show the countries with larges production based on weight, for pig. The broiler column gives the countries with largest production of chicken meat (including layer meat and backyard systems). In the layer column are countries with largest egg production. In the beef column are the countries with biggest cattle meat production (from both beef and dairy systems), and in the dairy column are the countries with larges milk production.

Ration composition and FCR are taken from MacLeod et al. (2013) for the monogastrics and Opio et al. (2013) for cattle. Production is taken from FAOSTAT. Our calculation of feed use give that pig, chicken and cattle together represent 32% of world cereal demand. According to Alexandratos and Bruinsma (2012), the world feed use of cereals accounts for 36% of total cereal use. Our lower value may be due to the fact that we only consider pig, chicken and cattle, and leave out e.g. buffalo, small ruminants and other poultry apart from chicken.

Table 3.1: *Global production of pig, chicken and cattle.*

	Pig	Chicken -broilers	-layers	Cattle -beef	-dairy
Production	66.6	84	5.3 (meat)		
-industrial			56.9 (eggs)		
-total	109	93 (all meat)	66 (all eggs)	35.4	27.7 (meat)
(Mt/y)					626 (milk)
Ration					
Cereal					
-grains	**66%**	**67%**	**64%**	**8.0%**	**9.0%**
	Maize grain	Maize grain	Maize grain		
	Wheat grain	Wheat grain	Wheat grain		
	...	...	...		
-byproducts	-	-	-	**0.9%**	**2.4%**
				bran	bran
				w.d.g.	w.d.g.
Oilseeds	**21%**	**26%**	**19%**	**2.7%**	**5.8%**
	Soybean meal	Soybean meal	Soybean seeds	meal	meal
FCR (LW)	2.7	2.0	2.3 (eggs)		
(CW)	3.7	2.8		74	
Feed (Mt/y)					
Cereal	252	184 (meat)	104 (eggs)	146	127
Share of world prod.	9.8%	7.2%	4.0%	5.7%	4.9%
Countries	China	USA	China	USA	USA
	USA	China	USA	Brazil	India
	Brazil	Brazil	Brazil	China	China
	Germany	Russia	Japan	Argentina	Brazil
	Vietnam	Mexico	Russia	Australia	Russia
	Spain	Brazil	Mexico	Mexico	Germany
	Russia	Iran	Brazil	Russia	France
	Mexico	Indonesia	Ukraine	France	NZ

3.2.3 Cereal as cattle feed

Tables 3.2 and 3.3 show some regional specifics of the beef and dairy cattle systems. The feed conversion ratios (FCR) are given as kg dry mass intake/kg protein output. As opposed to the industrialized pig and chicken systems, the cattle systems are very heterogeneous. The most efficient systems are found in North America, Europe and Oceania whereas production in South Asia and Sub Saharan Africa are particularly inefficient. Cereal consumption for feed is especially high in North America, despite the efficient systems, both due to the large production of meat and milk, but also due to the high share of cereal in the feed rations. Cereal consumption for feed is also fairly high in Latin America and the Caribbean, despite the low share of cereal in the feed rations, since the production of primarily meat is very high.

Table 3.2: *Beef cattle*

	Meat (Mt)	FCR (protein)	Cereal/ration	Cereal (Mt)
N. America	9.9	180	17%	56
Russia	0	-	-	-
W. Europe	2.2	150	12.3%	7.5
E. Europe	0	170	14.0%	0.1
NENA	0.1	425	0.9%	0.1
E & SE Asia	6.7	470	4.4%	26
Oceania	1.7	220	17.5%	12
South Asia	1.0	1625	0.1%	0.3
LAC	12.0	405	4.8%	43
SSA	1.7	1175	0.1%	0.4
World	63			

3.3 Connecting food, feed and bioenergy

There are two main factors that connect the markets for food, feed and bioenergy, which are both considered in this thesis, (see Fig. 3.4). The first is agricultural land which is a common but limited factor of production for food crops, pasture and bioenergy crops. The second is cereal, where the end-use can be either direct human consumption, feed for animals or feedstock for first generation bioenergy production.

Bioenergy is part of many scenarios of a future sustainable energy system. See, e.g., Deng et al. (2011), Azar et al. (2010) and Pacala and Socolow (2004).

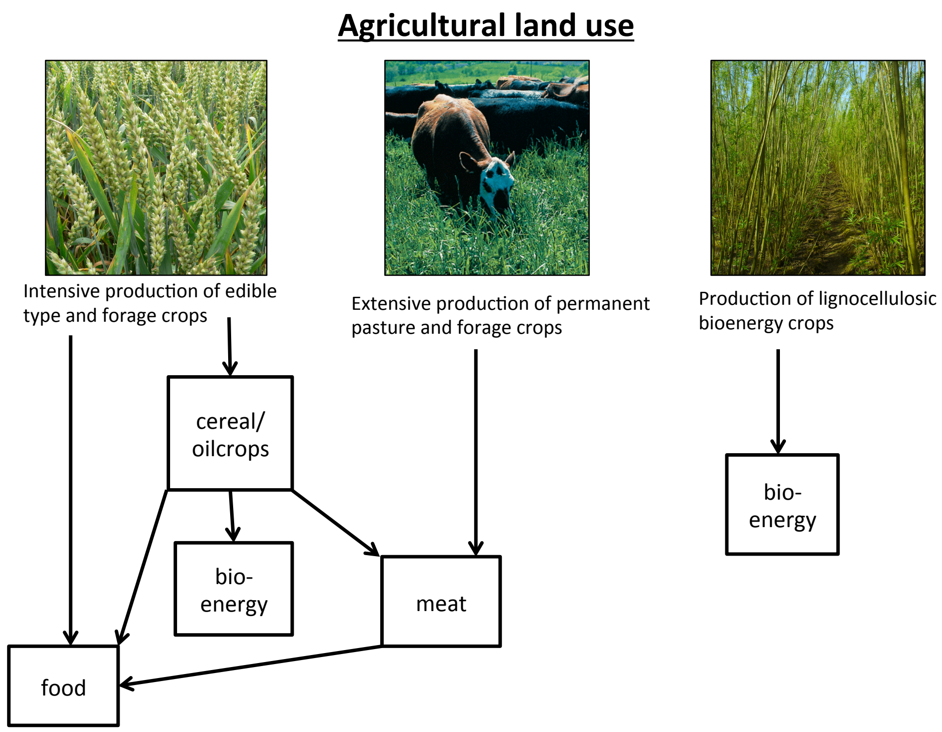

Figure 3.4: *Land and cereal link the markets of food, feed and bioenergy.*

Table 3.3: *Dairy cattle*

	Milk (Mt)	Meat (Mt)	FCR (protein)	C/R	Cereal
N. America	99	3.1	30	31.5%	37
Russia	32	1.6	60	10.1%	8.4
W. Europe	137	5.2	30	15.2%	26
E. Europe	42	1.3	35	12.1%	7.1
NENA	56	4.0	150	0.8%	3.2
E & SE Asia	52	2	75	7.7%	12
Oceania	30	1	40	14.3%	6.9
South Asia	77	1.5	200	0.2%	1.2
LAC	82	5.4	120	5.3%	24
SSA	20	2.5	400	0.2%	0.9
World	626				

It is expected that lignocellulosic biomass will be the major future feedstock, with the potential consisting both of residues and dedicated bioenergy plantations. In the more biomass-intensive scenarios dedicated plantations will be a requirement (Berndes et al., 2001). This brings us to land, our first issue, since energy crops such as miscanthus, willow and eucalyptus will compete for agricultural land with other uses such as food production and pasture. A conceptual partial equilibrium model of global land use was developed by Bryngelsson and Lindgren (2013a) to explore the long-term effects of large-scale introduction of bioenergy, under different policy cases. The model includes three types of agricultural land use: intensive production of edible-type and forage crops (IP), extensive production of permanent pasture and forage crops (EP) and production of lignocellulosic bioenergy crops (BE). They find that a large-scale introduction of bioenergy would raise food prices in all of their cases/scenarios investigated. If bioenergy production is restricted to “marginal land” the price impact on food is dampened, but incentives would be high for farmers with more productive land to cheat and also produce bioenergy crops. The division of land use into these three types of land use is adopted in Papers I-III.

The second factor connecting food, feed and bioenergy is cereal. About 36% of world consumption of cereals goes to feed. The share of cereals for biofuels was 3% in 2005, or 65 million tonnes, but is projected to increase to 180 million tonnes in 2020 (Alexandratos and Bruinsma, 2012). The effect on food prices of using cereals for biofuels has been investigated in a number of studies. Their conclusions deviate, though, as shown by Persson (2015). (The majority of the studies reviewed by Persson focus on the increased demand for corn ethanol in the US.) It is clear that the demand for cereal feed also affects food prices, at least in the short term. A way of exploiting this fact to hedge against food price spikes was proposed by Wright (2012) who suggested that option agreements between governments and animal feeders (or biofuel producers) could enable a diversion of grain from meat (or biofuel) production to human consumption in times of cereal shortage. However, Locke et al. (2013) showed that any grain diversion scheme in a developing country with vulnerable poor is unlikely to affect domestic grain prices if not export bans (in grain exporting countries), or mandatory import quotas (in grain importing countries) are imposed.

3.3.1 Biological lags and the emergence of cycles

The existens of hog cycles was observed as early as 1818 (see section 3.2.3). Cycles in prices and quantities of cattle were also observed and documented, at least as early as 1876 (Mundlak et al., 1995). As we have seen, Ezekiel explained the hog-corn cycles with naive expectations in markets with linear supply and demand. The reality is of course more complicated. Hogs and cattle may be slaughtered over night in response to market signals, but producing them again takes considerably longer time (Holt and Craig, 2006).

Jarvis (1974) pointed out that higher beef prices should induce rational farmers to increase the slaughter age. (With higher prices it is worth the extra effort of keeping the animals alive a bit longer, even though the marginal weight gain decreases.) The short-term effect of a price increase should therefor be a reduction in slaughtered animals. This contrasts with the supply respons of most other agricultural products, for which there is normally no reason to expect output to fall when prices increase.

Rosen (1987) backed up the hypothesis of short-term negative supply response, but only when the change in demand is expected to be permanent. An important mechanism in his model is the dual nature of female cattle as both a capital good and a consumption good. If the future meat price is expected to be high the rational farmer would save a larger share of the young females to increase the size of the breeding herd, thereby reducing the short-term supply of meat to the market.

Important for the cycles are the biological lags in the production of hogs and cattle. Rosen et al. (1994) showed that this feature made it possible to have regular cycles in the aggregate cattle stocks in respons to exogenous shocks, even when ranchers are perfectly rational and profit maximizing. This is not to say, though, that ranchers necessarily *are* perfectly rational and profit maximizing.

Aadland and Bailey (2001) differentiate between fed and unfed beef, the former being high quality meat from younger animals finished in feedlots, while the latter is lower quality beef from adult cows. With this assumption, and by keeping track of the age distribution of the stock Aadland (2004) manages to get a closer fit to real world cycles. The model presented in Paper III is inspired by Aadland.

3.4 Investment in the power sector

Over the last 20 years the electricity markets in the advanced economies have undergone a liberalization, abandoning their status as national monopolies (Ranci and Cervigni, 2013). Investment in new power capacity is now governed by expected profitability as opposed to the traditional approach, where investment responded to reliability and resource adequacy requirements. Engineering standards specified the acceptable hours of load shedding, based on the expected load variance and generator availability. In the present system investment in new capacity is made when the discounted revenues from the sale of electricity and ancillary services are expected to cover the investment cost, i.e., when the project has a positive net present value *(NPV)*.

In this chapter I discuss what discount rate an electric utility might use when assessing an investment opportunity, and how this discount rate relates to the perceived risk of the project (section 3.4.1). (However, I do not go into *how* the level of risk is determined.) The important point is that investors generally use a higher discount rate than the *social rate of discount* (explained in section 3.4.2). What discount rate to use in a modeling exercise depends on what the purpose of the study is. Are we trying to mimic the behavior of real market actors? Are we evaluating energy systems costs from a societal perspective? Are we perhaps assessing the potential of policy measures to improve the institutional environment for investors so that their risks are lowered?

The choice of discount rate tends to play a large role for the model output. Iyer et al. (2015) show that the carbon price needed for a certain CO_2 emissions target increases significantly when a more realistic representation of investment risk is adopted in an integrated assessment model, instead of using a modest and homogenous discount rate across all technologies and regions of the world.

In section 3.4.3 I discuss what selection rule is reasonable to implement in an ABM when agents choose among different projects to invest in. Even if we have decided what discout rate to use, and even if we want to model agents as simply maximizing expected profit, the choice is not trivial and it is a question that we spent a lot of time on when working with paper V. If agents simply choose the project with the highest *NPV* (assuming it is positiv), the model will exaggerate the expansion of large power plants and disfavor small ones. Richstein et al. (2014) solve this problem by letting agents select the power plant with the highest *NPV* per MW capacity. As you will see, we have chosen another route.

3.4.1 Risk and discount rates

The first criterion for electricity utilities when considering an investment opportunity is that it has a positive *net present value*, NPV. Let P denote a specific project under consideration, say an investment in a new power plant. If the investment cost and the future net cash receipts each year during the project's lifetime are known, the NPV of the project is

$$NPV(P) = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - I \tag{3.1}$$

where
$C_t =$ the net cash receipt during year t
$I =$ the initial investment
$T =$ the project's duration in years
$r =$ the discount rate, in this case the return on the best alternative safe investment in the financial market, which is foregone by instead investing in the project.

However, the revenues from the project are uncertain since the future electricity price is unknown, and the project also involves other risks. Should the power company undertake the project or not? A theoretical approach to choice under uncertainty is the expected utility model (Von Neumann and Morgenstern, 1944). The expected utility (u) of the project is

$$Eu = Eu(NPV(P)). \tag{3.2}$$

The utility function u of an investor is typically concave, which means that gaining 2 M€ is less than twice as good as gaining 1 M€. Why is it important to consider the expected utility of the project's *NPV*, and not the utility of the expected *NPV* of the project? Let us look at a simple example. Assume that a certain project can have two possible outcomes: it can cause a stream of costs and revenues with a *NPV* of either plus or minus 1 M€. Let us assume that both outcomes have equal probabilities so that the expected *NPV* of the project is 0 M€. Suppose that a 1 M€ loss would force the company to declare bankruptcy, but a 1 M€ gain would simply make the company somewhat better off. In this case it is obvious that the expected utility of the project's *NPV* is negative while the utility of the expected *NPV* of the project is zero. Using the expected utility method is therefore a way of handling risk. A standard constant elasticity utility function is

$$u(c) = \frac{c^{1-\eta}}{1-\eta} \tag{3.3}$$

where η is a measure of risk aversion and c in our case is the *NPV* of the project. $\eta = 0$ gives a linear utility function and complete risk neutrality while $\eta > 0$ is consistent with risk aversion. The observed behavior of financial actors implies a value of $1 \leq \eta \leq 5$ (Kolstad et al., 2014).

However, most companies do not perform this analysis but instead take a shortcut by simply calculating the *NPV* of investment opportunities with Eq. (3.1) using a discount rate that is substantially higher than the risk-free market interest rate. The proper discount rate to use in this case is the return offered by the best alternative risk-equivalent investment in financial markets (Brealey et al., 2011). This is the opportunity cost of capital since it is what you are giving up by investing in the risky project.

A rationally chosen discount rate is therefore project specific and depends on project risk, *not* on the company undertaking the project or on *how* the project is financed (with internal financing, debt or equity). In practice, however, it is often difficult for companies to determine the exact level of risk of a specific project. Therefore companies usually use the *company cost of capital* as a benchmark for the internal discount rate (Brealey et al., 2011). The company cost of capital can be defined as "the expected return on a portfolio of all the company's existing securities" and can be calculated as a weighted average of the company's cost of debt and cost of equity. For a project that is equally risky as the average of the company's other assets, the company cost of capital is the right discount rate. For projects of other levels of risk the company makes a subjective judgment on how much to add to, or subtract from, the company cost of capital. In the power market each plant type has its own risk profile that is also strongly affected by the overall capacity mix of the market (Tietjen et al., 2016).

3.4.2 The social rate of discount

The social rate of discount is used to evaluate the social value of long term projects such as education, roads or public infrastructure in general. It is used both for the *ex ante* decision of whether a specific project should receive funding, and the *ex post* evaluation of its performance. As Kolstad et al. (2014) explain, the social discount rate can be determined with either a descriptive or a normative approach. With a descriptive approach the way to determine its value is to empirically examine at what rate society is willing to postpone a unit of current consumption in exchange for more future consumption. A common assumption is that the market interest rate reveals these preferences. If this assumption is accepted the social discount rate should be set equal to the real returns on safe investments such as government bonds (which is assumed to be equal to the risk-free market interest rate). The choice of market interest rate as the social rate of discount can also be made using an arbitrage argument. If a project gives a smaller return than the risk-free market interest rate, the capital could have been better spent investing it in the government bonds. The arbitrage argument can be motivated when projects are financed by a reallocation of capital, but not when they are financed by an increase in aggregate saving (reduced current consumption). See e.g. Zhuang et al. (2007) for more details.

Using the market interest rate as a descriptive approach to determining the correct social rate of discount has its drawbacks. For several reasons it does not reflect true preferences of society. Market actors have difficulties of both obtaining correct information and making rational decisions under uncertainty, and they also tend to be more impatient than what is sensible (Diamond, 1977). The descriptive approach is also problematic since it merely captures the impatient attitude of current consumers toward transferring their *own* consumption to the future, not the preferences of individuals when they see themselves as part of society. When analyzing situations with more than one generation involved (time horizons of more than 30-40 years) there are good reasons to treat the choice of social discount rate as a normative problem (Kolstad et al., 2014; Zhuang et al., 2007).

The standard method of calculating the social rate of discount with a normative approach is to use the Ramsey rule (Ramsey, 1928):

$$r = \delta + \eta g \tag{3.4}$$

where r is the social discount rate, δ represents the pure time preference, η is the elasticity of the marginal utility of consumption (as in Eq. 3.3) and g is the long-term average real GDP growth per capita. The choice of g is a matter of making an informed prediction, while the choices of δ and η involve normative value judgments (although some scholars do attempt to derive these values empirically with different creative approaches (Zhuang et al., 2007)). When summarizing the views of "prominent authors and committees" on δ, η and g, the IPCC finds recommendations for the social discount rate r in the range of 1.4-16%/year, with most recommendations $\leq$ 6%/year (Kolstad et al., 2014). In practice there are several more ways of determining the social discount rate than what we bring up here, some being quite elaborate. Zhuang et al. (2007) gives a thorough review of what policy practices are actually followed by countries around the world in this matter.

In a model aiming both to predict the effect of different policies and to evaluate the outcome for society, a risk adjusted discount rate should be used to mimic the behavior of real actors, while the social rate of discount should be used for the ex-post evaluation of the outcome.

3.4.3 Prioritizing among projects

In an interview with representatives of Dutch power companies about their investment strategies, Groot (2013) found that an important goal is to select projects with a positive *NPV*. The study found that many other considerations also are taken into account before an investment is made. Among these are to maintain a healthy cash position, which puts a limit on the number and size of investments that a single company commits to. Some actors also find it important to not "do worse than the competition", which leads to an imitative behavior. Some actors wish to increase their experience level of a technology that is new or unknown to the company, e.g., renewable energy technology. In many cases a portfolio approach is adopted. Companies with a large market share may refrain from investing in a new power plant if the merit order effect reduces profitability of the company's old plants. Roques et al. (2008) note that for large electricity generators the optimal strategy, depending on the character of the market risk, may be to invest in a diversified plant portfolio.

The agent-based approach is well suited to included the kinds of investment criteria stated above. In our first study of investors in the power market we limit agents to maximizing expected profits, with no portfolio approach. The basic rule, according to theory, when assessing an investment opportunity is to accept it if its *NPV* is positive and otherwise reject it. However, in practice a company may have many different investment opportunities with positive *NPV* and if it is not possible to undertake them all at once the company will want to start with the most attractive one. At first thought it may seem obvious that the project with the highest *NPV* is the most attractive. However, with this reasoning a small power plant may never be built even if its return on investment is high.

One starting point is to assume that financial resources are limited, i.e., that there is *capital rationing*. For large corporations capital is generally *not* limited since they easily can raise large sums of money on fair terms. Why then do we need to consider capital rationing? Brealey et al. (2011) explain:

> "Many firms use soft capital rationing, that is, they set up self-imposed limits as a means of financial planning and control. Some ambitious divisional managers habitually overstate their investment opportunities. Rather than trying to distinguish which projects really are worthwhile, headquarters may find it simpler to impose an upper limit on divisional expenditures and thereby force the divisions to set their own priorities. In such instances budget limits are a rough but effective way of dealing with biased cash-flow forecasts. In other cases management may believe that very rapid corporate growth could impose intolerable strains on management and the organization. Since it is difficult to quantify such constraints explicitly, the budget limit may be used as a proxy."

When capital is scarce the choice of investment opportunity should fall on the project with the highest return on investment, or *profitability index*, where

$$profitability \quad index = \frac{NPV}{I}. \tag{3.5}$$

However, this method is not necessarily the best if new investment opportunities arise in the future and resources are constrained in more than one time period. In that case it may be preferable to select a project that generates early rather than late revenues so that this money can be re-invested. If two projects have equal profitability indices but different lifetimes, it is generally better to choose the one with the shortest lifetime. If all present and future investment opportunities are know, the optimal strategy can be found by working through all possible combination of projects to see which one maximizes the total combined *NPV*, given whatever constraints there are. Alternatively, a linear programming technique can be used which is usually quicker and easier. In paper V we simply let agents select the project with the highest annuity of the return on investment, i.e., the highest

$$\frac{CRF * NPV}{I} \tag{3.6}$$

where

$$CRF = \frac{r(1+r)^T}{(1+r)^T - 1} \tag{3.7}$$

is the capital recovery factor, T is the lifetime of the project and r is the discount rate, as before.

In real life not all companies behave in an economically sophisticated way. In a survey with 392 Chief Financial Officers Graham and Harvey (2001) found that 57% of them always or almost always use the payback period as a capital budgeting technique, even though this method ignores the time value of money and cash flows beyond the cutoff date. Only 12% of the Chief Financial Officers reported that they always or almost always use the profitability index. Investigating different investment criteria in an ABM is an interesting topic for a possible future study.

Chapter 4

Paper overview

4.1 Interacting cobweb markets

In papers I-III we take a land use model developed by Bryngelsson and Lindgren (2013a) as our point of departure and transform it into an agent-based model where the agents are farmers, each possessing land of different quality. The agents, in their production decision may choose among three generic crop types: intensively produced edible-type and forage crops (IP), extensively produced permanent pasture and forage crops (EP) and bioenergy crops (BE). In the first two papers we assume that all crops are put on a global market after harvest, where their prices are determined. In paper III we assume that the world is divided into different regions and that all harvested crops are offered at the regional market. Trade is allowed between these markets, but is associated with a transportation cost.

In paper I we apply the model to three cases with different bioenergy demand. Since land is a limited factor of production and agents can choose what market to enter, these markets are connected on the supply side, as explored by Dieci and Westerhoff (2010). We consider two types of predictor functions, in the style of Brock and Hommes (1997): "naive" and "rational", the latter having perfect information about next year's prices. We have two aims with the paper. The first is to extend the research on interacting cobweb markets that was initiated by Dieci and Westerhoff (2010), by applying a model of such a system to the question of competition for land between bioenergy and food production. The second is to introduce a new combination of heterogeneity that includes both production capabilities and price expectations to the cobweb model, which has not been done before.

We show that our model is highly unstable, which can be illustrated by Figs. 4.1 for one of our bioenergy cases. The graphs show the profits of growing each of the three crops on land of relative quality Y. Since the agents try to maximize profits, the most attractive crop on land of relative quality Y is the one with highest profit. The bottom panel shows the profitability in equilibrium, the upper left panel the profitability if prices are 15% below equilibrium, and the upper right panel the profitability if prices are 15% above equilibrium. We can see that relatively small changes in prices have large effects, on many pieces of land, on which crop is the most profitable to produce.

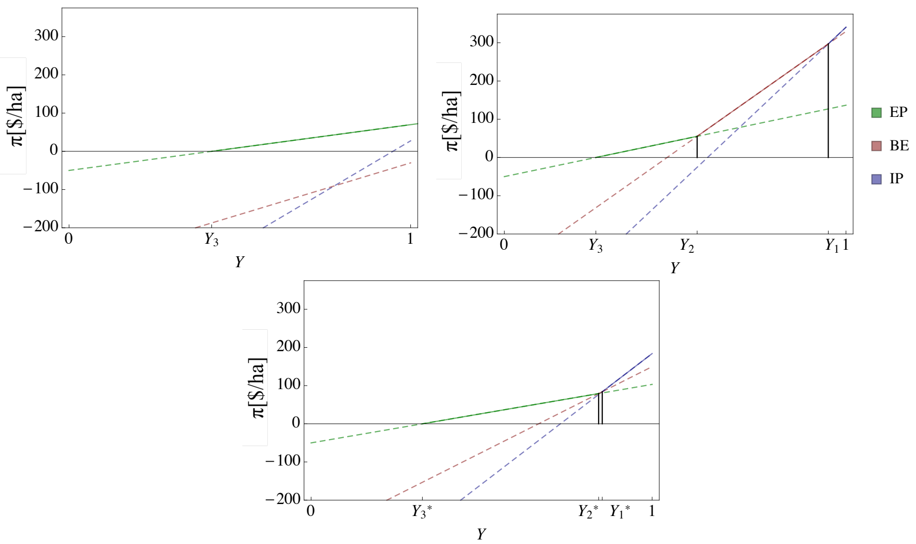

Figure 4.1: *Profitability for each crop type, on different land qualities, given that prices are 15% under equilibrium prices (upper left panel), at equilibrium prices (bottom panel), and 15% above equilibrium prices (upper right panel).*

In the paper, we show that, under certain circumstances, the agent-based dynamics can be projected to a dynamic based on aggregate quantities (and prices). This allows for a deeper analysis of the stability characteristics of the model. Two of the factors that influence the stability are the fraction of producers that have the opportunity to change crops at each time step (γ), and the share of rational agents (ρ). In the case when we have a uniform, and constant, distribution of the rational and naive agents, we show that an increasing fraction of naive agents tends to increase the volatility, while if the rational agents have a share that exceeds 50%, the system is always characterized by a stable steady state. If the fraction of agents allowed to change crops at each time step (γ) is sufficiently small, the steady state is stable regardless of which of the prediction methods the agents use. These results can be formalized in the following proposition which we present in papers I and III:

Proposition:

We consider the case when the quantity dynamics is unstable and characterized by real-valued eigenvalues $\lambda_j < 1$ and the most dominating one $\lambda_1 < -1$ when all agents are naive ($\rho = 0$) and all may change crops each time step ($\gamma = 1$). Now, assuming general values for the parameters γ and ρ, let $q(t)$ denote the quantity dynamics. The steady state q^* is stable if

$$\rho > \frac{1}{2} - \frac{2-\gamma}{2\gamma(-\lambda_1)}. \tag{4.1}$$

In a model extension we let agents dynamically choose predictor strategy, as in Brock and Hommes (1997), we find that the more costly "rational" predictor is concentrated on some key parcels of land, where fluctuations in what is produced otherwise would be very high (see Fig. 4.2). This enables the model to stabilize with a relatively low fraction of "rational" agents, which benefits agents also on other parcels of land, who themselves use a "naive" predictor. However, this adaptive dynamics in choice of predictor strategy can in itself cause boom and bust cycles.

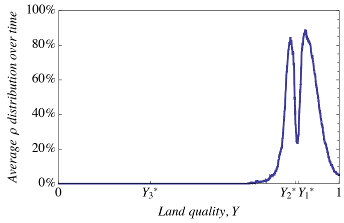

Figure 4.2: *Time averaged distribution of rational agents as a function of land quality. The rational agents are more frequent on land qualities where there is larger instability in terms of which crop is most profitable.*

In Paper II we extend our analysis of market interaction by also including demand side interaction. This link materializes when consumers are willing to substitute one good for another. This means that there is a cross-elasticity of demand between them, and the price of a good depends on the supply of *both* of the goods. In this version of the model we convert the generic crops in Paper I to generic crop *categories*, and allow more than one generic crop within each category. The reason for this is that we are interested in how larger number of crops would affect the dynamics of the model since many applied equilibrium models used for bioenergy assessments generally have a quite extensive set of crops (see e.g. Havlík et al. (2011)).

The aim of the paper is to answer the question of how much our system is destabilized by increasing the number of crops, and how much a "link" on the demand side (through substitutability of commodities) counteracts this destabilization.

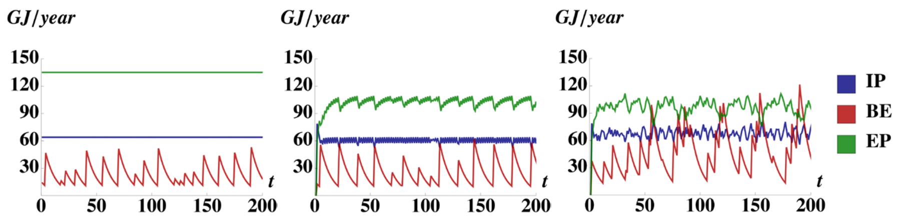

Figure 4.3: *Fluctuations in prices and quantities produced for different levels of supply side linkage.*

In the simulations we randomly allow 10% of the agents to switch crop each time step, with each time step representing a year. Fig. 4.3 illustrates the effect on model dynamics of providing increasing amounts of options to the agents (farmers) in their production decisions. In the left and center panels we have one single crop in each generic crop category. In the left panel agents are not allowed to choose which of these to produce, only if they will produce a certain designated crop or not. We can see that the markets for IP and EP are in isolation stable, whereas the BE market is highly unstable. In the middle panel the three crop types are "linked" on the supply side, as in Paper I. Quantities produced of all the three crops now exhibit non-periodic fluctuations over the years. We can deduce that the instability of the system is a result of BE being present as a land use option. The instability of the BE market is transferred to the IP and EP prices when the three markets are interlinked. In the right panel we have divided each generic crop category into four crop types, without any demand side substitution between them. The figure shows the total quantities produced of each generic crop category. We can see that the total quantities produced in each crop category is much more volatile than when there was only one crop within each category.

We now investigate whether a link on the demand side (i.e., a cross-price elasticity of demand between crops in the same category) can mitigate the added variability. We vary the degree of substitutability, from completely independent goods to perfect substitutes. Fig. 4.4 shows the standard deviation in prices, when there is either one or four crops in each category. In the left panel we show the extreme case with no cross-elasticity of demand between the crops (also corresponding to the center and right panels of Fig. 4.3). The right panel shows the other extreme, when the crops within each category are perfect substitutes.

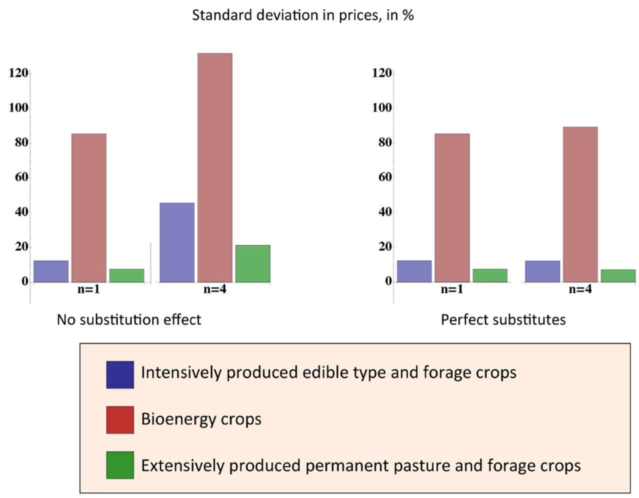

Figure 4.4: *Standard deviation of prices, in percent, for IP, BE and EP with each generic crop category divided into 1 or 4 sub crops. In the left panel crops are completely independent, whereas in the right panel crops within each category are perfect substitutes.*

We find that with perfect substitutability the number of crops within a crop category is essentially irrelevant for system stability. We conclude that in any study of price fluctuations in a cobweb model of land use the supply and demand side representations are vital for the outcome. Supply side interdependency tends to increase price fluctuations while demand side interdependency tends to reduce price fluctuations.

In paper III we discuss further the model features that make it possible to project the agent-based micro-dynamics to a closed form dynamics on the level of aggregate quantities. The projection from a high dimensional agent-based dynamics to a low dimensional dynamical system allows for the stability characteristics to be analytically approached. We show that even though our system is highly non-linear and the agents are heterogeneous (both in respect to production capacity and with respect to how they make price estimates as a basis for production decisions) the projection to a closed form dynamics is possible. The projection would also work if agents are allowed to invest in production efficiency, not only what crop to grow.

A prerequisite for the projection to work is that individual agents keep the same piece of land and the same prediction strategy over time. Also, the agents' choice of crop to grow, or choice to invest in production efficiency, must only depend on the price feedback from the market and not, for instance, on which product the agent had in the previous period or on any information exchanged between geographic neighbors. In paper I we let agents switch prediction methods over time, and as we saw the agents' tendencies to choose the "rational" prediction strategy depended on what quality of land they have. This is an example of a case when the ideal projection to a closed form dynamics does *not* work. In these types of model settings where the projection is not possible, it could still be interesting to see whether an approximate aggregate dynamics could function in a reasonable way.

4.2 Cattle cycles

In paper IV we present a model of beef cattle dynamics based on decisions taken by boundedly rational farmers. Decisions concern whether calves should be sent to feedlot for meat production or whether they should be saved for the breeding herd. Decisions are also taken on the culling from the breeding herd. Two types of meat are produced in this system: the fed meat from the calves selected for feedlot and unfed meat from the culled cows. We systematically examine the parameters determining the agents' expectations and decision mechanisms, and their impacts on the dynamics. These are a weighting parameter, for when agents consider the moving average of past prices, a parameter governing a discrete choice model for selecting calves to slaughter, and a parameter governing an anticipation model, where agents anticipate future price changes whenever the herd size changes. Markets remain stable when farmers react cautiously to new price signals and when they are capable of anticipating future price changes. Gradually relaxing these constraints we see the emergence of cycles in herd sizes, produced quantities and prices, as has also been observed in data during the past century. If we let the relaxation go too far markets eventually explode or collapse. In two suggested model extensions we highlight the link between beef production and grain price volatility. Cattle cycles generate a varying demand for feed grain, increasing price volatility. At the same time, the beef cattle system responds somewhat to shocks in cereal price, thereby dampening price swings.

4.3 Energy system transitions

In paper V we compare two types of models: and ABM and an optimization model, both representing the same stylized power system. The models are designed to study the electricity system and capture both investments in power plants made over time and output. Two main features distinguish the ABM from the optimization model: limited foresight and a discount rate that may be higher than the socially optimal one.

With the two models we study the dynamics of a large-scale expansion of wind power triggered by a carbon tax. The aim of the paper is to explore the importance of the investors' beliefs for the evolution of the electricity market and the transition to a low-carbon power system. We focus on three questions:

1. How does the required carbon price to reach a specific emissions mitigation goal differ between the optimization model and the ABM?
2. How does the choice of internal discount rate affect the energy system?
3. How is the electricity system affected by the introduction of a carbon policy and how does this play out in the two models?

We find that the required carbon tax to reach a specific emissions mitigation goal is significantly higher in the ABM than in the optimization model, when agents use a high discount rate. We also show that the agents on average would have made a net loss from their investments, due to their limited foresight, if they had not used the higher discount rate when assessing their investment opportunities. However, if the agents use the same discount rate as in the optimization model, the carbon tax may not have to be much higher in the ABM to reach the same emissions target as in the optimization model.

The expansion of wind power decreases the capacity factors of the other power plants, since wind has negligible running costs and comes first in the merit order. However, wind is intermittent, and with limited storing capacity dispatchable power plants will also be needed in the system. If an expensive but carbon neutral and dispatchable power technology becomes is available, and if the system is to become carbon neutral, the social optimum in our system is to limit the expansion of wind power capacity in the near term. However, agents who invest in wind power plants do not necessarily take into account the future profitability of other agents' power plants. When agents make large investment into wind power capacity, the carbon neutral and dispatchable power technology can only enter the market in the presence of a very large carbon tax. We conclude that reaching a climate goal may be more expensive than what an optimization model shows.

Chapter 5

Discssion

The models presented in this thesis are highly stylized, they are limited to describe only one or a few mechanisms at play in the real system, and none of them are intended for making predictions. So, in the words of Epstein (2008), “Why model”, if not for making predictions? Epstein mentions 16 reasons, and among them I will highlight a few that I think applies to the work presented in this thesis.

The first two are to explain and to illuminate core dynamics. Simple models may capture qualitative behavior of a system, and explain interesting phenomena. Thes models are often both transparent and easy to use in an explorative way and uncertainties are easier to understand (Köhler et al., 2015).

Another reason is to raise new questions. Many of the questions presented in this thesis came to us *after* we first started modeling our systems. One example is the question of when an agent-based micro-dynamics can be projected to a closed form dynamics of aggregate variables (papers I and III). Another question arose when we were working with paper V. We saw that limited foresight alone did not significantly raise the tax level needed in the ABM to reach the same emissions mitigation target as in the optimization model, when the available power technologies were limited to coal fired power plants, CCGT, solar PV and wind power. This raised the question of whether the results would differ if an expensive but carbon neutral dispatchable power technology also were available, which we also investigated.

5.1 Future research

There are two ideas of future research that we have planned to look deeper into. The first one concerns the land-use model presented in papers I-III. We would like to explore two specific mechanisms and their impact on system stability. The first one is the option of storing harvested crops from one year to the next. It costs money to store goods, and in the case of crops there will also be a certain share that will be destroyed after long-term storage. However, it might still be an attractive option for agents who believe that the future price will be significantly higher than the current market price. Another mechanism is the option to sign futures contracts allowing agents to settle a price in advance. The futures market can offer both a price insurance to producers and an opportunity for speculation. It is commonly thought that a high trading volume in the futures market stabilizes prices at "fundamental" values, while other scholars disagree, see e.g. Ghosh et al. (2012).

The second research idea relates to paper V and our models of a stylized power system. From the start our goal has been to allow agents to take a portfolio approach when making investment decisions. Before taking this step we chose to explore a more simplified version of the model with a less complicated investment strategy, which resulted in paper V presented in this thesis. Here, agents evaluate investment opportunities in isolation, not caring about how they might affect the profitability of incumbent plants. However, if an agent is a large actor in the power market, a new facility might shift the merit order curve in such a way that he makes a net loss by investing in the plant, even if the plant by itself is profitable. Another aspect is how a portfolio should be designed to handle risk in an optimal way. Agents may want to mitigate risk by investing in a variety of power plants instead of handling the risk of each investment opportunity separately. Agent-based modeling is a suitable tool for investigating these issues.

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