

Coupling Agent-Based Models of Natural Gas and Electricity Markets

Koen H. van Dam^{*}
Delft University of Technology
Faculty of Technology, Policy and Management
P.O. Box 5015
2600 GA Delft
the Netherlands
K.H.vanDam@tudelft.nl

Emile J.L. Chappin[†]
Delft University of Technology
Faculty of Technology, Policy and Management
P.O. Box 5015
2600 GA Delft
the Netherlands
E.J.L.Chappin@tudelft.nl

ABSTRACT

In this paper two agent-based models of energy markets are considered: one modelling the market for natural gas and the other of the electricity market incorporating a CO₂ market. Because the energy systems are highly interrelated it is interesting to study how they were conceptualised and to explore possibilities to connect the two models, creating a new model of interconnected infrastructures. Both models presented here are based on a shared ontology of socio-technical systems and they share a number of building blocks, but domain specific assumptions and additions had to be made in each case. The differences in conceptualisation are addressed before a new design is proposed in which the models are merged and the link between gas prices and electricity prices is made explicit.

Categories and Subject Descriptors

I.6.5 [Simulation and Modeling]: Model Development

General Terms

Design

Keywords

Gas market, electricity market, agent-based model, ontology

1. INTRODUCTION

Models of energy markets are in high demand to give decision support in a sector that is facing key challenges dealing with sustainability, affordability and reliability in a time when energy infrastructures are unbundled and privatised. Important changes in both the physical domain (e.g. development of new power plants and investments in the physical infrastructure) and the social domain (e.g. new competitors or new market rules imposed by the regulator) occur. To study the development of these infrastructures (including possible scenarios for the future) or the operation of the system, both physical and social aspects need to be included

^{*}Dr. Koen van Dam is researcher at the Delft University of Technology, faculty of Technology, Policy and Management.

[†]Emile Chappin, MSc, is PhD candidate at the Delft University of Technology, faculty of Technology, Policy and Management.

in one model. In other words, energy infrastructures with their markets are socio-technical systems and they have to be modelled as such [15, 2, 11].

In this paper two energy markets are considered: the market for natural gas and the electricity market. At first glance, markets for gas and electricity have a lot in common: they were both natural monopolies that have now been opened to market forces, with a national transport network operated by a network operator. A key concept in both the gas and electricity markets is the distinction between the commodity (electricity or gas) and transportation (via the electricity grid or national gas network). Different actors (often operating across the borders of countries) are active in the production, trade and sales of energy. In both markets a regulator safeguards the public values such as affordability and reliability. There are some significant differences between the markets too, for example on the time frame for balancing inputs and outputs and the way transport capacity is arranged. Walls [16] discusses the similarities and differences between these markets in more detail.

These two markets are highly interlinked: in the Netherlands, for instance, the electricity producers are one of the largest demand sectors with an expected demand of 14.3bcm (billion cubic meters) in 2010 on a total Dutch gas demand of 50.8 bcm [8] and throughout the world gas is an important source for electricity generation. Households, businesses and industry, on the other hand, are connected to both the electricity and the gas network. Where is the boundary drawn when modelling either the electricity or the gas infrastructure? And what are the possibilities to connect models to one another? These are the research questions addressed here. The focus in this paper is not on the individual models or even on a combined model, but on model development and the process towards coupling energy market models.

The rest of this paper is structured as follows. In Section 2 a model of the gas and one of the electricity market are introduced, after which the conceptualisations used for these two energy markets are compared in Section 3. Next, in Section 4, a proposal for connecting the two models is presented. Section 5 then discusses the consequences and opportunities for cross-sectoral learning.

2. MODELS OF ENERGY MARKETS

Next, two models of different energy markets are introduced. Both models use the agent paradigm to model the be-

haviour of the actors and stakeholders in the system. Other approaches, such as computational equilibrium models of both markets (e.g. [13]) are commonly used, but there are some significant advantages in the use of agent-based models. Because they are developed in a bottom-up fashion modelling the behaviour of the elements rather than the results of the actions, they are suitable for experimenting with different configurations. This means that, for example, new actors or physical systems can be introduced to the model during a model run, and the resulting structure that emerges from the interactions between the elements can be studied. Furthermore, this approach makes it possible to re-use elements from one model in another model, provided the interface between the components is shared. Van Benthem [14] came to the conclusion to use agent-based models for energy markets, focussing on the advantages of being able to include disturbances in the demand of gas.

Agent-based modelling is already a common modelling paradigm for energy infrastructures and markets, especially in the electricity domain. For example, Kraus et al. [10] present a comparison of Nash equilibria and agent-based modelling for the dynamics of electricity markets, Chen et al. [6] work on agent-based modelling of day-ahead bidding strategies, Bunn & Martoccia [1] present an agent-platform for modelling energy markets and Ortega-Vazquez & Kirschen [12] focus on investment in generation capacity, to name just a few ongoing research projects. See [14] for an overview of existing models of the natural gas domain, [18] for agent-based applications in energy and for example [17] for a review of agent-based wholesale electricity market models.

What most of these models have in common, however, is a focus either on the network level of the infrastructure or on the market level of the decision making. The models used in this paper, on the other hand, are developed to be able to include the full value chain. Decision making is considered from the network level to the strategic and operational decisions of stakeholders.

First, in Section 2.1 a model of a natural gas market is discussed, followed by a model of an electricity market incorporating a CO₂ market in Section 2.2. Basic descriptions of both markets can be found in [7] and [9]. Key elements are discussed below in terms of agents and physical systems, for both model conceptualisation.

2.1 Natural Gas Market: Studying strategic behaviour of shippers

In this section the background and conceptualisation of the natural gas market model are presented.

2.1.1 Background

The gas infrastructure in the Netherlands uses a national transport grid controlled by a transmission system operator (TSO). The network is designed to bring gas from producers (most gas comes from fields in the North of the country near the city of Groningen, but it is also imported through pipelines from for example Norway and Russia and in the near future from Liquefied Natural Gas (LNG) terminals, for example in the port of Rotterdam) to different sectors on the demand side (including households and small business who use gas for heating and cooking, electricity producers who fire their gas turbines, and large industry as input for their production processes).

Table 1 – Agents and PhysicalNodes and their relationships for the model of the gas market

Agent	Relationship	Physical Node
TSO	owns	National grid
Shippers	–	–
Households	owns	Houses
Businesses	owns	Offices
Industry	owns	Factories
Electricity producers	owns	Power plants
Export	controls	Interconnector
Groningen producer	controls	Large gas fields
Small producers	controls	Small gas fields
Import	controls	Interconnector

In the gas market supply and demand side do not trade directly with one another; *shippers* are active in the market to buy and sell gas and arrange transport with the transmission system operator. The role of shippers is a complex one, because they need to use a strategy to book capacity on the network on specific entry and exit nodes mostly with long term contracts, while they might trade gas at a different time scale. Furthermore, the playing field consists of heterogeneous actors: shippers differ in size and market power, as many are producers themselves also. Prices then emerge out of this network between all actors in the system and their interaction results in a wide variety of contracts with different time horizons and arrangements for security of supply.

For transmission system operators the liberalisation of the gas market and the vertical unbundling of transport, production and sales means that they have less insight in the market processes as they only deal with honouring requests for booking of entry or exit capacity by shippers without knowing how these transport contracts will be used. Transmission system operators have to make difficult decisions on investment in the network capacity and come up with policies that best support the liberalised market. To support the decision making process of a transmission system operator, a model of the gas market and the strategic behaviour of the shippers is being developed.

2.1.2 Conceptualisation

To model the gas market, a socio-technical perspective was chosen: the physical elements of the system (with nodes such as gas fields and factories, and edges such as pipe lines) are distinguished from the social elements (where the various actors in the system are considered as nodes, while transport and commodity contracts as well as money flows are considered as edges). This socio-technical perspective allows the modeller to capture the interactions between the two networks and provide decision support about changes in either of the networks. The agents, their physical nodes and the relationships between them are shown in Table 1.

The national grid is modelled as a single node, for which the underlying structure is represented as available capacity for entry and exit points. The TSO keeps track of the available capacities. In this proof-of-concept stage gas storage in bunkers is not considered yet, neither is the distinction between different qualities of gas (with higher or lower caloric

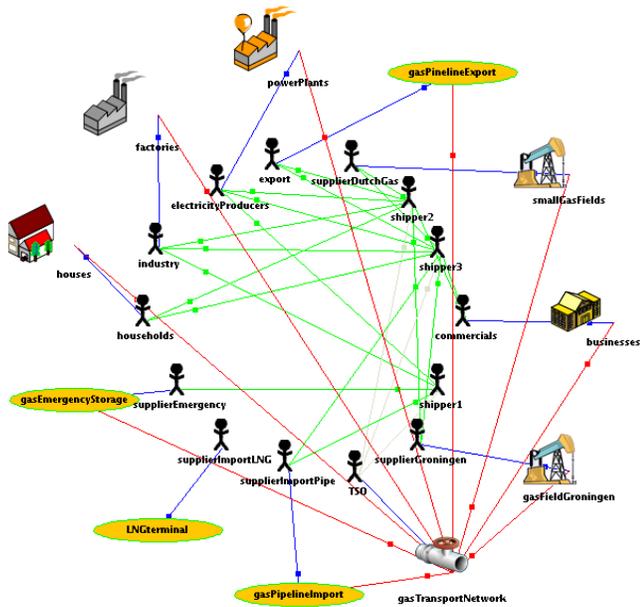


Figure 1 – Screenshot of the gas market model. The inner circle contains the agents and the technologies are shown on the outer circle. Edges between agents denote contracts for the commodity or transport; those between agents and technologies show the ownership relationship; and links between technologies are mass flows resulting from these transactions.

value).

Demand side actors contact all shippers to ask them about the sales of gas, and from all possible trade contracts they choose the cheapest on that fulfils their specific requirements for security of supply. Shippers then, in a similar fashion, check their contracts with supply side and they book transport capacity with the TSO. Prices for transport capacity are determined based on the supply and demand sectors, using a weighted average of the entry or exit tariffs respectively.

The gas price paid by the end users is built up from the commodity price and the transport price. The shipper pays the suppliers for their commodities (who may each charge different prices) and it pays the TSO for reserved transport capacity. In the proof-of-concept model the shipper charges a fixed 10% profit on both to the end users, but his costs may still be higher than his income when paying extra for overbooking capacity (to get a higher security of supply) or by the penalties involved in not booking enough capacity.

Figure 1 shows a screenshot of the model of the gas market, in which this conceptualisation has been implemented as an agent-based model. Three shippers are introduced, each with a different strategy for (over)booking capacity from the TSO. Otherwise the shippers are identical. The model produces statistics about the profits of the shippers and their market share. The model is currently in a preliminary stage and is being expanded to include fluctuations in demand and supply and the introduction of portfolios of long and short term contracts for either commodity or transport. The time

step of this model is one month to allow for seasonal effects on gas demand and we usually simulate 10 years in a simulation run.

2.2 Electricity Market: Evaluating policies for CO₂ reduction

In this section the background and conceptualisation of the electricity market model are presented, following the same structure as Section 2.1.

2.2.1 Background

The electricity infrastructure is crucial for the functioning of society. The infrastructure contains many actors and physical apparatus. The actors in the field meet one another in different electricity markets, of which the most important are a bilateral market for long-term contracts, the spot market for day ahead trade and a balancing market for real-time correction. Electricity is different from other markets because demand physically needs to meet supply at all times to prevent failures of service.

The electricity infrastructure contains two grids: a transmission grid that links different parts of a country and many distribution grids that connect to small and medium consumers. Some transmission lines cross the borders to other countries. In this paper, we will not focus on issues related to the electricity grid, such as the need for balancing supply and demand. Most power is generated in large-scale power plants, directly linked to the transmission grid. The exemption is production by individual wind mills and production at the site of consumers, by photovoltaic cells on the roofs of houses.

In our work on electricity market models, we have been focusing on the work on the evaluation of CO₂ policies. As of 2005, electricity generation in Europe is one of the sectors involved in the European Emissions Trading Scheme (EU ETS). Mostly power generation is affected by such policies, since that is the part of the infrastructure where the CO₂ is emitted. Power generation companies, now split up from retail companies, own, invest in and operate power plants. Some power generation technologies – coal, gas – result in CO₂ emissions. Others, such as wind, biomass, nuclear have no CO₂ emissions. Since demand for electricity is growing steadily, and is not sensitive to the electricity price, power producing companies aim to meet rising demand that entails a growth in emissions. Governments, however, aim at CO₂ emission reductions.

Emissions of power plants in operation cannot go down, because they are bound by fuel consumption. Affordable upgrades have only marginal effects and fuel switching is typically limited to 15% co-firing a CO₂ extensive fuel such as natural gas or biomass. Therefore, significant reductions need to come from investment in new power generation capacity, with a higher efficiency or different fuel. Consequently, investments play a crucial role in our models of the electricity infrastructure.

We have used the models to evaluate and compare three policies for CO₂ reduction: a no intervention policy was the base case, the EU ETS and finally a carbon taxation scheme, in which a tax has to be paid to government for emitting CO₂ [5].

2.2.2 Conceptualisation

To simulate the impact of decisions by power generators,

Table 2 – Agents and PhysicalNodes and their relationships for the model of the electricity market

Agent	Relationship	Physical Node
Electricity producers	owns	Power plants
Industry	owns	Factories
Households	owns	Houses
World market	owns	Fuel equipment
Environment	owns	Environment
CO ₂ market	–	–
Electricity market	–	–
Government	–	–

under different policy scenarios, we need to model the physical elements of the system, separated from the social elements, according to a socio-technical perspective, as discussed above in Section 2.1. For the electricity model the agents, their physical nodes and the relationships between them are listed in Table 2.

The transmission and distribution grids are not modelled as nodes, but assumed available, because the research questions we had so far did not require them to be represented explicitly. Households are represented in a single consumer agent, that has a demand for electricity, in the form of a load duration curve throughout a year. They request their demand from the electricity market agent, which is modelled after the Amsterdam Power Exchange (APX) spot market for electricity and also represents the bilateral market for electricity. Power producers offer their electricity on the same market. In their bids the power producers take the CO₂ policy implemented by the government into account, by using the expected CO₂ price in the model. After the market is cleared the power companies operate their power plants. In order to do so, they acquire the needed fuels from the world market agent, the only fuel supplier in the model. Furthermore, they extract any ubiquities from the environment and emit CO₂ and dissipate heat into the environment.

Besides the world market agent and the electricity market agent, the CO₂ market is also modelled as an agent, in which power companies bid for the emission allowances they need to be able to emit CO₂ at their power stations. The electricity market and the CO₂ market are interdependent (See [4] for a detailed discussion on this issue). In the case of a carbon taxation scheme, the electricity producers pay the required taxes to the government. With a carbon taxation scheme the tax level is fixed and not established through the market. Therefore, the tax is not interdependent with the electricity market.

In addition to the activities described so far, which are of an operational and tactical nature, the electricity companies can invest in new power plants and dismantle existing ones. Those decisions use the data from the operational activities, such as a history of prices on all the three markets, but also individual preferences, reflecting their management style. As a consequence of all these decision-makings, the electricity infrastructure evolves.

The time step of this model is one year and we usually simulate 50-75 years in a simulation run. Even though the smallest time step in the simulation is one year, seasonal effects are included in the load duration curve reflecting the

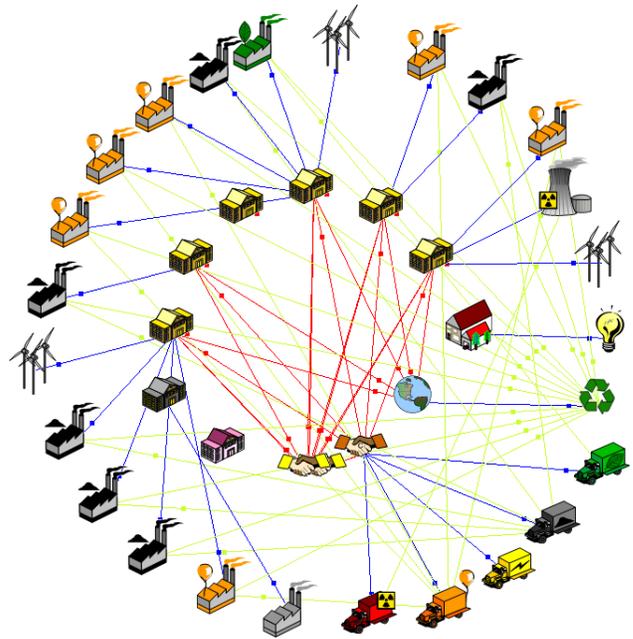


Figure 2 – Screenshot of the electricity market model. The inner circle contains the electricity producers, energy markets and other actors. The outer circle contains electricity generation technologies with different fuels and other physical systems.

demand for electricity for a typical Western European country. Figure 2 shows a screenshot of the first time step of model of the electricity market, in which this conceptualisation has been implemented as an agent-based model.

3. COMPARISONS IN CONCEPTUALISATION

To be able to design a model of the integrated gas and electricity infrastructures in Section 4, the conceptualizations have to be compared first. An integration of two models requires compatibility in conceptual terms and interfaces between the implementations of the systems. We compare the models in the following conceptual terms: 1) which agents are in the model and what they do; and 2) how the agents' decision-making is modelled; and 3) the main simulation properties.

3.1 Coinciding agents

From Tables 1 and 2 it can be deduced that the following agents appear in both models:

Electricity producers in the gas market model are represented in an aggregate agent reflecting the demand of gas used for electricity generation. In the electricity model, on the other hand, electricity producers are at the core of the model as they supply electricity to the market. The model contains six electricity producers who own generators that use different fuels; those electricity producers with gas fired power plants need to buy natural gas from the world market.

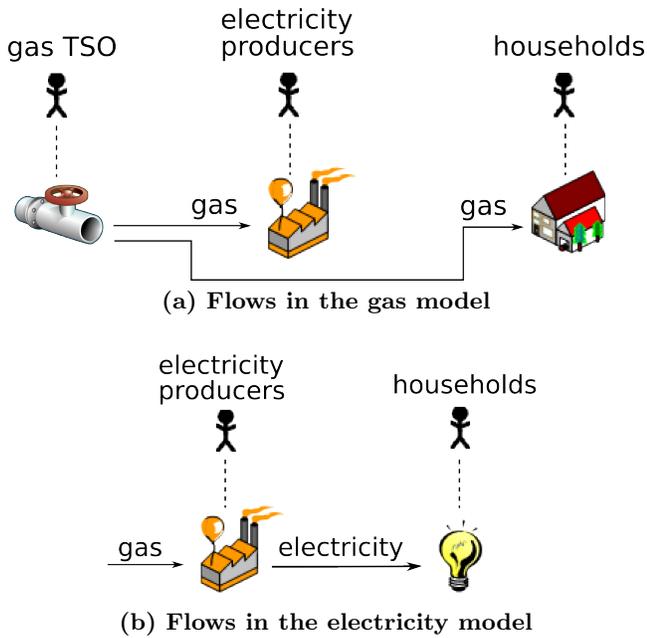


Figure 3 – Inputs and outputs of houses and power plants in the gas and electricity models. In the gas model the output of the power plants is not taken into account, while in the electricity model gas is only considered as a fuel for the power plants and the market for gas is outside the scope of the model. Dashed lines indicate the ownership relationship and a solid lines are mass flows.

Households in the gas market model are represented in an aggregate agent reflecting only the demand of gas used in households with a specific requirement for the security of supply. By contrast, in the electricity model the households represent an aggregate demand for electricity not only of houses, but the total electricity demand including that of industry and businesses.

Industry in the gas market model the industry is treated in the same way as the households, meaning that it represents an aggregate demand for gas. In the electricity market model the total demand was aggregated and no different sectors are distinguished. The industry in this model has a demand for emission rights only, competing with the electricity producers on the CO₂ market.

Where the role of agents differ between the models, the models cannot be coupled by just combining the behaviour: adverse and unwanted effects could occur, possibly even causing the simulation to crash. Before providing possible solutions to that issue in combining the gas and electricity model, we look more closely at the differences in electricity producers and household agents. For two physical systems, namely houses and power plants, the inputs and outputs within the boundaries of the gas model are shown in Figure 3a and for the electricity model are shown in Figure 3b. These Figures highlight the first two coinciding agents as an example of the similarities as well as the differences.

3.2 Modelling behaviour

In the gas model, the transport system operator agent coordinates supply of natural gas by giving out transport contracts to shippers. Gas flows from the suppliers to the transport grid at entry points and then at exit points to the power plants that use natural gas for electricity generation and the houses that use natural gas for their heating and cooking appliances. In contrast, in the electricity model gas is bought from the world market for fuels. At the world market gas supply is unlimited and against an exogenously determined price. Households in this model have no demand for gas; they only require electricity. Since both the gas and electricity grids are not modelled in the electricity model, all flows occur directly between generator and user.

Both models are demand driven, in the sense that the demand for either gas or electricity by the demand side drives the whole energy infrastructure. A distinction is made between strategic and operational decision-making [3], where strategic decisions change the infrastructure and consequently which components and physical connections are in the system. Examples are investments in new power plants, dismantling old power plants and investments in new pipelines or power connections. Operational decisions deal with issues given the set of components in the infrastructure. Examples include the operation of power plants, the scheduling of transport capacity and the consumption of gas. In other words, the operational decision making deals with activities for procurement, production and transport.

Security of supply is modelled explicitly in the gas model and different segments have different requirements for this. The concept also drives the decision making of the shippers. However, in the current version the disruption of demand or supply in the chain has not been considered in detail yet. As said, in the electricity model the supply of gas is considered to be unlimited.

3.3 Simulation characteristics

Below the simulation characteristics are compared:

Research questions and focus of the two models are different. The gas model was designed to analyse the effects of booking behaviour of shippers while the electricity market model was built to study and analyse long term effects of policy measures. Because of this different focus, different modelling choices were made of which the most important ones are discussed below.

Software tools used in the models are similar, namely a Java implementation with agents based loosely on the Repast toolkit and a knowledge base maintained with the Protégé ontology editor. Only for data analysis different choices have been made (Matlab, SPSS and Excel), depending on the required graphs and analyses.

The classes used in the models extend both the concepts of the Java class Agent (for all classes of agents). In both models, all physical apparatus are of the Java class Technology and links between objects are of the classes Ownership and PhysicalFlowContract. For the CO₂ market, however, different types of contracts are used since contracts for emission allowances are not directly connected to physical flows.

Initialization processes are used to prepare a model run: create a starting set of agents and physical installa-

tions. That is a tailored process for each model. For both models, blueprint agents and technological installations are imported from a shared ontology [15].

Simulation horizon and frequency are dependent on the type of question that is to be answered with the simulation. The gas model has a time step of one month, while in the electricity model that is one year. The electricity model also has a longer horizon to study the effects of investments while in the gas model a fixed yearly growth in demand was implemented because of its focus on the booking of transport capacity for a given infrastructure.

Schedule The schedule contains a number of actions that are executed in each of the ticks during the simulation. The schedule in the gas market contains the following sequence of actions, to take place each month:

1. Demand side buys gas from shippers
2. Shippers buy gas from suppliers
3. Shippers book entry and exit capacity with the TSO based on their portfolio
4. Suppliers produce gas and send it to the transport network based on their sales contracts and maximum capacity
5. The TSO connects flows to the parties that bought gas
6. All agents pay for commodities and transport
7. Update graphics and write data to file

Furthermore, once a year the demand of each sector is increased with a fixed percentage.

The schedule in the electricity model contains the following sequence of actions (adapted from [4]):

1. Set new scenario parameters, including electricity demand from consumers
2. Electricity producers invest and dismantle
3. Electricity producers place bids on the electricity market, based on expected costs for emission allowances
4. Electricity producers and the industry meet their expected demands for emission allowances at an auction
5. Go back to step 3 until CO₂ and electricity prices are stable
6. Electricity producers pay carbon taxes
7. Electricity producers buy fuels
8. Update graphics and write data to file

Mass and money flows each need to be in balance throughout the model. This means that money spent by one agent needs to be added to the balance of another agent, and that mass flowing out of a technology needs to flow in another ontology. That requires subtle interfaces between parts of the model and both models handle that in a different way. Methods for checks and balances verify related parts of the models.

Table 3 – Agents and PhysicalNodes and their relationships for the model with both an electricity and a gas market

Agent	Relationship	Physical Node
TSO	owns	National grid
Shippers	–	–
Households	owns	Houses
Businesses	owns	Offices
Industry	owns	Factories
Electricity producers	owns	Power plants
Export	controls	Inter-connector
Groningen producer	controls	Large gas fields
Small producers	controls	Small gas fields
Import	controls	Inter-connector
World market	owns	Fuel equipment
Environment	owns	Environment
CO ₂ market	–	–
Electricity market	–	–
Government	–	–

4. TOWARDS A UNIFIED MODEL

As said in Section 3.1, there are a number of actors that are included in both models, namely electricity producers, households and industries. Their respective physical systems (power plants, houses and factories) are also contained in both models. Since in the real system these nodes and the markets are interlinked, can the same be done with these models?

The inputs and outputs of two physical systems from Figures 3a and 3b are merged in Figure 4, resulting in a new interaction between the electricity producers and the households which was not available in the gas model and a demand for gas that was not modelled in detail in the electricity model. One can imagine a similar merge for the energy demands of factories.

Since the trading behaviour is demand-driven in both models and the decision which products to buy is not encoded in the agent behaviour but deduced from the required inputs of the technologies the agent owns (as defined in the knowledge base), ideally the two models could be merged by simply adjusting the initialisation to read all instances of both systems in one model from the shared knowledge base. However, the analysis of the different models performed in Section 3 revealed that while there are many overlapping issues and aspects, there are also a number of critical differences that prevent a seamless integration of the two models. Because of a number of assumptions, simplifications and domain and problem specific choices, it is not enough to only add electricity demand to the houses in the gas model, for example. In this section a design for a merged model is proposed and steps that need to be taken are discussed.

It is anticipated that the following tasks need to be executed to bring the models together:

1. Build a new project in which the agent classes (i.e. the description of their behaviour) of both models are included and create a new simulation file. Where required, the classes have to be merged. Names of methods from the building blocks (e.g. “buyResources” or “produce”) are already shared.

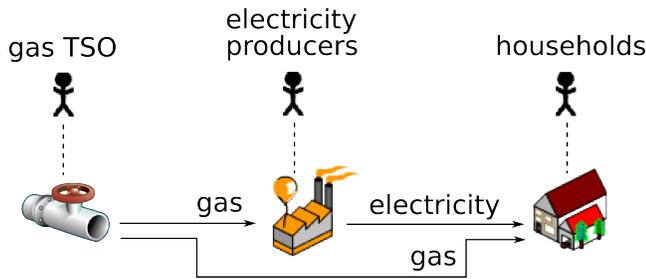


Figure 4 – Inputs and outputs of houses and power plants in an integrated model of the gas and electricity markets. Gas is input for both houses and power plants, and the electricity produced is input for the households. Note that other elements are left out of this picture for simplicity. Dashed lines indicate the ownership relationship and a solid lines are mass flows.

2. Create new instances in the shared ontology, following the description of social and physical elements from Table 3. At the moment there are two instances of, for example, the houses in the ontology: one with input gas, and the other with input electricity. A new instances could be created based on the design from Figure 4, in which houses require both commodities. The same must be done for the other demand sectors that require both gas and electricity. Natural gas should be removed from the goods sold on the world market.
3. Streamline the time dimension in decision making and scheduling of the various supply chain activities, including buying commodities and transport on different time scales in the two models. The smallest time step considered should be one month.
4. Structurally redesign the implementation of the electricity demand based on the load duration curve to allow for a smaller time step without losing the detail of peak and base demands (currently in 10 segments).
5. Implement display of metrics to be able to analyse the resulting system behaviour, including prices of gas and electricity over time and the profits of the key stakeholders (i.e. electricity producers and shippers).

5. CONCLUSIONS AND OUTLOOK

Since the infrastructure systems are connected in the real world, studying the merging models of the gas and electricity market to create a unified model of these two highly interconnected infrastructures is a useful exercise. While such a merge is not straightforward, the efforts required to do so are relatively limited compared to the development efforts of building either of these two existing models. The fact that both models presented in this paper have been based on a shared ontology that was designed from the start to deal with a wide range of infrastructure systems and which was initiated with the goal to enable cross-sectoral re-use, interoperability and interconnectivity makes it possible to establish connections between the two models [15].

Because the two models were developed in a different domain and with a different purpose, the conceptualisation of the two systems is not equivalent. The concepts used in the conceptualisation, however, are the same; the definition of the concept ‘natural gas’ is exactly the same in both models, a ‘trade contract’ for a commodity is also defined in precisely the same way. The agents in both models speak the same language. The key challenge here is thus to map the conceptual choices made in one model with those in the other, in particular when it comes to scheduling. The tasks indicated in Section 4 are relatively easy, with the reimplementation of the electricity demand over the year remaining as a major challenge. This is especially important because the gas fired power plants are typically the ones running only at times when electricity prices are high (i.e. in the peak hours). If demand would be averaged out over a month this phenomenon could not be observed.

The model of the electricity market contains a detailed CO₂ market implementing the emission trading scheme. In a first version of the merged model, however, it is envisioned that this will be left outside the scope. This is mostly for practical modelling purposes – the trading of emission rights and the commodity are parallel activities and prices effect each other, requiring several loops of electricity trading and trading of emission rights as described in Section 3.3. A different implementation of the electricity load duration would result in this loop no longer being functional. CO₂ emission tax, on the other hand, can be integrated without such a loop since the price is determined in advance.

To conclude this paper, we would like to reflect on the added value of creating a model in which both the electricity market and gas market are included. It should be stressed that a bigger model is not always a better model and the more complex it is, the harder to validate and base policies on its results. The aim of merging the two models is thus not to develop an overarching system which incorporated all aspects of the energy markets. There are, however, a number of research questions which could not be answered with either of the existing models. These relate to the link between electricity demand and prices with gas demand and gas prices. The current model of the electricity market only does include a world market for gas, but its prices are established exogenously. The result is that electricity prices in the model depend on gas prices, but not the other way around. In reality that is an important link, the more so because prices of other fuels (e.g. coal and oil) are also correlated. In the gas model, on the other hand, demand for gas by electricity producers plays an important role, but the competition with other fuels for power generation was left out. Finally, it must be stressed that it is also an interesting scientific challenge from a modelling perspective and a merge could be a show-case of the possibilities of connecting different infrastructure models in general.

6. ACKNOWLEDGMENTS

The authors would like to acknowledge financial support from the Next Generation Infrastructures Foundation.

7. REFERENCES

- [1] D. W. Bunn and M. Martocchia. Analyzing the price-effects of vertical and horizontal market power with agent based simulation. In *Proceedings of the*

- IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century, PES2008*, 2008.
- [2] E. J. L. Chappin and G. P. J. Dijkema. Agent-based modeling of energy infrastructure transitions. *International Journal of Critical Infrastructures*, 6(2):106–130, 2010.
- [3] E. J. L. Chappin, G. P. J. Dijkema, K. H. van Dam, and Z. Lukszo. Modeling strategic and operational decision-making — an agent-based model of electricity producers. In *Proceedings of the 21st annual European Simulation and Modelling Conference (ESM2007)*, St. Julian's, Malta, 22–24 October 2007.
- [4] E. J. L. Chappin, G. P. J. Dijkema, and L. J. d. Vries. Agent-based simulation of carbon policies and power generation. In *32st IAEE International Conference, Energy, Economy, Environment: The Global View*, San Francisco, USA, 2009. IAEE.
- [5] E. J. L. Chappin, G. P. J. Dijkema, and L. J. d. Vries. Carbon policies: Do they deliver in the long run? In P. Sioshansi, editor, *Carbon Constrained: Future of Electricity*, Global Energy Policy and Economic Series, pages 31–56. Elsevier, 2009.
- [6] H. Chen, Y. Yang, Y. Zhang, Y. Wang, Z. Jing, and Q. Chen. Realization of decision-making module in agent-based simulation of power markets. *Dianli Xitong Zidonghua/Automation of Electric Power Systems*, 32(20):22–26, 2008.
- [7] L. J. de Vries, A. F. Correljé, and H. P. A. Knops. *Electricity & Gas Market design and policy choices - NGInfra Academy*. TBM TU Delft, Delft, 2009.
- [8] Global Insight. Report for the department for business, enterprise and regulatory reform the LNG market — globally now to 2025 and the implications for the UK. Technical report, Global Insight, 2007.
- [9] IEA. *Energy Policies of IEA Countries - Netherlands-2008 Review*. International Energy Agency, 2009. ISBN 9789 264 043 398.
- [10] T. Krause, E. V. Beck, R. Cherkaoui, A. Germond, G. Andersson, and D. Ernst. A comparison of Nash equilibria analysis and agent-based modelling for power markets. *International Journal of Electrical Power and Energy Systems*, 28(9 SPEC. ISS.):599–607, 2006.
- [11] I. Nikolic. *Co-Evolutionary Process For Modelling Large Scale Socio-Technical Systems Evolution*. PhD thesis, Delft University of Technology, the Netherlands, 2009.
- [12] M. A. Ortega-Vazquez and D. S. Kirschen. Assessment of generation expansion mechanisms using multi-agent systems. In *Proceedings of the IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century, PES2008*, pages 1–7, Baltimore, Maryland, USA, 16-18 April 2008.
- [13] Y. Smeers. Computable equilibrium models and the restructuring of the european electricity and gas markets. *Energy Journal*, 18(4):1–28, 1997.
- [14] M. van Benthem. *Optimizing the structure of the natural gas market using an agent-based modeling framework*. PhD thesis, University of Groningen, 2010. ISBN 978-90-9025027-4.
- [15] K. H. van Dam. *Capturing socio-technical systems with agent-based modelling*. PhD thesis, Delft University of Technology, Delft, the Netherlands, 2009. ISBN 978-90-79787-12-8.
- [16] W. Walls. Natural gas and electricity markets. In J. Evans and L. C. Hunt, editors, *International Handbook On The Economics Of Energy*, pages 456–470. Edward Elgar Publishing, 2009. ISBN 978 1 84720 352 6.
- [17] A. Weidlich and D. Veit. A critical survey of agent-based wholesale electricity market models. *Energy Economics*, 30(4):1728–1759, 2008.
- [18] N. Yu and C. C. Liu. Multi-agent systems and electricity markets: state-of-the-art and the future. In *Proceedings of the IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century, PES2008*, 2008.