Published in: Tochtermann, K., Scharl, A. (Eds.):
Informatics for Environmental Protection - Enviroinfo Graz 2006,
ISBN 3-8322-5321-1, pp. 153-160, 2006

A Modelling and Simulation Environment for Real-time Pricing Scenarios in Energy Markets

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Abstract

We describe an agent-based simulation tool for examining the impact of real-time pricing methods upon the power consumption of domestic users (households). The main entities within the model are electricity suppliers and electricity consumers scheduling their demand according to real-time prices for electricity. The main aspect of the modelling and simulation tool consists in very flexible methods to calculate tariffs and in detailed methods for describing the behaviour of electricity consumers communicating with their electricity supplier.

1. Background and goals

Today's markets for electrical energy and the methods of generation of electrical energy are constantly evolving. Markets are becoming deregulated and the proportion of electricity generation by methods using renewable energy as e.g. solar power, wind power or biogas is growing.

Keeping peak demand as low as possible and being adaptive to the fluctuating output of solar power stations and wind power stations are both enabling factors for *consuming and generating energy locally* and thereby reducing costs for energy distribution. The latter contributes to a maximum utilisation of solar power and wind power entailing the reduction of emission of greenhouse gases. But the integration of many non-controllable power stations into the power grid also originates some new challenges that can be coped with on the basis of existing technology and methods.

Data communication is a fundament for controlling utilities and facilities within the power grid, but also for controlling consumers of electricity which is referred to as *load management*. Until today, load management is mostly limited to controlling large consumer loads. Several field studies in controlling households have also been carried out. Given the enormous advances in data communication and microcontroller technology and their penetration to the market, it now seems realistic to perform load management of households and office buildings on a large scale.

Equipment for measuring and communicating data about consumption of electrical energy, devices for informing customers about current costs of electrical energy and for switching loads, and finally programmable controllers based on standards for influencing behaviour of e.g. household appliances in dependency of control information already exist. Controllers are often built into devices, however currently mostly lacking suitable data interfaces for control. Power line data communication systems are expected to become a cost-effective technology for data communication of home devices.

There are two types of load management: Direct load management involves the switching of equipment by power companies. Indirect load management can be achieved by offering incentives to consumers for

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shifting load from peak demand periods to periods of low demand. Such incentives can be based on real-time pricing contracts providing for communication of changing energy prices for the next billing period, e.g. hourly energy prices can be communicated one day ahead of the usage period (Goldman 2005). Yet a different method of indirect load management based on the assumption of completely deregulated markets assumes that providers and consumers of electrical energy attain a balance of production and consumption by reaching a market equilibrium of bids and demands during auctions between software agents representing providers and consumers (Akkermans et al. 1998, Ygge 1998).

While a lot of research has already been conducted in the field of load management and some studies on consumers' behaviour facing real-time pricing (Goldman et al. 2005, Morovich et al. 1998) already exist, the following general questions are not finally answered:

- Which type of tariff is best suited to achieve maximum load shifting of household-level consumers?
- How long do consumers take to adapt to varying costs for electrical energy and for which time periods can they adapt their demand?
- How does load shifting and curtailment differ between directly managed loads and indirectly managed loads?

Moreover, assuming a technical layout with controllers enabling automated self-adaptation of households to dynamically changing tariffs, it is most important to investigate which scheduling strategies are best suited for load-shifting at the household level and also how controller intelligence should be distributed between power companies, households and household appliances taking into account characteristics of different communication channels which might be used to implement indirect load management.

As a first step towards answering the mentioned general questions and with a special interest in examining the technical layouts described, we developed a prototypical modelling and simulation tool for load management by price incentives for electricity consumers which we will presented in the following.

2. Models and Scenarios

A model in our framework currently consists of three types of actors:

1. an electricity supplier (power company) calculating real-time prices for electricity,
2. different classes of electricity consumers (households) modelled in essential by their scheduling mechanism of energy consuming tasks,
3. power stations and electric generators as e.g. wind energy conversion systems (WECS) modelled as sources for time series of available electrical energy.

Each actor is represented by an agent connected to other agents by communication channels allowing to coordinated actions defined by specific interaction protocols. The paradigm of agent based modelling is used in our framework, since the following components of a scenario have to be modelled at a great level of detail:

1. The mechanism to calculate real-time prices at a power company.
2. The communication between the different types of actors.
3. The behaviour of consumers with different mixes of household appliances and specifically the scheduling of tasks to achieve optimum load shifts and curtailments as reaction to real-time prices.

As a basis for modelling adaptive consumers we need both, information on the use and load shifting potential of devices typically occurring in households and information about the mix of household appliances and appliances typically present in different classes of households. Non-adaptive consumers are not modelled in high detail, since long-term demand sets exist for this type of consumers and can be used as input information for the tariff calculation. Temporary input about the electricity supply for calculating tariff information is reduced in our models to wind power predictions given as time series combined with previously calculated generation of conventional power stations. Additionally, a time series containing price incentives granted by a power company for load reduction can be imported.

Consequently, a simulation scenario consists of a model and various parameters such as:

- Inputs to the energy provider sub-model: characteristic demand set of non-adaptive consumers, wind power prediction, parameters to the tariff calculation function,
- instantiation of consumers of several classes by their device use profiles and ability to shift load,
- advance warning intervals and validity intervals of tariffs.

3. Modelling consumer behaviour

In this work's context *consumer* denotes the entirety of electrical devices that are attached to a single electricity meter and also comprises the persons whose needs are satisfied by these devices' operation. Simulation of consumer behaviour serves the purpose of generating an actual electric load both realistic and realistically changing. To this end, each consumer (represented by an agent within the simulation model and within the simulation) has a characteristic equipment of devices and associated usage profiles. Each consumer agent internally simulates a service platform oriented network with a scheduler for adaptive resource planning. A control unit processes information about probable usage periods to yield concrete points in time for switching devices on or off. Managed devices then announce the intention of usage to the scheduler planning the actual operation and sending the start signal to devices at appropriate times. This allows simulating the automated adaptation of an intended device usage to a variable tariff.

The internal model of adaptive consumers used within our simulation is also depicted in figure 1. Information about the time-varying probability of a device's usage is currently a property directly attached to the device model. Depending upon the current price the probability of device usage might change. From this information, the control unit may derive proposed periods of activity for each device. It is then the scheduler's task to alter these according to a given tariff and to produce an optimal schedule for all manageable devices. Concurrently, a steady metering of the electrical load induced by non-manageable devices results in statistical information about the average non-adaptive electricity consumption for given periods of a day. The information about non-adaptive electricity consumption together with information about scheduled device usage finally results in a load forecast which can then be used as input for a new tariff calculation.

The following device types are supported in the current prototype version:

1. Regulating devices: This device type encompasses appliances continuously connected to the electrical network and serving the purpose of keeping an environmental condition (e.g. temperature) within a tolerable range. Freezers, water heaters and air conditions are examples of such devices. For controller equipped devices the possibilities for current and future operating modes depend upon decisions taken in the past. Ant colony optimisation has been chosen to adapt behaviour of this type's devices to the current tariff, because it has been proven that the problem is NP-complete (Bremer 2006).
2. Programmed devices: After receiving a start signal devices of this type process a program. Typical representatives of this device category are dishwashers and washing machines. Planning for this device type is driven by a tabu search algorithm to find appropriate starting times (Vogel et al. 2006).
3. Non-adaptive devices: This device type encompasses appliances whose usage characteristics cannot be automatically modified by a scheduler without impact on comfort. Example devices are television sets and lighting. While scheduling is not appropriate for these devices, a scheduler can still learn their usage and load characteristic and use this information. For some special cases load characteristics can be also derived from environmental factors (e.g. daylight or outdoor temperature).

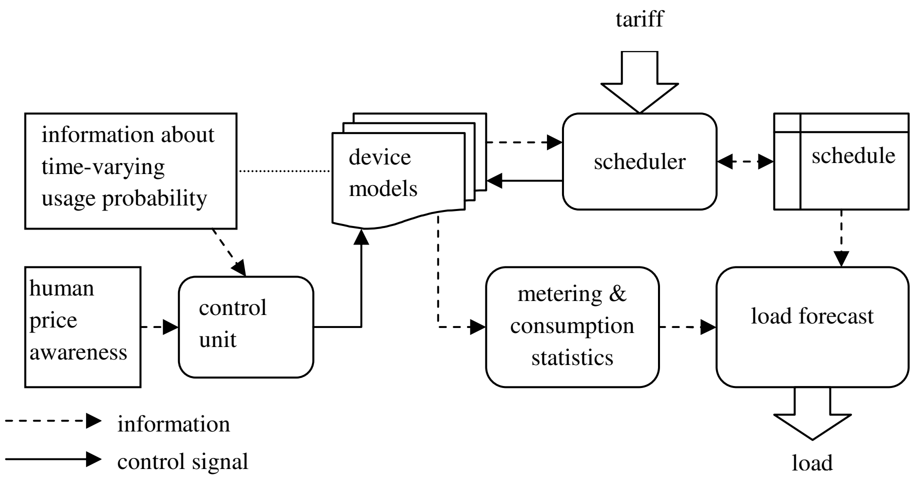

Figure 1: Internal model of an adaptive consumer.

The prototype already allows to model households having usage preferences associated to devices. In future increments of the simulator we want to take into account heterogeneous populations of consumers within residential areas, and integrate personal price awareness of individuals.

4. Modelling tariff calculation

The goal of tariff negotiation is the adaptation of energy demand to a desirable load level at any given point in time. Tariff negotiation consists of (1) tariff calculation based upon inputs from different sources (e.g. energy exchange, utilities, consumers) at different times and (2) a protocol based communication between those sources and the power company. Input to tariff calculation is contributed to by components generating electricity and by consumers of electrical energy. Inputs change with time, e.g. inputs from utilities generating electrical energy from wind power change due to time dependent weather conditions, and inputs from adaptive consumers about planned energy usage may change as reaction to tariff forecasts having being sent at earlier points in time. Therefore, tariff calculation should be repeated “from time to time”. Given the fact, that we want to analyse and compare different real-time pricing scenarios, both protocols and tariff calculation methods must be easy to modify.

The inputs needed currently for tariff calculation are – depending on the concrete method – (1) forecasts about the amount of electrical energy available from generators taken into account by the model and (2) forecasts about consumer load that are often based upon long-term experience. Optionally, it is possible to take regulatory constraints into account.

Tariff calculation yields a sequence of tariff messages either being a *forecast* or a *notification*. Each message carries a validity time interval subdivided into n time slices of equal length and a cost function for consumers to calculate their costs based on the electrical work used during each time interval.

There are many different approaches to calculate prices from the given inputs. So far, we have identified mathematical functions, fuzzy logic, rule systems and case-based reasoning as promising techniques (Rapp 2006). Further methods might be appropriate. For testing purposes, different mathematical functions for tariff calculation have been implemented in Java-Script files that can be exchanged dynamically. However, for reasons of flexibility implementation of other tariff calculation functions will be based upon JSR-94 compatible rule engines, an approach allowing rule-engines to be changed without changing other simulator components. So far, this was tested using the rule engines Drools (Drools 2006) and Jess (Friedman-Hill 2003).

5. Simulation engine

The simulator makes use of the Repast framework (North et al. 2006) offering a comprehensive infrastructure for agent-based modelling and simulations including mechanisms for communication and synchronisation. Agents do not pursue their tasks in real-time but execute concurrently based on a common global simulation time. Developing the ideas from (Rölke 2004) this allows for partitioning a complex process of interaction into independent, loosely coupled software entities.

Communication between agents is based upon the underlying simulator engine. To guarantee its extensibility, the flow of communication is specified within replaceable interaction protocols implemented through a control unit and a monitoring unit. Communication channels are configurable (e.g. by allowing for specification of bandwidth or message-delay by the modeller) and they are separated from the communication methods used (e.g. messages or handshakes). While inter-agent communication is unidirectional; bidirectional communication may be achieved by combining two unidirectional channels.

Aside from messages, events may influence the behaviour of agents within the framework. Whenever an event occurs, an agent may react to it or choose to ignore it. One possible reaction might be to send a message. Thus messages are both, based on events and can themselves possibly be the origin of events.

The simulator allows specification of contents, purpose and other properties of messages and moreover it offers a broadcasting functionality that can be used for agents sending a message to multiple receivers.

6. User interface for modelling and configuration

The simulator's user interface (Brunhorn 2006) allows to compose scenarios and to interactively influence simulation runs.

Models may be built using a number of freely positionable components that can be positioned within a specialised view. Those components represent power companies, generators of electricity, consumers of electricity and objects for modelling support (groups, aggregations and input variables). Each model component features inputs and outputs that serve for interconnection with other model components. By specifying a component's type, a modelling user implicitly specifies the allowed connections for that component, too. For certain types of model components it is possible to edit executable scripts that specify parts of the component's behaviour.

A further view serves the purpose of visualising selected data about the simulation's state after the start of a simulation run. A simulation run can be paused at any point in time, allowing user's to modify the input variables even during a simulation run.

The user interface is built modularly in order to support extensibility and adaptability. For example, extending the user interface to allow simulation of further component types does not require changes in existing source code. Instead, all component types and their specific properties are specified in an XML format. This approach allows for using the simulator's user interface in entirely different contexts.

The following code snippet illustrates a simplified specification of a power station component type:

```
<component type="agent" name="powerstation">
 <representation model="/md2/powerstation.md2" icon="/images/powerstation.png" />
 <output type="energy" name="energyOutput" min="1" max="1"/>
 <parameter name="maxenergy">
  <value type="integer">2000</value>
 </parameter>
 ..
</component>
```

A parameter view and an associated wizard allow specification of model parameters. Based upon the model's specification, these generate suitable input forms using specially adapted standard controls as text fields and selection lists, but also new controls developed on purpose as sliders and editable time series.

Model parameters are syntactically verified during input and are only stored internally after syntactical tests have been successfully passed.

Storage of model components and model parameters is based on JDOM elements (Hunter et al. 2006) that in turn represent an XML structure. This both facilitates extension to new model component types and parameter types and allows to store model data as plain text.

To keep the user interface appealing and at the same time reduce resource consumption, two techniques are used. The Standard Widget Toolkit (SWT) from the Eclipse project (Eclipse 2006, MacLeod and Northover 2001, Northover 2001) is directly based on methods from the underlying operating system thereby assuring most efficient execution. The modelling and simulation views are based upon OpenGL adapted to hardware acceleration of three dimensional, animated objects that can be used for representing all types of model components. Hardware acceleration almost consumes no CPU time and can thereby be used to render information about simulation state, simulation events and simulation results.

Exchange of scenario data between the user interface and the simulator engine is based on an XML-format different from the one for specifying component types and their properties. Interaction of users with running simulations and live display of simulation results is achieved through ring buffers.

7. A modelling example

In this section we present an example model, and a possibility of tariff negotiation together with the associated result. As depicted on the left hand side of figure 2 the example model consists of two wind energy conversion systems delivering wind power predictions, a single power company performing tariff calculation, and two adaptive consumers organized as a group. These agents are interconnected through communication channels to transmit messages. An interaction protocol containing a choreography for negotiating tariffs between the power company agent and the adaptive consumer agents is also part of the model.

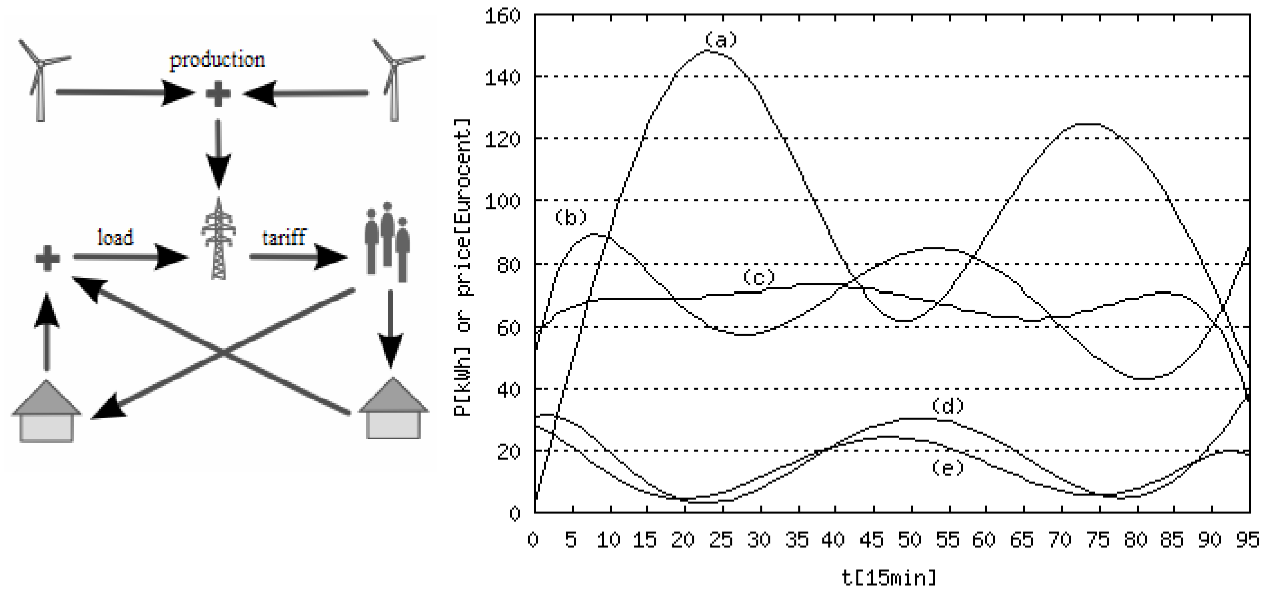

Figure 2: The schematised model (left hand side) and the result of one simulation run (right hand side).

The interaction protocol dictates the following procedure: After the power company agent has been prompted by the simulator to devise a new tariff, it requests a forecast on electrical power availability from the WECS connected to it. As reaction to this request, the corresponding agents provide power availability forecasts for each time slice of a time interval whose length has been defined beforehand. In parallel to this, the power company agent generates a load forecast based on historic information about consumer behaviour and on the power company's experience. By raising and lowering the price per kWh in different time intervals the power company tries to match availability and demand curves thereby being able to satisfy the demand. As a result, the power company sends a tariff forecast to consumer agents enabling them to schedule power consumption of devices. The resulting schedules are used by consumer agents as basis for a load forecast subsequently sent to the power company, which in turn compares the demand forecasted by consumers to the previously assumed demand. If demands correspond, the tariff forecast becomes a tariff notification which is then issued to consumers as valid tariff. Otherwise the power company agent tries again to adapt the forecasted demand curve to the forecasted availability curve. This process is repeated until supply and forecasted demand curves match sufficiently or another predefined stop criterion is satisfied. As mentioned above, tariff forecasts and tariff notifications consist of timed pricing information and constraints upon the maximum load usable by consumers to which the tariff applies. A tariff forecast differs from a tariff notification in that the latter is binding on all parties for a predefined time interval (e.g. 24 hours).

An exemplary simulation run of the model described above leads to the result depicted on the right hand side of figure 2, containing graphs on (a) the forecasted electrical power availability, (b) the power company's load forecast based on historic information as trend, (d) the initial tariff forecast as trend, (c) the final demand transmitted by adaptive consumer agents after scheduling their power consumption of devices as trend and (e) the power company's tariff forecast as trend leading to trend (c). Although not all graphs are shown in detail, an adaptation of energy demand against energy supply is recognisable. The achieved adaptation is not as good as possible because of the following reasons: The simulated scenario contains only two consumers, each with only a few devices. Thus load shifting potential is too small. Furthermore, low prices do not induce additional demand because no energy storages are involved.

While the described scenario of tariff negotiation is rather unlikely to be implemented during the next ten years due to its complexity, it is well suited to explain our tool's capabilities. Note however, that for reasons of simplification, non-adaptable consumers, base load power stations, and controllable power stations were omitted from the scenario.

8. Further work

Work on the modelling and simulation prototype has just been finished. The simulation runs to be conducted will serve the purpose of comparing different settings for real-time pricing among each other with respect to achievable load shifting. Scheduling strategies for adapting power consumption to dynamically changing tariffs will also be investigated.

To extend modelling of consumer behaviour we plan a number of extensions to the presented tool. These include support for modelling additional device types, e.g. required to deliver a given work at a specified point in time. It is also planned to provide support for automatic generation of heterogeneous agent populations in order to facilitate modelling of entire residential areas or growing wind farms. An other useful extension for consumer side modelling would be the inclusion of device types for modelling equipment able to store limited amounts of energy (e.g. fuel cells). Furthermore, a learning component could be used for optimising the scheduler. Renewable power stations can be modelled in more detail by using Homer (Lambert et al. 2006) so that it would be interesting to link our framework to Homer models.

The graphical user interface will be extended by views supporting analysis and comparison of results from different simulation runs. Furthermore it seems reasonable to develop a component to check some consistency features of models automatically.

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