Global natural gas market model: An agent based approach to the natural gas market

Berend A. Huisman
Technical University of Delft

Abstract

Scenario analysis is the art of telling the future, however without a glass boll this becomes increasingly difficult. The next best thing we have at our disposal are our best modeling efforts. This paper examines existing models of the natural gas market and reflects upon their strength and weaknesses for scenario analysis. Next we will introduce a different approach where we introduce a simulation model based on Agent Based Modeling. We will conclude that an Agent-Based Matching modeling is a useful formalization for solving complex real world market problems and help to provide strategic advice, thereby supporting scenario planners to anticipate the future. Last we will suggest further research in other possible fields of application that might benefit from an ABM approach.

1 Introduction

"Only a fool, a charlatan or, possibly, the Chancellor of the Exchequer claims to be able to predict what will happen in the future, yet, despite the evident failures of these attempts there is an abiding interest in the future and what it might hold.[6]" This opening of the paper of Coyle about the values of future studies is a little deceiving as to what his stance on future studies turns out to be. His argument is that although nobody is able to predict the future, an inevitable outcome beyond doubt, being able to provide a forecast is essential for dealing with uncertainty and being able to plan against it. Even when future studies are done with the glasses of the past they still teach us what might happen if nothing is to change. Even though we should acknowledge that change is imminent, future studies can help us shape that change.

Techniques like Field Anomaly Relaxation (FAR) and Delphi are qualitative techniques that rely on experts' input. They help us broaden the horizon by envisioning a future less dependent on a history bias. Before the focus of future research switched to become more qualitative, Forester published in the 1970's one of the best known future research models, known as WORLD1[9]. These models were based on system dynamics and painted a picture based on the trends and technologies of an imminent collapse of the world as we know it by a depletion of resources and widespread contamination by pollution. The strength of these quantitative studies lies not in their accuracy but in the tools they provide policy makers to influence the future.

Coyle points out in his suggestion for further research that numerical approaches to future studies lack an understanding of what techniques are suitable for which circumstances. It has been a long time since Forrester pioneered on numerical future research, modern techniques and computation powers open up new possibilities to address future research from a quantitative perspective. Within this paper we will apply the relatively modern field of Agent Based Modeling and explore its applicability in scenario planning. We do this by converting a qualitative story line about the future of natural gas, developed on the basis of expert interviews and brainstorm sessions conducted by an energy company, into an Agent Based simulation Model (ABM). This energy company is particularly interested in how the Northwest-European natural gas market is going to develop in order to fit their strategy to these long term forecasts.

After this introduction we will discuss previous models of the natural gas market and discuss their results and methodology in the light of scenario planning. After that we will show how we implemented the model and what the results were. We conclude by pointing out further research opportunities.

2 Literature

When approaching the modeling of markets the most obvious that comes to mind is, do we not have economic theory for that? There has indeed been a standing body of theorems going back as far as Marshall in the late 1890[23] that study markets and the position of firms and countries in competition. In this topic we examine a selection of economic models focused on crude markets with a focus on natural gas markets. These models typically simplify the world into a series of supply and demand equitations and compare the found optimum with real world values. Another typical economic approach would be time series analysis of historic data possibly combined with trend exploration.

We will however not limit ourselves to economic models. Natural gas experts tend to see the world as a network, consisting of nodes and edges. Edges represent transport routes and nodes represent demand and supply regions. These models are typically Linear optimization programs. LP programs will balance supply and demand given a series of equations and study congestion. The price on any node in the Network should be equal to one of its neighbours plus the transportation costs. When there is a price deviation this means their is congestion on the network[2].

The third and last category of models discussed are complementarity models, a relatively new type of non linear modeling technique. It defines the problem in a series of separate optimization problems bound by the combined complementarity problem, expressed in KKT[1] conditions[10]. The computational complexity of this approach in general limits its applicability allowing to consider only a limited group of actors to be completely strategical[11]. The strength of this technique lies in the fact that it takes a holistic approach by also defining the problem in terms for less prominent actors like traders and shippers, which in virtually all other approaches are considered to be static.

In the summary below I will try to group the different models according to the above-given characterization. This is arguably also the way this field of study advanced, giving the story line a historic context.

Golombek falls in the classical economic equilibrium theory. He studies the impact of liberalization of the EU energy market on the natural gas market in Northwest Europe in a series of maximizing social welfare functions under scenarios of successful liberalization of the energy market and without liberalization. His findings suggest that liberalization increases social welfare and, combined with a breaking up of selling consortia, decreases profits for non-European producers[13].

Krichene takes a world-scope in modeling natural gas market prices over the time period over the whole 20th century. The study focuses on the price elasticity and market shocks during this period and finds that shocks on the oil market have a great impact on the price of natural gas. Furthermore he studies how shocks on these markets impacted the price elasticity of consumption and production. He modeled short- and long-run price elasticity with a statistical time series model and concludes that long-term price elasticity of demand of crude oil shrunk in response to market shocks. The mechanism at play was the response from importing regions, which led to a shrinking of the elastic demand portion through taxation, energy saving and substitution, leaving only a non-elastic base. In response the price elasticity of producers decreased as well signaling the movement from a competitive market to a market-maker structure during the 1970's. However the price elasticity of natural gas increased in this period signaling natural gas to be one of these substitutes[20].

The earliest model discussed in this paper is the model Manne made in 1986. This model researches how the security of supply relates to import tariffs. The main output of this model is the probability of disruption of supply to Northwest Europe. The model tests which import policy best serves general social welfare. In the status quo policy the EU will be dependent for more than 40% - 60 % percent on insecure imports by the year 2000. This undesirable situation can be dealt with by market instruments, which can roughly be categorized in quotas, setting the quantity requirements and leaving the price to the market, or tariffs, influencing the price and leaving the exact quantities to the market. Which of these policies is optimal depends on the disruption probability[22].

Abada assesed the gas market in a primary linear optimization model and adds the non-linearities as KKT conditions. It builds upon assumptions made in Mannes model. The model assumes perfect competition and is tested to two case studies where this is obviously not the case. Due to the oligopolistic nature of the supply side of the market and the highly regulated transport market discrepancies are expected. However Manne predicted that a security margin would apply next to the expected oligopolistic margin. Within the case studies performed by Abada a security model consistent with the likelihood of disruption is found[1].

Perner uses the simulation tool EUGAS to forecast for a period up to 2030, although the model has run until 2060 to make this forecast agree with the long lifecycle of the assets. Investment decisions in new production and transportation are made autonomously. The model aims at identifying possible security of supply issues and investment decisions. The model shows no gas scarcity for the coming decades up to end of its horizon in 2030. Diversification of supplies and political considerations are the main determinants for the EU market, the model foresees significant transportation investments within this time frame[25].

Chyons model describes the European gas market until 2030 and assesses the economics of the South-stream project. The gas market is modeled on a global scale using aggregate gas consumption and production regions. The focus of the model is an economic valuation of the planned South Stream project, the findings suggest that there is no economic rationale for this project. The main benefits of this project lie in the non-economic, in this particular case political, gains[4].

Holtz uses the GASMOD model[16] with a time horizon until 2025 the model uses the Mixed complementarity format with a PATH solver. The model focuses on the European market and the sources of import. The model predicts a growing LNG hub in the UK serving the mainland and predicts that a diversification of import regions will serve the growing import[17].

Lochner focuses on the differences in prices at the different nodes. When the price difference at the nodes exceeds the transport costs to this node there is congestion. In the literature on market integration the price difference between markets is referred to as the parity bound [2].

The (improved) TIGER model of Lochner studies the price difference between these nodes, hence the aggregate interconnector capacity between two countries. The main bottlenecks are found in Eastern Europe and between Denmark and Germany. Congestion however is from a society point of view efficient since the cost of lifting the elevation can exceed the benefits. This is probably the case between the UK and Belgium[21].

Dieckhöner extends the above model and assesses a longer time horizon. Lochner predicts the state of the gas market in 2015 where Dieckhöner looks at projections until 2019. The model is tested in five scenarios where different future projects are integrated into the model. The model suggests that a lot of the congestion is located in Eastern Europe, this is roughly the same as the conclusions from the above Lochner model. The projects undertaken to alleviate these risks are mainly undertaken in the NW-E gas market where market integration is already high and therefore does not alleviate the expected congestion[7].

The MAGELAN model is used to capture the dynamics between the gas markets in the USA, the EU and Japan [21]. Not surprisingly this focuses on the role of LNG, since this connects the markets. The role of LNG will grow although in a different way in each region. LNG will decrease in the EU because its geographical location transport by pipeline is expected to be the major supply method. The US and Japan are expected to be more exposed to the LNG market.

Gabriel's study is more a show case of his conceptualization than a means to analyze the future of the gas market, as he conclude himself in his conclusion. He models the natural gas market as a complementarity problem and solves the resulting model with a PATH MCP solver. The model studies market power of suppliers and the security of future supply to the European market. In order to limit the complexity of the problem he only awards full strategical behavior to the suppliers and defines all other actors on the gas market as price takers, what he judges to be a realistic assumption of the distribution of market power in the European gas market[11].

Author	Year	Output	Meth.
Manne	1986	Probabilities of disruption under different import policies	Eq[2]
Golombek	1995	Effect of liberalization on social welfare	Eq
Krichene	2002	Effect of market shocks on the elasticity of consumers and producers	TS[3]
Chyong	2014	Predicts gas flows in the European region, with the main finding that there is no economic rationale for South Stream project Global	NPV[4]
Perner	2004	EUGAS model predicts no supply side scarcity, big transportation investments are needed	LP[5]
Lochner & Bothe	2009	The TIGER model assesses the role of LNG will be relevant even if volumes are modest, since it is the marginal producer	LP
Abada	2011	The model describes the European market as if it were in perfect competition and studies the imperfection	NLP[6]
Dieckhöner	2013	How do planned projects alleviate the expected congestion in EU	LP
Holtz	2009	Predicts gas flows in the European region and imports sources, with the main finding that a major LNG hub will provide EU mainland	MCP[7]
Gabriel	2012	Mathematically formulates the problem for a broad variety of actors, compares the market power and optimal solution of market prices in a handful scenarios	MCP

How do these models differ in methodology and their conclusions about the gas market? Manne foresees the imports from unstable regions to be problematic and suggests either a quota or tariff imposed by the importing nation. Manne's model (as well as Lochner's model) has the unique characteristic of being caught up by reality. Imports have increased but this has not caused problems of disruption in Northwest Europe, tariffs and quotas on the importing nation side have not emerged. The debate about security of supply is still on the agenda and the discussion proposed in the paper is still relevant today as the share of imports from unstable regions is expected to grow significantly in the future. Abada found an import tariff on East-European markets - where securtiy of supply is a major concern - although not imposed by the state. Holtzs model contradicts Manne's viewpoint, diversification leads to security of supply in his model and imports from Russia (which are of the main concern of Manne) stabilize at roughly one third of imports. Holtz states that there is enough supply side reserve and capacity so that security of supply is not threatened.

On the supply side reserves and production capacities the reviewed literature that incorporates this in their analysis or assumption roughly agrees. Holtz, Perner, Lochner and Dieckhöner all see enough reserves. Diversification of suppliers for the European market is expected due to declining reserves and production capacity, world-wide production is more than able to supply this fallback.

The role of LNG in the European gas market differs among the models studied, even by the same researchers. Volumes will increase in the coming decades but the share and importance is not agreed upon. Lochner (2009) and Bothe see a modest role, but an increased importance on the world gas market where shares are expected to quadruple and prices converge. Locher (2005) and Perner predict a significant role in NW-E with the UK as a major LNG regasification supplier. Dieckhöner foresees a more modest role for LNG.

All of these models expect increased liberalization on the European mainland. Liberalization will lead to an integrated market with converging prices. All models expect increased interconnector capacity and international pipelines to facilitate the liberalization process. Dieckhöner notes that most infrastructural investments at this moment are planned in NW-E, a market that is already interconnected. Congestion is expected in Eastern Europe. Liberalization is a means to an end, namely a fully integrated and free gas market in the EU, congestion that hampers integration is therefore a threat to the free market. Golombek quantifies the benefit of liberalization in increased social welfare and decreased market power for non-European producers, subsequently limiting the profits for these non-European producers.

Gabriel foresees that the majority of trade flows to the EU will be by pipeline, in the range of 85%, while 15% are expected to reach Europe via LNG facilities. Flexibility is key in providing security of supply. This can either be done by expanding the pipeline connections to regional suppliers of natural or by LNG. Observing the high investments in LNG infrastructure Gabriel assesses LNG to be the provider of future flexibility to Europe. His numerical results show that there is no serious security of supply issue, even in the case of curtailment on transport routes from either Algeria or the Ukraine.

When assessing this wide variety of models one comes to think about what else there is to wish for. What is still missing from these approaches and is is there a blind spot among these techniques? The modeling techniques are all using the optimization techniques to determine the path to the future. Optimization either from a god-like stand standpoint pinning to a global optimum of the solution state, hence where should we alleviate constraints in order to improve our optimum, or from an actor standpoint optimizing the outcome for a certain market actor. Although this might sound reasonable to an economist, it is hard to argue that actors on crude markets always behave in an economically sound way. Let alone in the interest of social welfare of mankind. From the modeling done in the above-given examples we are unable to conceptualize irrational behavior. Note that this irrational behavior does not mean that we expect the actor to purposefully hurt his own interest. The basis for this behavior could either lie outside the optimization scope, e.g. state-run actors who have to take domestic issues into account, or the fact that certain information might not be disclosed to the actor or he might even be purposefully mislead.

Another drawback of the discussed models is the limited applicability to social and technical challenges. The mathematical formulation makes it hard to adjust to the socially desired outcome or build-in technical paradigm shifts. In short the models above are all based on some sort of optimization algorithm which by definition is not extensible. This limits the model for scenario analysis since it is impossible to detach ourselves from the 'normalcy bias'.

From our literature study we conclude there is a variety of modeling techniques being used in the natural gas market and we observe a development of modeling to a more holistic and lower scale approach. However the methods leave open a gap of knowledge in implementing more complex behavior. A new approach to modeling the gas market which addresses this behavior is a promising academic opportunity. From a societal and company viewpoint it could be a useful tool in the art of scenario analysis. In the next chapter we will introduce a new approach to gas market modeling and discuss its formalization and implementation.

3 Methodology and formalization

The models discussed use optimization or equilibrium economics to arrive at future market conditions. If we want to break with the inherent bias of that approach we need to find another way in order for a seller to decide to which buyer he sells his product at what price. How do we match seller and buyer? To find an answer to this problem we take a small side step away from markets and resort to Gale[12], who encounters a problem of how to deal with college applications applying to colleges. Since the colleges do not know exactly who has applied for more than one college and might withdraw his application, they have to strategize their behavior. Subsequently the college applicant does not know who might accept him and might apply to more than one college to be sure. Gale shows that we must not seek to an optimal outcome but must resort to stable outcome, which he defines as a situation where nobody is able to switch places in order to be better off. In a second example of an imaginary society of women and men who have to seek their spouse, he proves that there will always be a stable optimum, however this optimum is not necessarily unique. Who benefits is determined by who is allowed to propose and who is allowed to reject.

The above-iven example is however a little removed from reality and it does not provide proof that the construct is applicable to markets of traded goods. Easley and Kleinberg show that a stable outcome is possible when we apply matching to market theory[8]. Their theorems provide proof of the feasibility to use matching as a market clearing procedure in a graph. We will address in a minute why it is important to make sure that matching is feasible in a network. First we will discuss a previous application of market matching.

Ostrovsky studies the application of matching markets in a vertical supply chain and uses the formalization of the theorems of Gale by Hatfield[14]. The main difference in the previously discussed examples is that Ostrovsky introduces intermediaries, hence not all matches are substitutes for each other. Ostrovsky extends Hartfield formalization to an algorithm of markets with intermediaries. In this two-sided market he finds at least two stable matchings, one optimal for the upstream party and one optimal for the downstream parties[24]. This is in line with the the theorem of Gale, that it matters which party initiates the matching.

In this paper we use an experimental economics approach in order to study the applicability of matching mechanisms in the natural gas market. The value of experimental economics alone on studying market designs is perceived to be limited by experimenters and designers. However in combination with other methods they play an important role in messaging and proving applicability to complex markets[19]. Since Ostroversky, Easley and Kleinberg already demonstrated theoretical proof for a networked market, experimental design by agent-based model simulation is a logical next step in proving the specific applicability to the natural gas market.

The above theoretic brings us to the following formalization. We simulate the natural gas market as a two-sided market where both supply and demand submit their bids and asks. We define an intermediary constructed under the name "Market" which aggregates all available supply and demand and determines the market price by computing the intersection point of the aggregated slope[3]. The matching price will be used to clear individual bids in the `annotate_ledger()` function provided later in this section, which is merely a bookkeeping of individual bids. The function given below provides the mathematical clearing. Note that in our formalization this first round is committal and buyers and sellers will be held accountable for their bids.

```
def get_clearing_price(self):
        # buyer drops bids, sort to merit order
        b = self.get_bids()
        s = self.get_asks()
        # highest to lowest
        self.b=sorted(b, reverse=True)
        # lowest to highest
        self.s=sorted(s, reverse=False)

        # More buyers or sellers?
        # Drop the excess; they won't compete
        n = len(b)
        m = len(s)

        # there are more sellers than buyers
        # drop off the highest priced sellers
        if (m > n):
                s = s[0:n]
                matcher = n
        # There are more buyers than sellers
        # drop off the lowest bidding buyers
        else:
                b = b[0:m]
                matcher = m

        count = 0
        for i in range(matcher):
                if (self.b[i] > self.s[i]):
                        count +=1
                        self.last_price=self.b[i]

        # copy count to market object
        self.count = count
        return self.last_price
```

Now let us to reflect again on why it was significant that the theory of matching is applicable to networks. The natural gas market is 'tale of three markets' where three demand nodes all have their own demand value characteristics[5]. The demand nodes are Europe (TTF), North America (Henry Hub) and the East-Asian market (JKM). Supplies to North America are for the majority local suppliers and indigenous production by pipeline, the JKM is for the majority of supply dependent on the LNG market. All these markets can be studied in separation on a short-time horizon. However when we address scenario planning of crude markets we tend to focus on the sustainability aspect and the finite of current reserves. In other words, when planning for scenarios on the natural gas market, it makes little sense to pick a scope that is unable to answer the depletion of reserves.

The LNG market connects the three natural gas markets with each other, since supply ships can route to all these demand regions. LNG connects hard to reach supply regions to the natural gas market, but since it is a global market the price will be set by the global marginal consumer in the real world. To mimic this specific behavior we manipulate the previously discussed order of clearing. The LNG market is forced to be the last one to clear and will aggregate the bids not cleared by other markets. In order to know what bids are not cleared and therefore available to other markets, the market has to keep track of what happened to all bids and communicate them back to the sellers and buyers. This is done in the ledger attribute of the market agent, whose main function is given below. The market agent uses the clearing price of the `get_clearing_price()` and reports the uncleared bids back to the agents. Subsequent markets will only receive the unmatched bids of the buyers and sellers during their matching procedure.

The clearing mechanism is however unable to deal with a situation where the market does not clear. In order to deal with this specific case we must instruct the market agent to move on and declare all bids on the market 'not cleared'. As described the stable outcome is not necessarily unique and could be dependent on the order in which the markets are called. However from the formalization provided in literature the market price is not. Therefore the order does not make anyone worse off, this can be deduced in the following thought experiment. An 'ask'that is not matched has no market to go to where the price is lower than his ask-price, the same holds true for the bids. There is no corresponding demand on the market for the uncleared bid.

```
def annotate_ledger(self,clearing_price):
        ledger = self.book.get_ledger()

        # logic test
        # b or s can not be zero, market has to clear
        b = self.get_bids()
        s = self.get_asks()
        if (len(s)==0 or len(b)==0):
                new_col = [ 'False' for i in range(len(ledger['cleared']))]
                ledger['cleared'] = new_col
                self.book.update_ledger(ledger)
                return
        # end logic test

        for index, row in ledger.iterrows():
                if (row['role'] == 'seller'):
                        if (row['price'] < clearing_price):
                                ledger.loc[index,'cleared'] = 'True'
                        else:
                                ledger.loc[index,'cleared'] = 'False'
                else:
                        if (row['price'] > clearing_price):
                                ledger.loc[index,'cleared'] = 'True'
                        else:
                                ledger.loc[index,'cleared'] = 'False'

        self.book.update_ledger(ledger)
```

4 Numerical results

We applied the above formalization of a natural gas market to three long term scenarios. The model was run along the time frame from 2013 to 2050. The scenarios envisage three different worlds and provide the external context for the model.

In Scenario 1 the penetration of renewables is accelerated. One of the policy mechanisms to support renewables is carbon tax, which pushes coal down on the merit order and will lead to an increase in natural gas demand in the electricity sector in the short and medium term. In the long term natural gas will be out-competed by renewables as well. This scenario foresees high economic growth and a reduction of demand in natural gas in the built environment. In scenario 2 there is no clear focus on transforming our energy consumption to a sustainable system. The economy enters boom and bust cycles where unfulfilled promises of cheap energy hamper economic growth. In scenario 3 economic growth in the EU trails behind that of developing countries due to political uncertainty about the future of the European Union. Shale gas leads up to its promises and reshapes the endowment of natural gas world wide. This scenario foresees low penetration of renewables and a lasting dependency on crudes.

Supply in all scenarios is expected to reach the EU primarily by pipe-line, with short periods of LNG imports when production does not keep up with demand. The reason is that the EU as a demand center is relatively close to supply regions. There is existing infrastructure to Russian gas fields and known reserves in Central Asia on the East-European border. Northern Africa has known gas reserves and some existing infrastructure which is expected to increase in the coming years. And on the eastern border of EU there is potential for shale gas. This makes Europe a less likely candidate for LNG shipments that will probably be priced outside our willingness to buy range. Prices are expected to rise since indigenous production gets depleted. How much the prices are about to rise is dependent on how our demand for natural gas shapes up. Electricity producers and heavy industry consumers have a greater price elasticity and can therefore contain prices. However inelastic agents like household heating with a seasonal profile will drive the price and the potential for market power. Due to the fact that there is a high probability of a dominant supplier, the intermediary needs to find a strategy to guard against market power on the supply side.

5 Conclusion

In this article we propose a new way of modeling the natural gas market. We propose matching as a market clearing mechanism and show how we implemented this in. The results are promising and open up new possibilities of natural gas and energy market modeling from an ABM paradigm. It provides a new set of opportunities to model complex behavior. Our goal was not to find an optimum but to make quantitative modeling a useful toolset for scenario analysts. The application of this technique should therefore not be seen as a replacement for future exploration techniques as Delphi and FAR. The techniques presented in this paper should provide a way to complement a story line for a future scenario developed in such a setting. The presentation and communication of such scenarios could be supported by showing a numerical analysis. It would also open the door for experimental economics to test possible strategies to deal with the uncertainties of the scenarios developed.

Implementing the market as an intermediary is consistent with how Blume implemented an auction model[3]. He proves that any equilibrium outcome leads to the efficient allocation of goods. So we can thence assume our model does so well. Under this assumption the applicability of ABM market matching has a potential beyond future simulation.

Now that we successfully implemented an exchange model in an Agent-Based model the question arises if this technique can be used outside the scope of modeling markets of goods. Coleman [18] approached decision making in social systems as a web of actors for the exchange of interests and control over the process. He called this the Linear System of Action (LSA) and formalized this exchange of interests in linear functions. Hermans and Cunningham proved in a laboratory setting that this theorem is applicable to public policy making [15]. The notion that the brokering of interests between stakeholders can be assessed as an exchange opens the door to agent-based simulation as a tool to support decision making processes.

We started this paper by quoting Coyle in his skepticism about the ability of anyone to predict the future. We might as well end with what immediately follows this quote. The practical value of future studies, apart from providing a way to deal with the human fear of not knowing what to come, is that understanding what might lie ahead improves our decisions now, in the sense that it might make our decisions future proof or might bring about a better future[6].

By doing so we might act in the spirit of one of the founding fathers of market modeling Marshall[23].

> Economics [...] is on the one side a study of wealth; and on the other, and more important side, a part of the study of man.

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Notes

[1]KarushKuhnTucker
[2]Equilibrium Modeling
[3]Time Series
[4]Net Present Value
[5]Linear Programming
[6]Non-Linear Programming
[7]Mixed Complementarity Modeling