Simulation Tool For Energy Consumption and Production

The development of a simulation tool for measuring the impact of a smart grid on a building

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Abstract—In order to promote adoption of smart grid with the general public it is necessary to be able to visualize the benefits of a smart home. Software tools that model the effects can help significantly with this. However, only little work has been done in the area of simulating and visualizing the energy consumption in smart homes. This paper presents a prototype simulation tool that allows graphical modeling of a home. Based on the modeled homes the user is able to simulate the energy consumptions and compare scenarios. The simulations are based on dynamic weather and energy price data as well as a controller unit of the user's choice. The results of the simulations can be compared using a dynamic reporting window that allows the user to create custom charts of the data. The application has been designed such that it can easily be extended with additional controller units, price and weather data as well as appliances and other electrical components used in the modeled homes.

Keywords-Smart grid; simulation; modeling; controller; smart home; software; graphical user interface; end-user application;

I. INTRODUCTION

According to a Danish workgroup [1], the government needs to increase the awareness of the smart grid technology with the consumers to smooth the transition to smart grid. Following the above mentioned recommendation a tool that helps people realizing the effects of smart grid integration in private homes is needed.

The power grid today is highly affected by variations in the use of power during a day. The energy use during the night is very low, but the use of energy increases significantly during a couple of hours in the morning, afternoon and evening (called peak hours) when people come home from work. Today the demand in these peak hours are met by powering up so called *peaker plants* that can be started up rapidly when more power is required [2]. These typically run on oil or natural gas and are very expensive to operate. Furthermore, they produce a significant amount of pollution [3]. In some countries the consumption in the peak hours is reaching, or even exceeding, the full capacity of the grid and results in frequent power outages [4]. A way of shaving these peaks in consumption would be to give the consumer a motivation for moving her energy consumption to other periods of the day. Such a motivation is likely to be of economic character, e.g. by making energy cheaper outside of peak hours.

In order to maximize the economic gain of dynamic pricing, energy should be consumed at the cheapest possible time. Several systems [5, 6], so called *controller units*, have been developed that control the energy consumption in the home by automatically increasing consumption when the prices are low and decreasing consumption during peak hours. This includes the Control4 EMS 100 controller system [5] and Tendril Connect [6] among others. Both of these systems can control any energy consumption in the home such as heating, lights and appliances as well as charging electric vehicles.

A. Network Architecture of the Smart Grid

The smart grid is based on a tiered architecture of a number of networks that connects all the parts of the smart grid, from power plants to the private home. The communication goes both ways so that each partner in the smart grid can communicate with each other, in theory. The smart grid can be divided into three main networks; Wide Area Network (WAN), Neighborhood Area Network (NAN) and Home Area Network (HAN).

The solution described in this paper only focuses on the HAN, as this network is responsible for the communication between the appliances within the house. There are currently two overall approaches for constructing a Home Area Network without looking at which technologies to use. Common for both of the approaches is that a smart meter is connected to the HAN along with all the appliances.
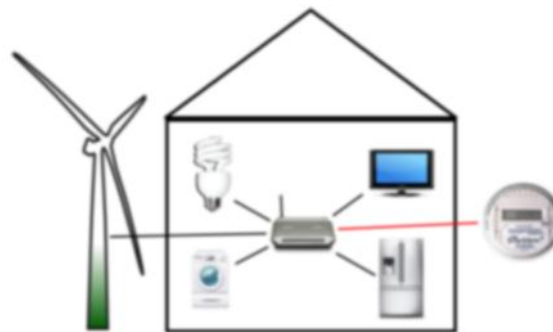

Figure 1. An example of a centralized HAN.

- A Decentralized HAN solution is where each appliance on the network will be responsible for their own scheduling. Each appliance is communicating with the smart meter directly using the chosen standard and they contain embedded controller software that based on the current power price decides how the appliance should act. This price is the current market price for a kWh which the smart meter receives from the distribution network.
- A Centralized HAN network is a network where all the appliances are connected to a router which may be connected to the Internet. The smart meter and a control unit are also connected to this network. In this scenario each of the appliances, which are connected to the network, only provides a software interface that can be used to control the appliance. This interface can then be accessed by the controller unit on the HAN. The controller unit will control the appliance based on the power price information that the controller unit gets from the smart meter.

A Home Area Network in itself does not provide any intelligence to the home. This intelligence comes from the controller units connected to it (or partly by the individual appliances). By making the consumer aware of the dynamic prices she can save a significant amount of energy. A report from California Energy Commission [7] states that the average household can save 34.5% through technology used to inform people of the varying prices and each units automatically adjusting their consumption according to the price. In order to maximize the benefit from this information, however, one needs something that can control energy consumption 24 hours a day. This is the so-called *controller unit*. A controller unit is placed in a centralized or decentralized HAN (here it is actually not a physical unit, but a unit distributed in all devices). The centralized approach can be divided into two types of controller units: A physical unit installed in the home that controls each unit based on the customer's preferences or an external service communicating with the household over e.g. the Internet.

B. State-of-the-Art Simulation

A number of simulation tools that examine the energy consumption in homes have been developed. Many tools such as GridLab-D [8] and EnergyPlus [9] examine the energy consumption with focus on heat generation and thermal load of a building. Very few tools examine the home in the context of a smart grid where the price of energy varies throughout the day. One of the few tools that were found is PowerMatcher Simulation Tool [10]. It is, however, only intended to demonstrate the PowerMatcher technology which is a home controller system and the tool is therefore limited in features. It does e.g. not provide any means of modeling accurate energy consumption patterns based on many independent appliances, but simply allows the user to create a static *energy demand* [11].

None of the existing simulation tools consider the effects of using different controller units for controlling the home's energy consumption and none of them provide a modeling environment that allows the user to create an accurate representation of her home to be used in the simulations. This means that the existing tools cannot properly show a consumer how turning her home into a smart home will be of value to her. These points are addressed in this work.

The remainder of this paper is organized as follows. Section 2 describes the identified requirements for the simulation tool and the targeted audience. Section 3 presents the core features of the prototype simulation tool and shows the Graphical User Interface (GUI). Finally, conclusion and future work are presented in sections 4 and 5. For an extensive explanation of the developed tool see the report that this paper is based on [12].

II. SOLUTION REQUIREMENTS

The simulation tool that was developed in this work can provide reasonable simulations of how a private household is (financially) affected by a smart grid implementation. The simulation tool focuses on allowing the user to create a virtual household and add electrical appliances (washing machines, dish washers, refrigerators etc.) as well as local energy sources (such as wind turbines, solar cells etc.) to the household using a user friendly drag-and-drop approach. The focus of the simulations is to see how different scenarios affect the power bill when the energy consumption is controlled using various controller units.

In order to simulate this, the application will use environmental variables which includes the weather (affecting power generated by wind turbines, solar cells etc.) and the prices of buying energy from external energy sources at any given time. Most of these variables will be importable from real sources or manually configurable. The application supports the creation of multiple home scenarios and lets the user compare these, giving the user the possibility of evaluating the value of potential appliances that might be added to the house in the future. The scenarios can also be executed without smart-scheduling, thereby allowing the user to compare the scenarios with and without smart-scheduling enabled to see the effect of using controller units to schedule the energy consumption.

A. Target Audience

Three groups of people have been identified as potential users of the application. These groups are *the consumer*, *energy advisers/salesmen* and *educators/educates*. Each of these groups has been analyzed and their preferences in four categories have been compared: *Focus, Interaction with Tool, Desired Output* and *Generic vs. Real Data*. *Focus* refers to what the user wishes to achieve when using the application. *Interaction with Application* indicates what is most important to the user in the way she interacts with the application. *Desired Output* is the kind of output that supports the focus of the user in the best way.
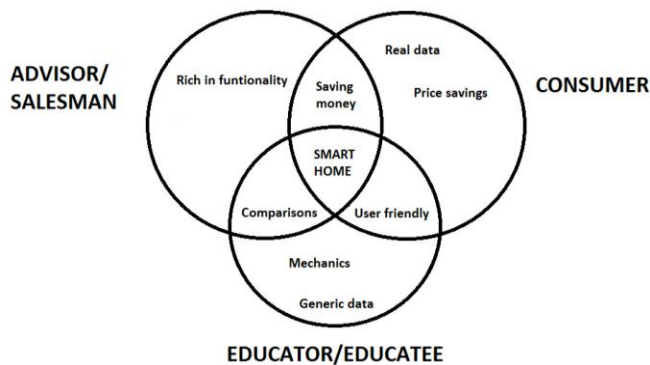
Figure 2.   Shared interests between target audiences.

Finally, *Generic vs. Real Data* refers to whether or not the user prefers realistic data about weather, energy prices, and more importantly manufacturer specific appliances or generic versions of the appliances and customizable weather and prices.

The three user groups have a number of shared interests that they find important; Money savings, user friendliness and scenario comparisons. From the three main focus areas of the program it seems realistic to develop an application that can be used by all three user groups. Therefore the target audience is a combination of the three user groups.

B. Electric Components in the Home

In order to give the user the best possible results, the program needs to be as realistic as possible when modeling scenarios that they want simulated. Therefore the program has to contain realistic and user-customized content.

In the program a home can consist of a lot of components such as lights, refrigerators, freezers, computers, TVs, washing machines etc. Some of the components, such as washing machines, can be scheduled based on dynamic prices while others, such as TVs, computers and lights, cannot. While you can still implement energy saving initiatives for non-schedulable components such as automatically turning off the components when you're not home, the work described in this paper focuses on how components can be scheduled based on dynamic prices during a day. Therefore components will be placed in two groups; schedulable and non-schedulable components. Schedulable components will, as the name indicates, be scheduled by the simulation based on the dynamic prices, whereas the non-schedulable components will simply be run during a user-defined period each day regardless of the electricity price.

III.   SOLUTION PRESENTATION

When the developed application is started the user is met by the main window. This window is shown in Fig. 3 and the four main regions of the program are marked.
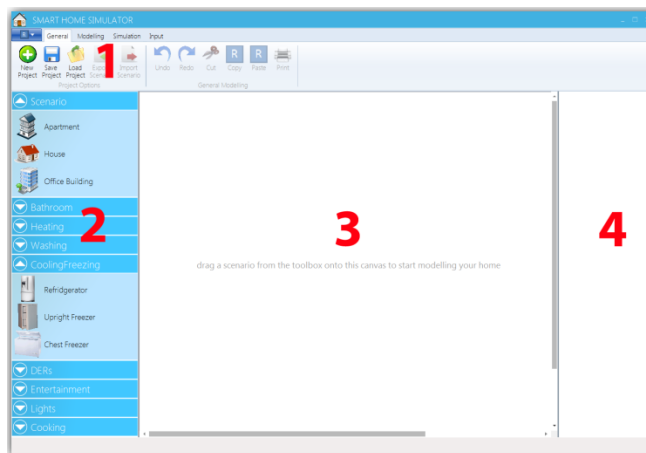

Figure 3.   The main window of the application with each of the primary regions marked.

1. **Ribbon navigation**: This region provides the user with various options to manage the project including created models and simulations.
2. **Toolbox**: This region contains all the elements that can be used when modeling a home.
3. **Canvas**: The elements from the toolbox can be dragged onto this region to create the desired models of houses.
4. **Summary**: This region provides a brief overview of the yearly power consumption distribution in the modeled homes.
A. **Input**: The application provides data about power prices and weather to be used during the simulations.
B. **Simulation**: The simulation component of the program simulates the consumption of the modeled homes and provides the results to the user. This is not shown in Fig. 3.
C. **Reporting Window:** The reporting window allows the user to analyze the results of the simulations provided by the simulation component. This can be seen in Fig. 8.

The user can now start adding content to the Canvas (3) by dragging elements from the Toolbox (2) onto the Canvas or he can go through the options within the ribbon navigation (1). Initially the text on the Canvas informs the user that he can drag elements onto the canvas to start modeling. If the users choose to add content to the Canvas (3) the text on the canvas will change to inform the user of the next step, i.e. adding components. Once the user adds components to the scenario the Summary (4) will update. The summary region will contain a sum up of the content currently on the canvas, with information about their estimated yearly consumption and their overall part of the consumption of the house (Scenario).

A. Modelling - Toolbox

In the left side of the program's main window is a toolbox containing all the elements that can be dragged onto the centered canvas. The toolbox is divided into logical categories where each category contains the elements related to it. The *Cooking* category could e.g. contain an oven and a stove as well as other cooking appliances. Clicking the expander arrow of a category unfolds it and clicking it again collapses the category.

It is possible for the user to create new, delete or edit existing toolbox elements. This allows them to create exactly the elements that they use within their home and reuse them in another project. When the user wants to edit or delete elements they can do this from two places; from the modeling tab in the Ribbon and from a context menu that appear when right clicking on an element. Creating new elements can only be done from the modeling tab in the Ribbon.

When choosing to delete or edit an element through the Ribbon the users will be prompted with a simple window where they can choose the element to edit or delete. When the user chooses to delete the element from either the window above or from the context menu, the element is deleted and will be removed from the toolbox.

When choosing to edit an element the user is prompted with a new window which contains all the possible properties which can be edited on the selected element. Before saving the changes the input values are verified in order to ensure that they are of the correct format. It could be that numbers do not contain letter and so on.
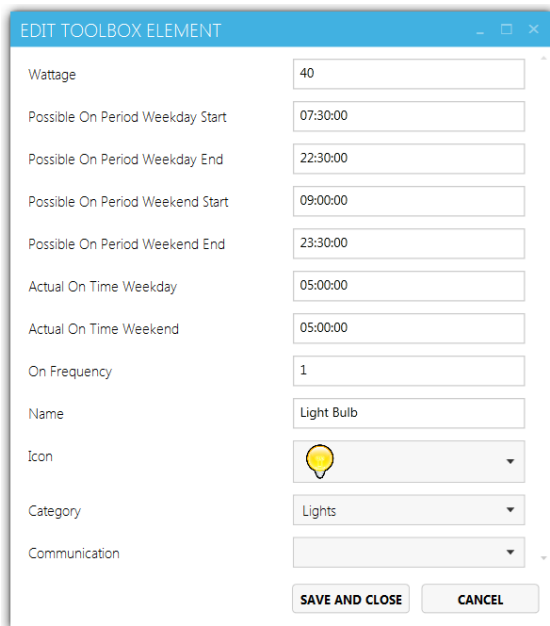
In Fig. 4 a screenshot of the edit window can be seen, containing fields and values related to a Light Bulb element. As seen in the figure two buttons are placed in the bottom of the window. These buttons allow the user to cancel changes and close the window or save changes and close the window.

The window for creating a new element is very similar to the edit window. The main difference is that when creating a new element you need to choose which type of element you want to create before the related fields will occur. When new elements are added to the toolbox it is automatically refreshed to include the new element.

B. Modeling - Canvas

The canvas is a crucial part of the modeling in the program. It is responsible for containing and presenting the result of the users modeling actions. Graphically the canvas is only a white background, but the elements which are shown on it are represented by an icon and some small buttons used for control and information.

The estimated yearly consumption of the component is shown in the top right corner of its icon (see Fig. 5). The color indicates how high the consumption is; the darker red, the higher consumption. The component can be edited by right clicking it or through the controls that appear when hovering the mouse over it.

When modeling a home the components added to the home are connected via colored lines. The colors of these lines represent the category the component belongs to as seen in the toolbox.
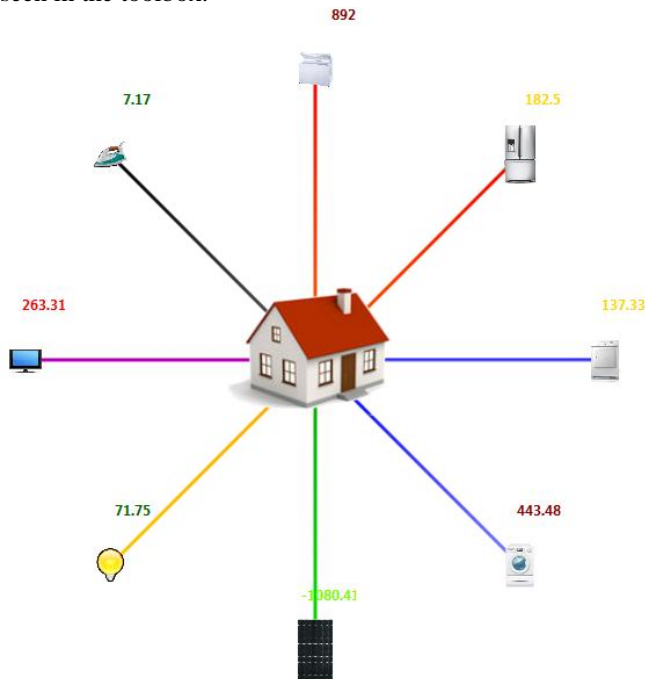

Figure 4.   The Edit Toolbox Element window that allows the user to edit properties of an element in the toolbox.

Figure 5.   Example of a modeled house with eight connected components.
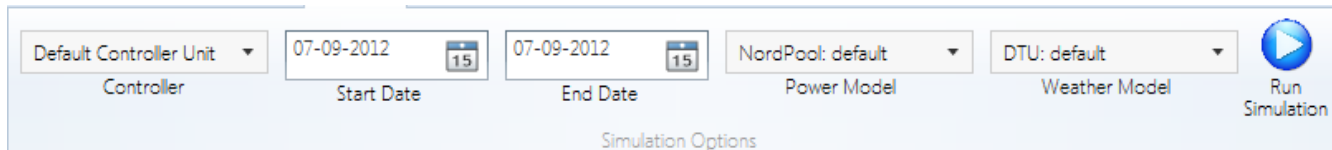
Figure 6   The simulation tab of the ribbon navigation menu.

C. Modeling - Summary

As mentioned above a graphical summary of the estimated consumption of the scenarios on the canvas is shown in a view to the right of the canvas (see Fig. 7). The summary contains a section for each scenario on the canvas in which the consumptions of the components connected to the scenario is summed up and grouped by their category. The estimated consumptions are also displayed as a pie chart along with an estimated total yearly consumption for the scenario. The color of the categories is the same as the colors used by the lines connecting the components with the home. This makes it a lot easier for the user to identify which components are members of what category such that the reasons for a high consumption in a particular category can be identified quickly.
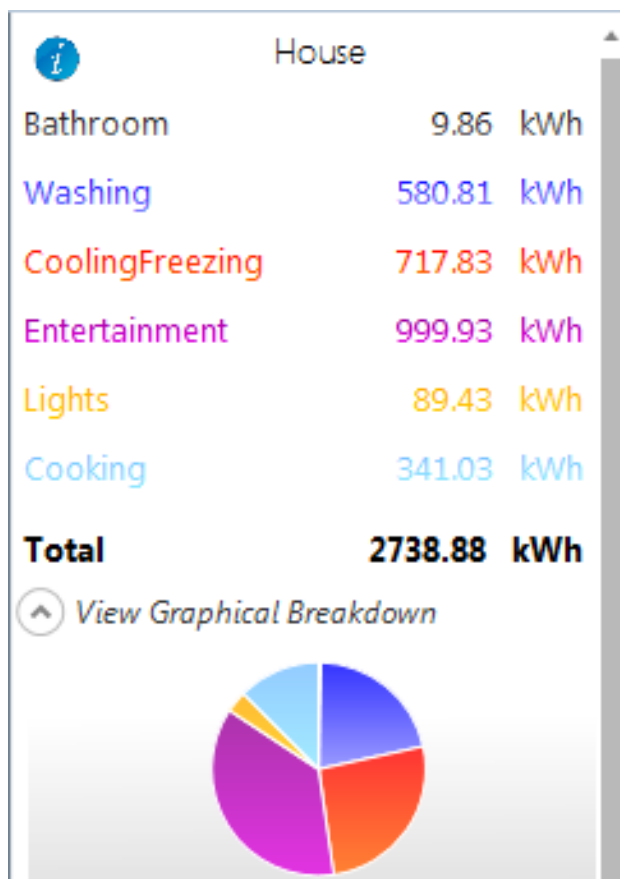

Figure 7.   The summary displaying a breakdown of the consumption of a scenario.

D. Input Data

There are currently two types of input windows in the solution, one for weather data and one for power data. They are two very similar windows in which it is possible to retrieve data from a selected data provider. The window can be accessed through the buttons from the input tab in the ribbon navigation. In the top of the window is a drop down menu containing the providers you want to retrieve data from. Multiple different weather and power providers can be added to the application and selected here. Next to the drop down menu are two calendars where the user can select the start and end date for the period that he want to retrieve data for. Clicking the "Get Data" button retrieves the specified data and displays it in the window. In the current implementation no CO_2 data is retrieved although it is part of the simulations as there are currently no accessible sources for this information.

To create custom data models the user can add or edit values in the fields by selecting the field with the cursor and then typing the new value into the field. This enables the user to create her own examples of data for special events like storms or increasing oil prices and use these when performing simulations.

E. Simulation

To perform a simulation the user has to navigate to the Simulation tab, which can be seen above in Fig. 6. In this tab the user can either inspect previously performed simulations or perform a new simulation, as described in this section. Before starting a new simulation the user has to consider the values in the five settings controls to the left of the "Run Simulation"-button.

As seen in Fig. 6 the users starts off by choosing which type of controller they want to use for their scheduling. The application supports having multiple different controllers using different simulation strategies to choose from. Then the users need to set the time span that they want to run the simulation over, by setting a start and end date. Finally it is possible for the users to select which power and weather data they want to use for the simulation. Here it is possible to select the earlier created input models (Weather and Power), such that they can simulate a user created setup. To run the simulation the user presses the "Run Simulation"-button and then waits for the program to notify when the simulation is finished. While waiting, the user can see the progress of the simulation in a window that opens when the simulation starts.

The simulation divides the modeled components into two main groups: Components which consumption can be automatically controlled and components which are turned on and off manually by users. Components that can be controlled will be scheduled based on the price model chosen for the simulation such that the total consumption of the component is as small as possible while still respecting defined rules for the component such as temperature limits for refrigerators or total on-time required for washing machines. Components that cannot be scheduled will consume energy based on the pattern defined by the user when modeling the scenario. The algorithms used for calculating the consumption of components are very general and the intention is that the prototype is extended with models of real components containing more specific calculations for the given component. The consumption of the components is calculated independently of each other.

F. Reporting

Based on every simulation performed, one or more reports can be made. A report consists of an overview of the simulation results along with a number of charts. The reporting window lets the user see and edit the reports of a simulation. The reporting window can be found either by clicking on the *"Show Report"* button when a simulation is finished or by choosing an older simulation in a drop down menu in the ribbon and clicking on the *"Inspect Selected Simulation"* button. The reporting window can be seen in Fig. 8.

At the top left is a drop down menu saying *"Apartment"* in Fig. 8. This menu allows the user to choose for which home to show the simulation result (in this screenshot the name of the chosen home is *"Apartment"*). The chart called *"Overview"* shows the consumption pattern of each of the components of that home in the simulated period.
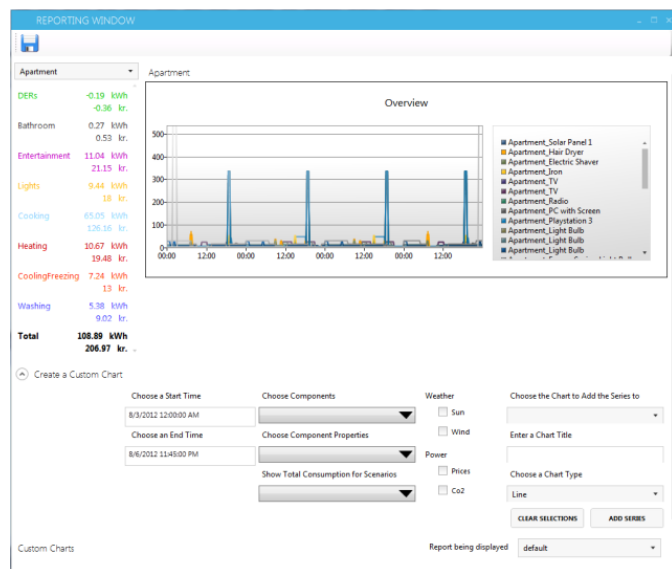
The x-axis shows the time and the y-axis shows the consumption at the given time in watt-hours. To the left of the overview chart is a view very similar to the summary. This area works similarly, but instead of showing the estimated yearly consumption it shows the consumption in the simulated period for each category as well as the total price for the power used by each category. These values are from the actual simulation rather than estimations and should therefore be more accurate than the ones found in the summary in the main window. These categories are also shown in the specific color of the category as in the summary. Upon cursor hovering over each category an estimation of the yearly consumption, price and CO_2 emission can be seen, calculated by scaling up the simulated results to match a year. Therefore the longer the simulation period is, the more accurate these results become (see Fig. 9).

Below the overview is a region called *"Create a Custom Chart"*. It provides the user with controls to create charts based on the simulation results. The charts can be generated from a wide range of parameters. The first column of controls allows the user to choose the start and end time of the data for the new chart. By default this is the first and last data entry of the simulation result. The second column allows the user to select which data series to add from the model. In the first drop down the user can select what components to include in the chart. The second drop down holds the properties to be displayed for the selected components such as price, CO_2 emission, consumption or on-time intervals. The last drop down allows the user to add data series to the chart that shows the total consumption of the homes selected in this drop down. All three drop down menus allow for multiple elements to be chosen at the same time.

Figure 8.   The reporting window used to analyze the results of a simulation.
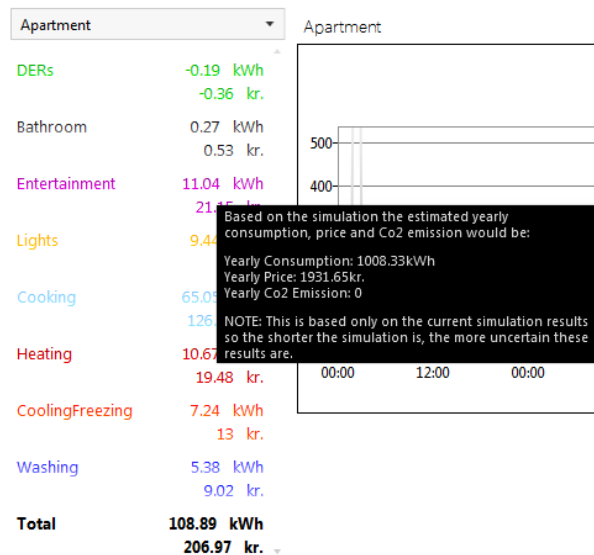
Figure 9.   A screenshot showing the tooltip displayed when hovering the cursor over a category in the overview.

In the third column the user can choose which input data to display in the chart such as wind speeds, power prices etc. By adding these it becomes easy to see how the components have been scheduled compared to the fluctuating prices and weather. The final column specifies information about the chart that should hold the series specified in the other columns. The first drop down allows the user to add series to an existing chart or to choose to add them to a new chart. If *"New Chart"* is chosen (i.e. leaving the value empty) the user can specify a title and a chart type (line, bar, pie etc.) for the chart. Clicking the *"Add Series"* button creates the series and/or chart specified and adds them to the *"Custom Charts"* region.

Fig. 10 shows two examples of charts that have been created. The first one contains series showing the prices over time for a refrigerator and a washing machine in the home. The second chart shows the fluctuating power prices in the same period. It is important to note that all series (consumption, prices, wind speeds etc.) can be combined in the same charts. This provides a very high flexibility when creating charts, but also means that the y-axis of the custom charts is without unit as it may at the same time represent currency, watt-hours, m/s and more. Additionally, some series, such as consumption of washing machines, will show very large values whereas some series, such as power prices, will show very low values, making these series impractical to have in the same chart. Therefore it is advisable to separate them into two charts and compare these as shown in Fig. 10.

In the upper right corner of each chart are three buttons: Edit, save and delete. The delete button removes the chart from the report. The edit button opens an *Edit Chart* window (see Fig. 11) in which the user can change the name and type of the chart as well as remove series from the chart by clicking on the trash bin next to the series.
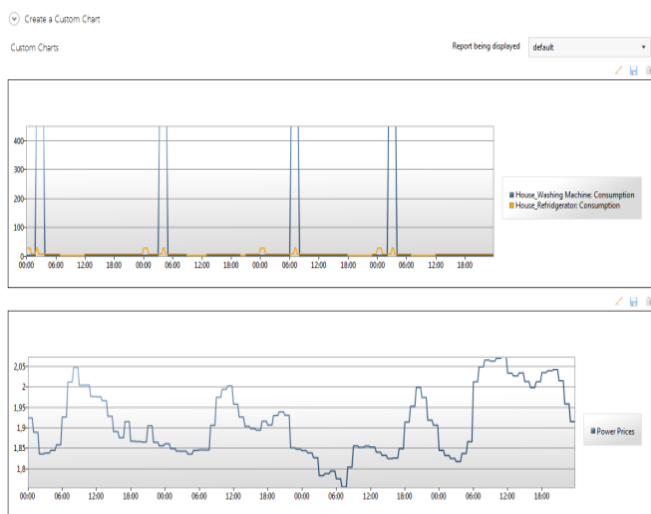

Figure 10   A selection of the reporting window showing the Custom Charts section in which the charts created by the user are displayed.
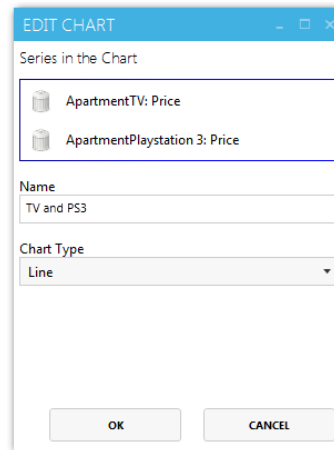

Figure 11   The view in which the user can edit an existing chart.

When a report has been created with the desired charts it can be saved using the save icon in the upper left corner of the reporting window. This allows the user to choose a name for the report and when it has been saved the user can toggle between which report to show, using the drop down menu just above the region with the custom charts. Since reports are connected to a single simulation result only reports connected to the same simulation result can be displayed this way. If reports connected to another simulation result needs to be displayed the reporting window must be closed and the desired simulation result should be found in the drop down menu in the ribbon using *"Inspect Selected Simulation"* as explained earlier in this section. It is, however, possible to have two reporting windows open at the same time showing different simulation results if comparison across simulations is required

IV.   CONCLUSION

As mentioned in the beginning of the paper the Danish workgroup, Smart Grid Netværket, recommended that the knowledge of the smart grid should be increased at consumer level in order to increase the acceptance of the smart grid. The presented work contributes to reaching this goal by allowing consumers to model their own home and see how their energy consumption would change if the appliances were smart grid enabled and the house used fluctuating energy prices rather than flat rate prices.

An analysis of the state-of-the-art simulation tools showed that very little work has been done in the area and that the existing tools are mostly non-graphical and therefore not very easy to use. The current work offers a low entry barrier for people to model their own home energy consumption. Additionally, previous work does not provide much opportunity to model specific homes and the incorporation of real energy and weather data is non-existent. Lastly the graphical analysis and comparison of different simulations were virtually absent in all previous work. These above mentioned facts provided the incentive for developing this simulation tool.

Additionally, a number of other areas have been identified in which the application may prove valuable. This includes salesmen that wish to illustrate the economic benefits of their product (see Fig. 1) and utility companies that wish to measure the flexibility of the homes connected to the grid, as identified during a meeting with a leading manufacturer of smart home controllers in Denmark.

The application has multiple uses. One of them is to answer the question: "How will the smart grid affect my energy bill?". This question can be answered by creating a model of the home and running a simulation using no smart grid enabled components and a flat rate power model and running a simulation using smart grid enabled components and fluctuating energy prices. A case study has been performed that models a typical four person house with dryer, washing machine, dishwasher, freezer, refrigerator etc. The case study showed that changing from flat rate to fluctuating energy prices the consumer can save €78. If the consumer also invests in smart grid enabling all the appliances the savings increase to €148 for the house [12]. This should be enough motivation for most users to participate in the smart grid [13]. Obtaining such a saving requires investments in new equipment and the price of such investments is difficult to estimate due to the limited range of products and the unsettled prices. Therefore the return of investment of the modeled setup is not easily predicted.

V.   FUTURE DEVELOPMENT

The goal was to create an application that would be simple and easy to develop further. Therefore, one of the main focus areas of the application was extensibility and the application was designed with the best practice software principles of *loose coupling*. A list of the most significant suggested extensions is shown below.

- Integration with other simulation tools, such as GridLab-D, to include other aspects of consumptions for e.g. heating of homes.
- Include floor plans of the modeled household to provide more precise heating calculations.
- Provide a list of components based on the simulations that would provide lower energy consumptions than the components in the home.
- Support dependencies between components, such that the scheduling between them can be synchronized when simulating, such as TVs and DVD players.
- Historic consumption data from the user could be integrated to provide knowledge of usage patterns and thereby provide even more accurate results.
- Web based deployment such that the application can use more computational power and the users can get access to the application through a web browser.

The application's installation files can be found at [14].

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