A Tool for Modeling and Optimization of Residential Electricity Consumption

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Abstract

Today's households face a huge variety of electricity consuming devices on the one hand, and increasing electricity prices and increased awareness for environmental sustainability on the other hand. Fluctuating electricity tariffs currently evaluated by electricity suppliers have the potential to make it even more complex for the electricity consumer to keep costs low. We want to help the consumer to manage this complexity and increase her or his awareness for the electricity consumption of the household's devices. Therefore, we have developed a tool which allows to model and simulate the set of electricity consuming devices, their loads, and electricity tariffs. It is possible to create schedules for the usage of devices, calculate the resulting load curve and automatically optimize the schedule based on fluctuating power tariffs while paying attention to customer definable constraints. Furthermore, the tool allows to compare modeled and metered load curves, which is especially useful to evaluate correctness and completeness of the household's model. To decrease the modeling effort, the tool can access libraries of predefined devices and tariffs via the Internet.

1.   Introduction

Scarceness of energy resources causes energy prices to increase. Additionally, an energy supplier's problem is that the energy consumption varies strongly during a day and that the energy production of many renewable energy sources depends on particular weather conditions, like sunlight intensity or wind speed. To adjust imbalances between power demand and power supply on a short term scale, the production of expensive balancing energy is necessary. As the control of the production of renewable energies is constricted, Demand Side Management (DSM) is viewed as an additional approach to overcome this problem. The general term 'Demand Side Management' (Gelling and Chamberlin, 1988) summarizes all utility activities that influence use on the customer's side of the meter. A major focus in DSM is on energy conservation or energy efficiency, but by relocating loads from periods of low availability of electricity to periods of peak availability (load shifting) also a better match between supply and demand can be supported by DSM (Brauner et al., 2006), (Klobase and Ragwitz, 2006).

In the year 2004, German households consumed about 140 TWh of electrical energy. This is about 27% of the entire consumption of electrical energy in Germany (VDEW, 2004). But residential customers cur-

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rently consider electricity as a 'low interest product'. Tariffs for residential customers currently do not contain any incentive to contribute to the solution of the load balancing problem. But this situation is changing: currently a lot of research focuses on new methods to optimize power consumption by application of information and communication technologies (Franz et al., 2006). Motivated by this trend we started to design a software tool that allows residential customers to look into their electricity consumption in more detail. This has basically two aspects:

- First, it is in the consumers' interest to decrease their electricity consumption as far as possible. That way they can not just save money but actively support a healthier environment. The presented tool allows to model all power consuming devices of a household and show their impact on the household's total power consumption. Using the tool increases the user's awareness of electricity consumption and thereby gives the customers the basic skill to change their private set of power consuming devices for the better. This goal can be achieved instantly.
- Secondly, fluctuating power tariffs are addressed. With time-variable tariffs, the consumer's objective is to avoid power consumption whenever power becomes expensive and re-direct the usage of their devices for times when electricity is cheap. The introduced tool allows to create optimal schedules for household devices and, based on fluctuating tariffs, predicts the total power consumption and cost.

2. Scope

The main focus of the introduced tool is modeling residential electricity consumption for increasing the users' awareness for energy consumption. It assesses the substitution of household devices by more energy efficient ones and computes the costs of the usage. In particular, the tool allows to model the schedule of household devices and to calculate the cost of a schedule depending on fluctuating power tariffs.

Time varying tariffs are currently used with some large customers and sometimes in a restricted manner for off-peak power in private households. In order to reduce balancing energy, dynamic pricing is also researched for controlling the energy demand. An introduction to dynamic pricing programs, where electricity prices vary depending on current production costs can be found in (Borenstein et al., 2002). The concept and the acceptance of dynamic pricing in private households have been researched e. g. in a field test in Eckernförde, Germany (Prager, 1997).The California Demand Response Program researches the problem of of establishing time-varying power tariffs in California (Orans et al., 2006). In (Sonnenschein et al., 2006) also a tool for modeling and simulation effects of real-time-pricing for households was introduced. That tool integrates a modeled reaction of a group of households to a dynamic power tariff, but the tool is not intended to be used for the analysis of a single household.

The project BEMI of the University of Kassel aims at developing a control tool for household devices (Bendel et al., 2006). Unlike our system, BEMI is designed to control specific devices dependent on fluctuating electricity prices. Furthermore, BEMI treats the input of renewable energy produced by the household into the power grid .

3. Requirements

The essential functional requirements for our software tool are:

- The modeling of a household with all of its electrical devices, their usage and their power demand, as well as diverse tariffs must be supported.
- The comparison of (measured or computed) load curves must be possible, in order to locate the hidden load, which is caused by devices running in the background without user's knowledge or awareness.

- Users of the software should be supported in identifying the influence of single devices on the total electric power consumption.
- The application should be able to suggests the substitution of devices with devices of lower energy consumption.
- Based on dynamic energy prices, a scheduling component should compute a low priced schedule which also respects usage constraints.

4. Model

The model of an household consists of the following concepts:
- An electrical device is characterized by its energy efficiency grade, and a set of operational modes, which can differ in their energy consumptions. For example, a vacuum cleaner can be able to operate at 500, 800 or 1000 watts.
  The energy consumption of a device can be constant or modeled as a load curve. Furthermore, a device can be member of one or more device classes, whereas every device class describes a specific device feature. For example, a microwave oven might also have the feature „barbecue" as part of the device's specification.
- Device compositions allow the aggregation of a set of devices, for example VCR, TV and sound system. Device compositions can be handled like single devices. They can appear as one task within a schedule or within another device composition.
- An electricity tariff defines the price of electricity for the customer. It can be constant, or time varying. Typically one tariff describes one utility's electricity offering.
- The envisaged usage of electrical devices is determined by a schedule. In a schedule, the user associates devices with an activation interval, a duration of usage, and an operational mode. Every entry in the schedule is referred to as a 'task'. Tasks can be related by constraints which restrict the activation times of the corresponding devices. Possible relations are parallel or mutual exclusive execution of tasks or ordering of tasks.
- A schedule is also attributed by a tariff allowing to calculate the total electricity cost of a schedule. In the case of time varying tariffs, a schedule can be optimized by setting all activation times to starting times in the activation intervals which fulfill the given constraints and cause minimal cost.
- A load curve describes electricity consumption of a single device, a device composition or the household over time.

Being aware of the huge amount of information that is necessary to model a single household and the time necessary to do the modeling, databases are needed to store predefined device information and tariff information, resp. These database can be downloaded by the modeler from a dedicated Internet server, which is in particular essential for the use of dynamical day-ahead announced tariffs.

5. Realization

The project has been conducted by a students' project at the University of Oldenburg, Germany. In a project group, a team of students has to fulfill all demands of modern software engineering from requirements analysis to the delivering of the product within one year and with an average work load of 16 hours per person per week.

The solution for the given problem consists of a Java 5 based desktop application and a web-based server. The desktop application can act as a client to communicate with the server, but it is important to note that the desktop application neither depends on the server nor on any network connectivity to be fully functional.

5.1 Server

The server's goal is to act as a data source for the user. It maintains libraries for devices and electricity tariffs. Both can be administrated via a web interface and can be imported by the desktop application.

To facilitate a fast growth of the device library, a device which has been created within the desktop application can directly be uploaded to the server. For ensuring quality control, uploaded data must be approved, before it can be downloaded by other users.

Furthermore, the server can automatically import electricity tariffs from various online sources to keep the tariff library up to date.

5.2 Client

The desktop application offers in its interface three perspectives for handling the basic tasks of organizing data, scheduling devices and examining results :

- The "Profile Perspective" provides the environment for creating, editing and organizing devices, device compositions and tariffs, and for storing them in the profile directory. Entities can be copied from the device or tariff library. This perspective also allows to import load curves from CVS files. For detecting hidden consumers, the profile's 'completeness' can be checked against a commonly available equipment of households. The application ships with a predefined set of device groups, whereas every device group is a set of device classes. For example, the device group "kitchen" contains the device classes "stove", "water heater", "oven", "microwave", etc. If the user selects "kitchen" she or he can check, if the created profile contains devices for all the mentioned device classes.
- The "Scheduling Perspective" provides functionality to create and edit schedules. If a time-varying tariff is used, the schedule can be optimized automatically. Additionally, a guided substitution of present devices with more energy efficient devices is supported. Based on energy efficiency grade and operational mode appropriate suggestions for the schedule's devices are made.
- The "Statistic Perspective" allows to visually compare graphical representations of calculated load curves, tariffs, and the resulting cost of a schedule, and to calculate statistical values.. That way the user can quickly examine which schedule or substitution leads to minimal total energy cost, or minimal total energy consumption based on their priority. Furthermore, measured loads for a set of devices or a complete household can be compared with calculated loads of the same devices. Detected differences trace back to an insufficient quality of device data, or to devices the user has not modeled yet.

Every data structure is defined using XML schema (XSD) and stored as an XML file, which are all located within the application's workspace, also referred to as "profile". Apart from XML files, the profile can contain arbitrary sub folders. The desktop application is based on the Eclipse Rich Client Platform (RCP) and utilizes Eclipse's Workbench concept for perspectives, editors and views. Visualization is done using the Eclipse GEF's Draw2D component. All persistent data structures are modeled as XML schemes and the Eclipse Modeling Framework (EMF) has been used to automatically generate the data model's Java implementation from it.

The server uses the same data structures, but stores them persistently in a Postgres database using the EMF extension Teneo and the persistence and query service Hibernate to bridge the gap between the EMF based model and the SQL based database. Thus, the server runs in any servlet container, providing a web based interface for administration and XML based communication with the desktop application.

The developed software is released as open source software (https://sourceforge.net/projects/diem/), which makes the application available and usable for everyone having a personal computer.

6.   Example

This section gives an example how to create a profile, to schedule the household's devices and to analyze the resulting schedule with the given software.

6.1 Profile

Modeling a household starts with creating a profile which contains the household's devices and electricity tariffs. It is recommended to start with an update of the devices' and tariffs' library from a central server, since the library serves as copy&paste source for devices and tariffs and therefore helps to keep the effort of modeling as low as possible. Figure 1 shows the profile on the bottom left and the two libraries above the profile. The language of the GUI is currently German, but by using the Eclipse string externalization mechanism in the software it is easy to translate the text in the GUI to other languages.
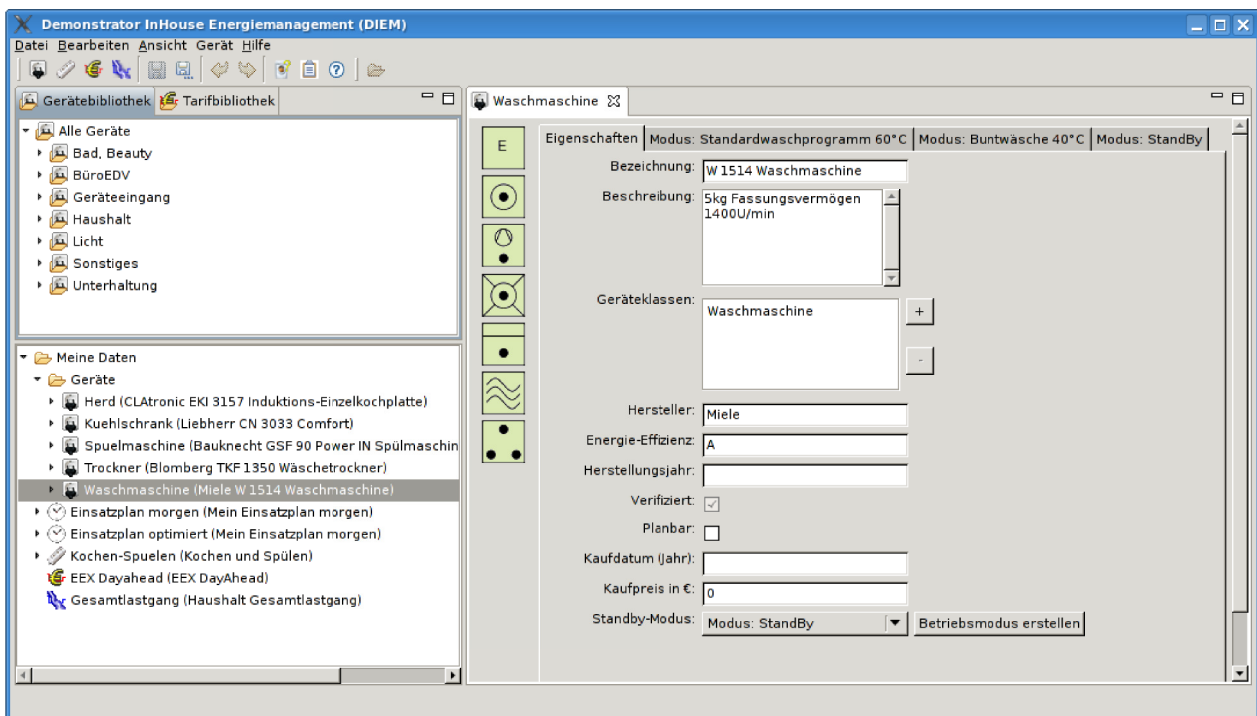

Figure 1: Profile View

When a new device is created (by clicking on 'Datei' ==> 'Neues Gerät'), a device editor opens. The input mask is shown in Figure 1 on the right side. Next to the properties tab ('Eigenschaften'), there are tabs for every operational mode of the device. The most important property of every mode is its power consumption. If it is not found in the library, it has to be obtained from its documentation (e. g. type plates or manuals). The tool also allows to import a measured load curves for an operational mode of a device. This allows a more detailed representation of the time dependent energy demand.

Data acquisition can be quite a time-consuming process, if the device library has to be manually replenishedt. But as the household's electricity consuming devices have to be identified, the user benefits from this by a raised consciousness of his or her electricity consumption.

If the tariff library does not provide the used tariff, the tariff editor can be used for creating adequate tariffs . Fixed-price tariffs are described by the price per kilowatt hour. Time of use tariffs and real-time-pric-

ing are defined by time-price-pairs for each variation of the price. One can set and edit these pairs with the graphical editor.

6.2 Schedule

To schedule devices for future use within a household, the user has to switch from the 'Profil' perspective to 'Einsatzplanung' and create a new schedule. Figure 2 shows the schedule editor on the right hand side. It's properties tab contains general information like the schedule's start time and it's duration. The other tab contains the actual schedule editor which holds the scheduled devices. Devices or one of their operational modes are added by moving them via drag&drop to the schedule editor. Thereby they become tasks that can be moved to the wanted position using the mouse or by specifying the absolute values in a dialog that is available via context menu. Tasks can also be configured to be base loads, which means that they are active from the beginning to the end of the schedule.

Constraints like mutual exclusion or succession of tasks can be specified visually by drawing a connection between the connection points of tasks. Depending on the point's position a mutual exclusion, parallel execution or succession constraint is created between these tasks. In case of ambiguities, a context
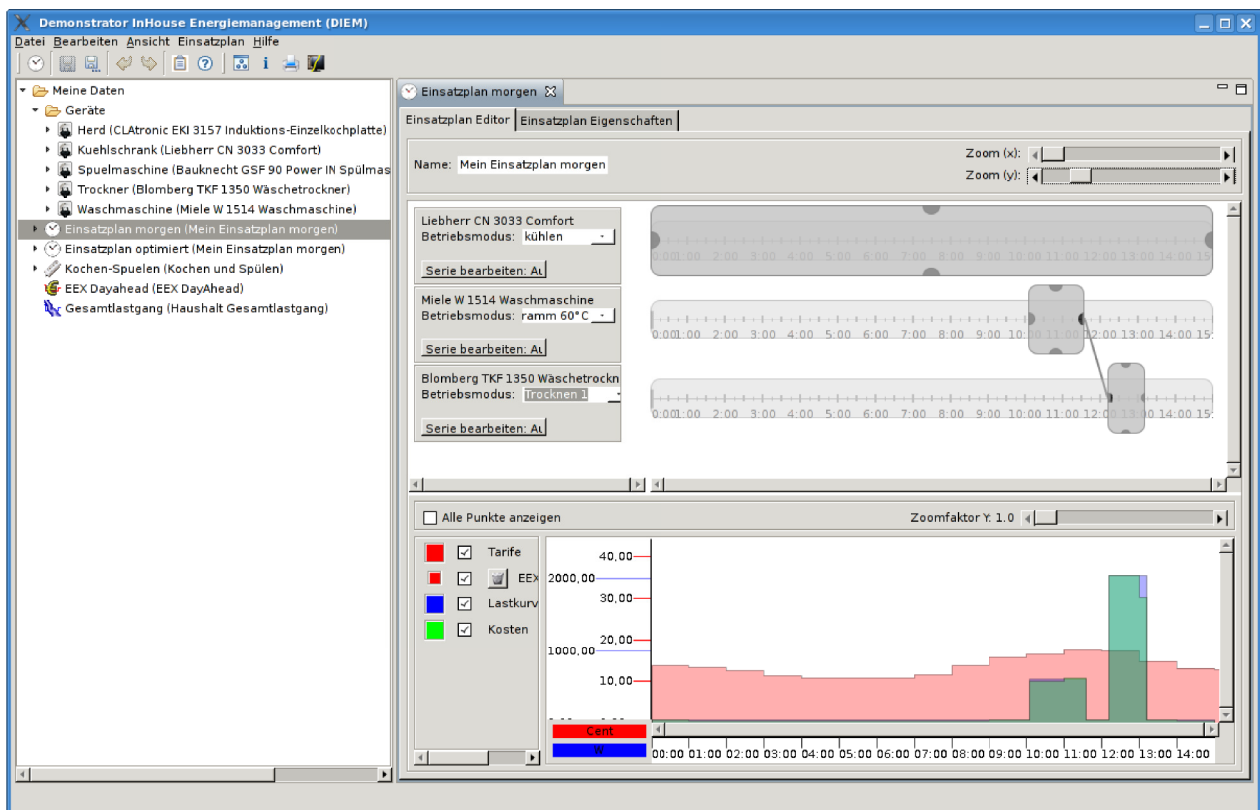

Figure 2: Schedule View

menu asks for a choice. The editor hints to unsatisfiable sets of constraints by highlighting them.

Thethe lower area of the schedules' editor visualizes the associated tariff, the schedules power consumption and the resulting costs. They are distinguished by colors that can be configured manually. The graph in this area is refreshed instantly if changes in the schedule occur.

The automatic schedule optimization algorithm ('Einsatzplan' ==> 'Autom. Einsatzplanoptimierung') tries to find a schedule with minimal cost, which takes into account the earliest start time and the latest due time for each task as well as the defineded constraints.

6.3 Statistics

To work with the created schedules the tool allows the comparison of tariffs, load curves and the calculated cost curves for schedules in the Statistics perspective. Figure 3 shows two views of the statistics perspective on the right hand. The upper part here visualizes tariffs as well as cost curves. Our example shows one tariff and the cost curve of a user defined schedule for doing the laundry around noon (peak costs around 9:30 and 11:30) on the one hand, and the cost curve for the optimized schedule on the other
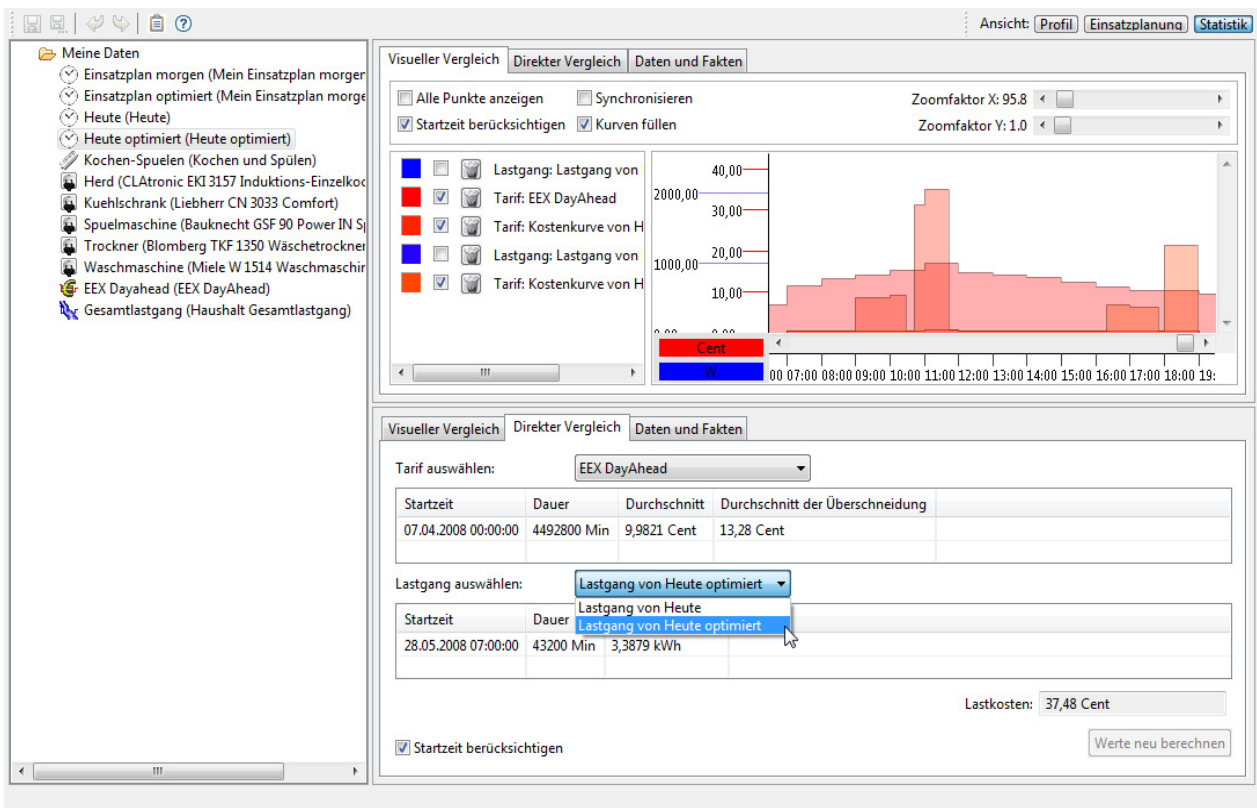

Figure 3: Statistics View

hand which suggests to do the washing in the evening (peak costs around 17:00 and 18:00). It is easy to see that the peaks of the optimized schedule are lower and hence the resulting total costs are less. Therefore, the operation of the devices will be favorable in the evening.

The lower part of the statistics perspective illustrates this result by the means of calculated costs for each alternative. The user may choose the attribute to be calculated from a drop-down box. In this example, the operational costs of the scheduled devices could be reduced from 52,74ct to 37,48ct which is about ~30%. Naturally not all devices are that easy to optimize, so this result should be seen as an optimistic demonstration.

7.   Conclusion

The application provides an easy way to model a household's device set and its energy consumption. It helps to detect hidden energy consuming devices of which the user might be oblivious, calculates an optimal schedule for devices based on a fluctuating tariffs and can suggest more energy efficient devices. Thereby, the application increases the consumers' awareness for electricity consumption and helps to save electricity as well as to decrease the amount of money spent for electricity.

To archive a good support for generating household models, it is essential to offer high quality and quantity of device data. So far, the device library has been built up manually in a very time consuming process. It would be interesting to establish device libraries for business enterprises which would support them to optimize their energy consumption with the presented tool.

For future prospects, it is worth considering to increase the applications interactivity with its environment, for example, to provide interfaces for load measurement tools and to provide controllers to automatically execute schedules.

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