Development of a Smart Residential Load Simulator for Energy Management in Smart Grids

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***Abstract*—This paper describes the development of a freeware Smart Residential Load Simulator to facilitate the study of energy management systems in Smart Grids. The proposed tool is based on Matlab-Simulink-GUIDE toolboxes and provides a complete set of user-friendly graphical interfaces to properly model and study smart thermostats, air conditioners, furnaces, water heaters, refrigerators, stoves, dish washers, cloth washers, dryers, lights, and poolpumps, as well as wind, solar, and battery sources of power generation in residential houses. The impact of different variables such as ambient temperature, solar radiation, and household activity levels which considerably contribute to energy consumption are considered. The proposed simulator allows to model the way appliances consume power and helps to understand how these contribute to peak demand providing individual and total energy consumption and costs. In addition, the value and impact of generated power by residential power sources can be determined for 24h horizon. This freeware platform can be a useful tool for researchers and educators to validate and demonstrate models for energy management and optimization, and can also be used by residential costumers to model, and understand energy consumption profiles in households. Some simulation results are presented to demonstrate the utilization and performance of the proposed simulator.**

***Index Terms*—Smart grids, house appliances, smart thermostat, energy management.**

ABBREVIATIONS	
AC	Air Conditioner
APACHE	Applications Program for Air-Conditioning and Heating Engineers
BTU	British Thermal Unit
CFL	Compact Fluorescent Lights
CHVAC	Commercial Heating,Ventilation and Air-Conditioning
CW	Clothwasher
DW	Dishwasher
HVAC	Heating, Ventilation and Air Conditioning
SRLS	Smart Residential Load Simulator
TOU	Time of Use
WH	Water Heater
HT	Furnace
SOC	State-Of-Charge

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I. INTRODUCTION

SMART grids coupled with renewable energy resources can yield significant economic and environmental benefits. The Smart grid's ability to improve safety and efficiency, make better use of existing assets, enhance reliability and power quality, reduce dependence on imported energy, and minimize environmental impacts is a market force that has substantial economic value. These grids are growing fast, but if this is to be sustained, their value must become more clear to all stakeholders, especially residential consumers. The latter are an important part of electricity demand, since for example, the residential sector accounted for 25% of the peak demand and almost 30% of the electrical energy demand in Ontario, Canada in 2005 and 2008 [1], [2]. Also, residential energy consumption in the US was 22% of the total consumed energy in 2010 [3], and similar values were reported for the European Union in 2009 [4].

Space heating/cooling systems, water heaters, refrigerators, dishwashers, cloth washers, dryers, lighting, and cooking ranges are the most common appliances in the residential sector [1]-[4]. Heating, ventilation, and air conditioning (HVAC) and water heaters are major energy consumption devices. Therefore, controlling the residential end-use electricity demand can have a significant impact on reducing the peak demand and optimize energy consumption, which can be accomplished in smart or intelligent homes with automation systems to control residential loads [5]-[6].

Several studies have been reported in the literature regarding the prediction of load-shape and optimization methods for energy management, since some appliances can be easily scheduled to reduce energy cost and consumption without affecting customer comfort. For instance, a model to minimize the peak load by scheduling pool pumps, air conditioners (AC) and water heaters (WH) is proposed in [7]; a mixed integer linear programming model is developed to minimize the energy cost and maximize costumers comfort while taking into account the influence of price signals on the household. Some projects focus on scheduling the start-up of HVAC and/or water heater by making use of wireless thermostat technology to optimize cost and thermal comfort, as in the case of [8].

References [9]-[15] explore different ways of creating appliance-level load models based on statistical data to predict load-shape demand for load management purposes. Some simulators have been developed to model HVAC systems and buildings, such as the EnergyPlus software which models thermal energy in building [16]. The CHVAC software calculates the maximum heating and cooling loads for commercial buildings [17]. The Applications Program for Air-Conditioning and Heating Engineers (APACHE) is a graphical user interface to analyse thermal performance and energy use of buildings [18]. None of the existing modeling tools take into account other appliances and some are not easy to use. Hence, there is a need for user-friendly simulator to understand how appliances interact with each other with respect to energy consumption, as well as facilitate the study and application of mathematical models for home energy management systems.

This paper presents the development of a smart residential load simulator with a user-friendly graphical interface, which can simulate optimal on/off decisions of residential appliances to validate residential optimization models for a 24h horizon. Local power generation such as roof-top-solar, battery energy storage, and wind turbines are considered in this simulator, so that the benefits of these resources can be also studied.

The rest of the paper is structured as follows: Section III presents a general description of the proposed simulator, together with the associated graphical interfaces, and explains the main appliances' interfaces and models. An example is presented to demonstrate the functionality of proposed simulator in Section IV. Finally, the main conclusions and contributions of the presented work are provided in Section V.

II. SMART RESIDENTIAL LOAD SIMULATOR (SRLS)

The developed tool which is available at www.power.uwaterloo.ca is a new Matlab-based simulator that represents most of the important residential loads and power sources. The toolbox is provided with a complete graphical interface as shown in Fig.1. Factors such as solar radiation and ambient temperature that play important roles on the energy consumption of a household are considered as user-defined inputs to the SRLS. Other inputs are electricity tariffs by season and time-block rates (off-peak, mid-peak, and on-peak) to represent Time of Use (TOU) tariffs. The user can also define real time prices (RTP). All and each of the appliances shown in Fig.1 are modeled and can be simulated individually or as a group.

Figure 2 shows the interface for plotting the simulation results, where consumed and generated power by the appliance and sources is illustrated together with the levels and costs of consumed and generated energy. In addition, the user can select each appliance and resource individually to plot its energy consumption/generation profile.The charge and discharge profiles of battery storage can be also depicted. Moreover, the interface provides consumption and generation tables where the cost of consumed energy by appliances and sources during off, middle, and on-peaks periods are detailed. Finally, gas consumption and its costs can be also illustrated by the interface. The models of the appliances and energy sources considered in the simulator and explained next.

A. Water Heater (WH)

The WH is a cylindrical tank enclosed by insulation and covered with a metal sheet, which can be simulated by using a classical thermal model [19],[20]. Storage tank water heaters are the most common types used in North America; therefore, electric and gas storage tank water heaters are modeled in the SRLS.

Figure 3 shows the graphical interface of the WH in the SRLS. The inlet water and ambient temperatures around the tank, capacity of the WH, and its efficiency are considered as inputs. The power consumption is reported in W when an electric WH is chosen, and in BTU for a gas WH. In both cases, typical values are provided as default, corresponding to values applicable in southern Ontario, Canada, for inlet water and ambient temperatures. Generally, the efficiency of electric WHs are in the range of 85-94%, while for gas WHs is 50-65%. More details and information regarding the WH mathematical model are provided by pressing the "Help" button.

Figure 4 shows the circuit used to model the WH, which comprises the mass of water (m), specific heat of water (C_p), characteristics of fiber glass (C_W, UA), gas or electric rated power (Q_{e_g}), and the efficiency (η) [19]. The following equation represents the energy flow in the WH that is used to implement the model:

$$\frac{dT_w}{dt} = \frac{mC_p}{C_w}T_{inlet} + \frac{UA}{C_w}T_{amb} - \frac{UA + mC_p}{C_w} + Q_{eg}\eta \quad (1)$$

where T_w is the temperature of the tanks' wall, T_{inlet} is the inlet water temperature, and T_{amb} is the ambient temperature around the tank. The procedure to calculate the hot water usage is explained in detail in [21], which depends on the number of family members.

B. Household

The material properties of buildings influence the thermal performance and their energy consumption patterns. The walls, floor, roof and windows have central thermal conductivity, and allow circulation of warm/cold air in the house. The energy consumption depends on the house characteristics, specifically on its geometry. Therefore, in SRLS, the house geometry is defined by the size and the numbers of rooms, which are assumed to be from 1 to 4, modelled using the average of length, width and height of walls and windows. The thermostat is assumed to be placed in one of the rooms. Figure 5 shows the graphical interface to represent the house where the user inputs the required house, profile information.

Figure 6 depicts the circuit model used to represent a single room, which considers the outside environment (T_{amb}), the thermal characteristics of the room (thermal resistance of walls R_w and windows R_c, and thermal capacitance of the wall C_w and indoor air C_i), and the AC or furnace system which are represented by the Q_{ac_ht} thermal source. Using this model, the room's temperature, the power consumption in the room, and the corresponding cost of consumed energy can be calculated. The following differential equations can be obtained from Fig. 6 [22], [23]:

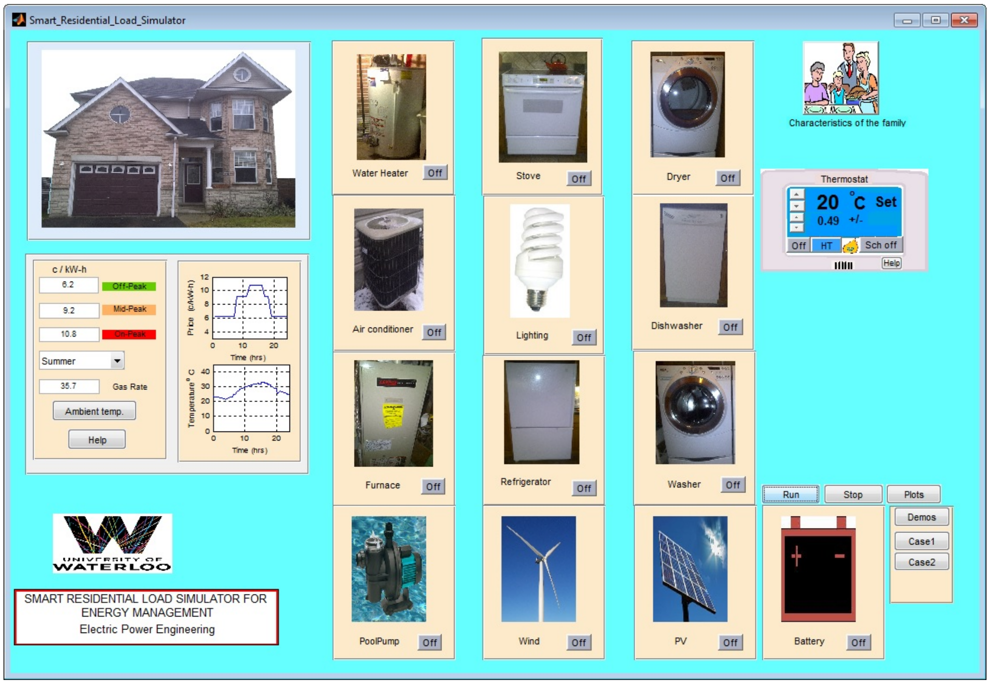

Fig. 1. Graphical interface of Smart Residential Load Simulator.

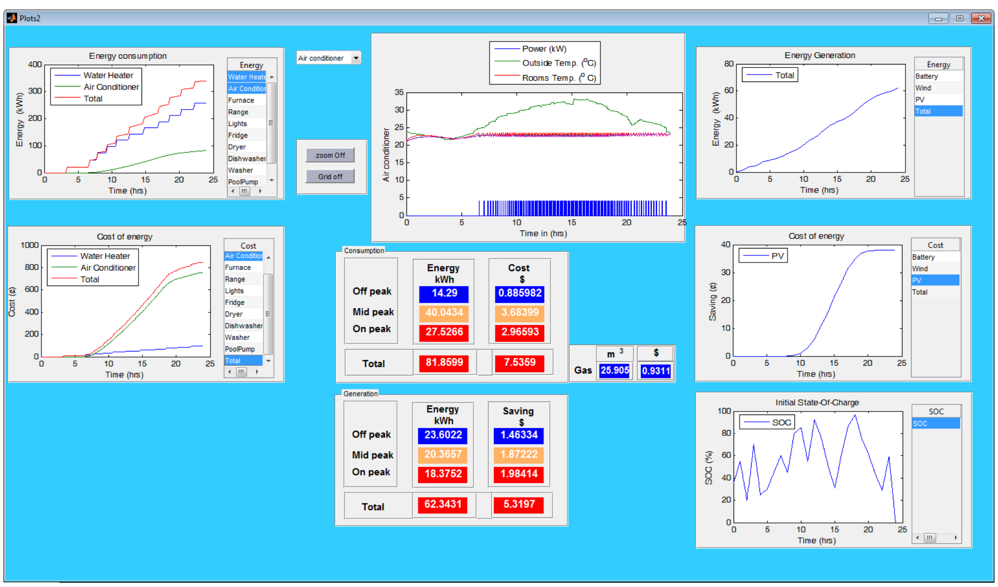

Fig. 2. Graphical interface for plotting of simulation results.

$$\frac{dT_w}{dt} = \frac{Q_s}{C_w} + \frac{T_{out}}{R_w C_w} + \frac{T_{in}}{R_w C_w} - \frac{2T_w}{R_w C_w}$$

$$\frac{dT_{in}}{dt} = \frac{\left(Q_{in} - Q_{ac\_ht}\right) S\left(t\right)}{C_{in}} - \frac{T_{in}}{C_{in}}\left(\frac{1}{R_w} + \frac{1}{R_c}\right) - \frac{T_w}{R_w C_{in}} \quad (2)$$

where S is a binary variable representing the ON (1) or OFF (0) state of the AC/HT.

C. Air Conditioner (AC)

The AC equipment is often specified by its cooling capacity in terms of BTU. This capacity is the amount of energy used by the equipment to remove heat from the air, and regulate the temperature and humidity in a room or the entire house. There are two types of AC systems: window and central AC. A typical window AC has a capacity of around 6000-18000 BTU. A central AC with split configuration uses ducts or pipes to distribute cool air to one or more rooms, and its typical capacity is around 9000-60000 BTU. Figure 7 shows the graphical interface of the AC in the SRLS, where the user can select the capacity of the equipment.

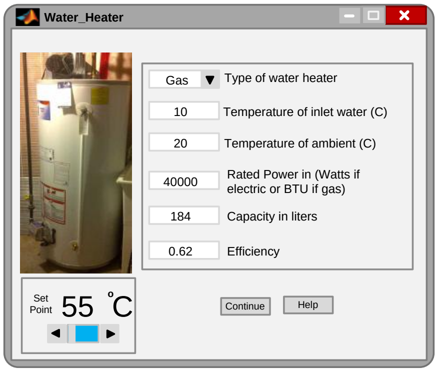

Fig. 3. Graphical interface for water heater.

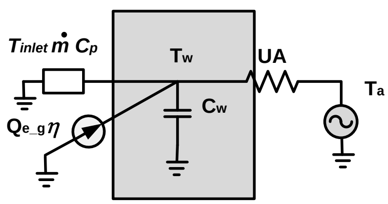

Fig. 4. Circuit model for water heater.

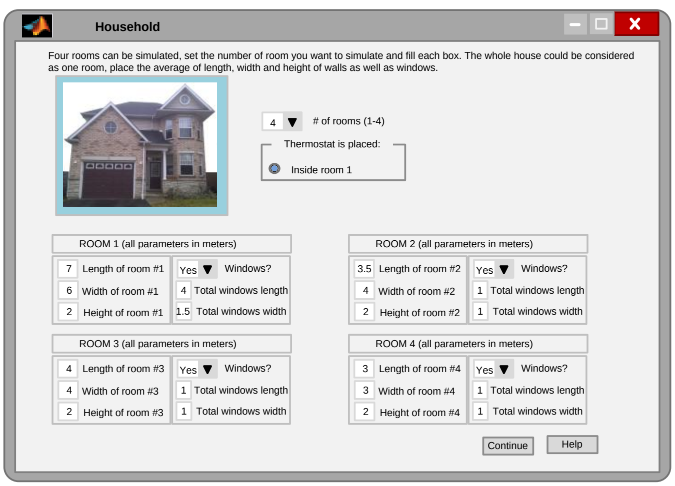

Fig. 5. Graphical household interface.

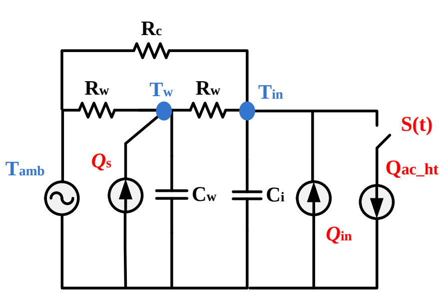

Fig. 6. Thermal circuit model of a single room.

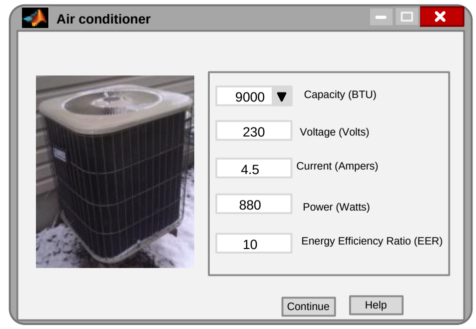

Fig. 7. AC graphical interface.

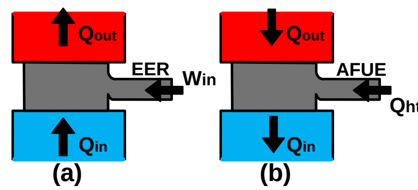

Fig. 8. Carnot machine representation of (a) AC and (b) HT.

The modeling of the AC is represented schematically by the heat flow diagram in Fig. 8 (a). The Energy Efficiency Ratio (EER) denotes the amount of cooling effect provided by the AC as follows:

$$EER = 3.412\frac{-Q_{in}}{W_{in}} = \frac{Q_{in}}{Q_{in} - Q_{out}} \tag{3}$$

where Q_{out} is the required energy used to extract the heat Q_{in} from the rooms, and the electrical input W_{in} represents the energy required to do this work.

D. Furnace (HT)

Central gas furnaces are normally used in households to inject hot air into the rooms. The most common type is a natural gas fired furnace inside an enclosed metal casing, which injects and distributes heated air in the house. The graphical interface of the furnace is shown in Fig. 9, where only the capacity and Annual Fuel Utilization Efficiency (AFUE) values are needed as inputs.

The heat flow diagram of the heating system is depicted in Fig. 8 (b), where the efficiency is known by the furnace AFUE rating. The following equation represents the thermal model of the furnace.

$$AFUE = 3.412\frac{Q_{in}}{Q_{ht}} = \frac{Q_{in}}{Q_{in} - Q_{out}} \tag{4}$$

where Q_{ht} represents the capacity of the furnace and Q_{in} represents the heat inside the house.

E. Smart Thermostats

Programmable thermostats are used in most households with central AC and/or HT. Such thermostat is designed to adjust the temperature according to user preferences at different times of the day, and helps regulate the home temperature in both summer and winter. Therefore, the thermostat can be set

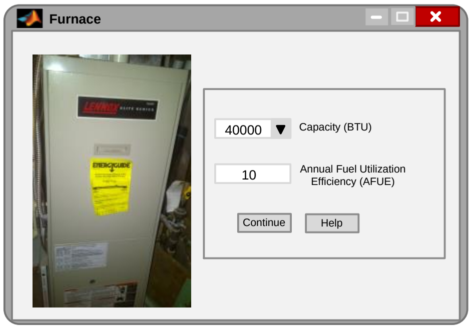

Fig. 9. Graphical interface for furnace.

Fig. 10. Graphical interface for (a) conventional and (b) programmable thermostat.

according to the family's schedule and preferences to regulate the temperature of the house.

Both conventional and programmable thermostats are considered in the SRLS. Figure 10(a) illustrates a conventional thermostat, where the user has to select the desired temperature. Figure 10(b) depicts a programmable thermostat where the user can specify four time periods, as well as upper and lower temperature set points. Figure 11 illustrates the thermostat model used in this simulator, where T_{hi} and T_{lo} are the upper and lower temperature limits, respectively, within which the thermostat maintains the house temperature. This values are set by the user pressing the $+/-$ button.

F. Stove

Normally, gas or electricity stoves are used. About 87% of families in the U.S use electric range-ovens for cooking [3]; therefore, only electrical stoves are considered in the SRLS. Energy consumption in the stove is calculated by multiplying the consumed power by the duration of use. The graphical interface of the electrical stove is depicted in Fig. 12, where it is possible for the user to select the number of heating elements and their corresponding heat intensity for three time periods in a day.

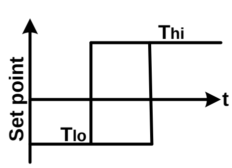

Fig. 11. Thermostat on/off decisions.

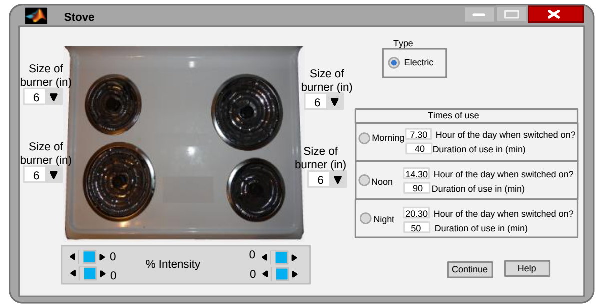

Fig. 12. Graphical interface for stove.

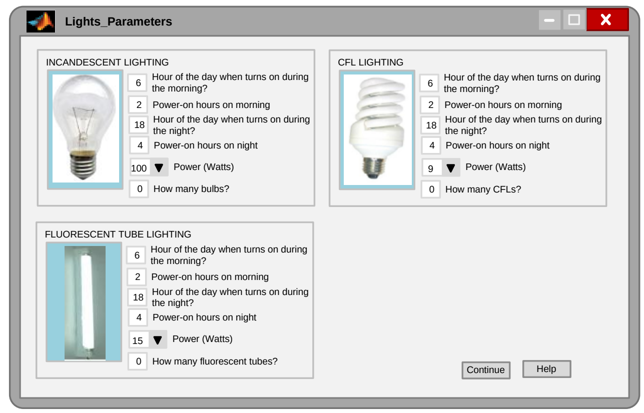

Fig. 13. Graphical interface for lighting.

G. Lighting

The most common types of lights used in residential houses are the traditional incandescent bulbs, Compact Fluorescent Lights (CFL), and fluorescent tubes. Residential houses usually use a mixture of these three types of lights. CFL and fluorescent tubes are more expensive, but they have a longer life and use much less energy, thus resulting in significant savings in energy and cost.

Figure 13 shows the graphical interface for the lighting system in the SRLS. The number, power rating, and operation (time and duration of use) of the lights are determined in this interface, from which their energy consumption can be readily calculated.

H. Refrigerator

The refrigerator is modeled as a thermal system with an insulation of fiber glass. The corresponding model is similar to the room model mentioned earlier; therefore, it can be represented using the same circuit model by simply changing the parameter values [22]. Figure 14 depicts the graphical interface used to define the refrigerator main characteristics.

I. Dryer

Gas and electric dryers use large amounts of energy in a household. Electrical dryers are commonly used in North America, and hence only these are considered in the SRLS. An example of the energy consumption pattern of a dryer is

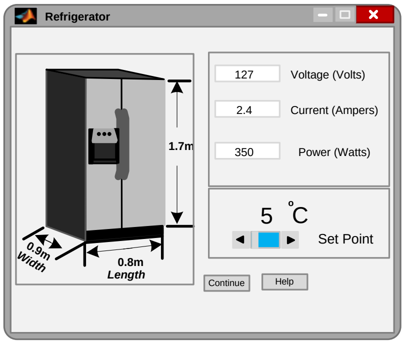

Fig. 14. Refrigerator graphical interface.

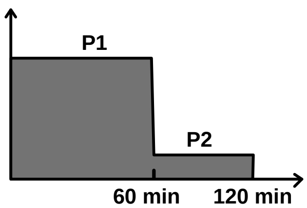

Fig. 15. Power consumption pattern of dryer.

shown in Fig. 15 [25], where power P1 is in the range of 2,000 to 2,500 W during the first period and P2 is 500 W for the next period. In the SRLS, a typical 2,000 W is assumed for the first 60 minutes of use, and 500 W for the remaining period. Figure 16 shows the interface for the dryer, where the user can select up to three loads per day and the corresponding duration of use.

J. Dishwasher (DW)

The DW represent a small share of residential appliances energy consumption. However, DWs draw a high power during short periods of time, which makes them relevant for peak demand programs [27].

Figure 17 shows the sequence of operations of a typical DW. At first the DW fills up with water for about 15 minutes and a constant power P1 is drawn; then, it provides electric heating, increasing its power to P2 for a time period that depends if it is connected to hot water or cold water [1]. After that, hot water and detergent are sprayed over the dishes, draining and refilling alternatively with rinse water; this consumes an

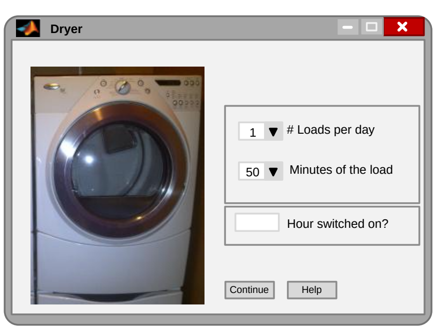

Fig. 16. Graphical interface for dryer.

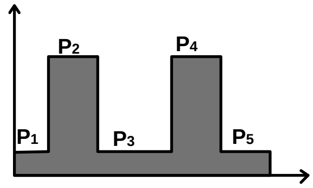

Fig. 17. Power consumption cycle for Dishwasher.

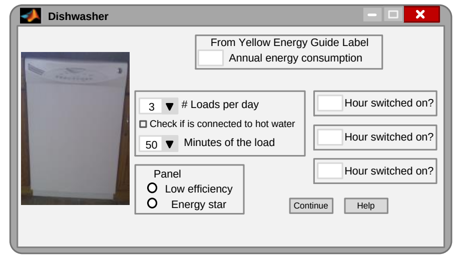

Fig. 18. Graphical interface for Dishwasher.

amounts of power P3. The dishes are dried using the electric resistance element consuming P4 power, and finally, the hot air remaining in the DW, consuming P5 power. According to [26], about 55% of the energy used by a DW goes to heat the water when connected to a WH, and 65% if cold water is used. The time period of power consumption depends on the efficiency of the DW. The SRLS model fits Fig. 17 to the Yellow Energy Guide under standard conditions, and the specifications provided by the user in the graphical interface shown in Fig. 18. Three loads per day, duration and time of use can be entered by users.

K. Clothwasher (CW)

The CW process is controlled by a step timer or an electronic control device. Electrical energy is used mainly for driving the drum motor and heating up the water, if it is not hot enough, in spite of the fact that about 2/3 to 3/4 of the water used is cold water for rinsing [27],[28].

Figure 19 shows the graphical interface for CW in the SRLS. The number of loads per day, time and duration of use, water temperature, and type of efficiency can be input by the user. An example of the CW power demand profile is shown in Fig. 20, where P1 and P4 powers correspond to the filling and draining of rinse water, and P2 and P3 correspond to heating the water. The model developed in the SRLS to determines this powers from the Yellow Energy Guide and the user defined inputs.

L. Poolpump

Considerable amount of energy is needed for heating and maintaining water temperature in pools, in addition to the energy used by the poolpump to circulate and filter the pool water. Pool water heating can be solar, gas, or by an electrical heat pump. In a swimming pool, 76% of electrical energy is used for pumps, 6% for chlorination cells, 14% for electric heaters, and 4% for timers and controls [29].

A typical poolpump consumption pattern is shown in Fig. 21. Generally 200-500W single-phase pumps are used for

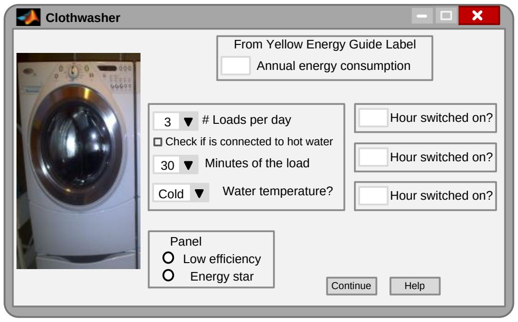

Fig. 19. Graphical interface for clothwasher.

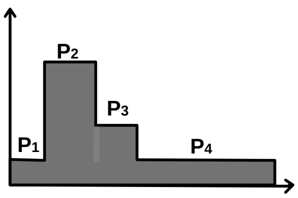

Fig. 20. Power consumption cycle of clothwasher.

residential swimming pools, with 3 to 8 working hours per day for water filtration, depending on the pool size, pump size, environmental conditions such as outside temperature and sunshine, water filtration equipment, how often the pool is used, and other pool manufacturer recommendations. Usually, poolpumps are controlled by electro-mechanical or electronic ON/OFF clock timers with start- and end-times manually selected by users. Figure 22 presents the interface for the user to define up to three loads per day, specifying the time and duration of use.

M. Local Generation Resources

Wind and solar photovoltaic (PV) power generation are considered as local power sources supplying residential loads.

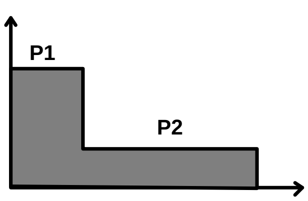

Fig. 21. Power consumption cycle of poolpump.

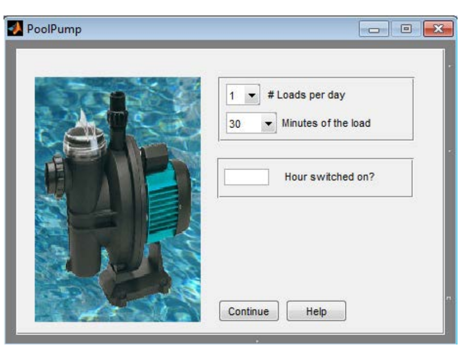

Fig. 22. Graphical interface for poolpump.

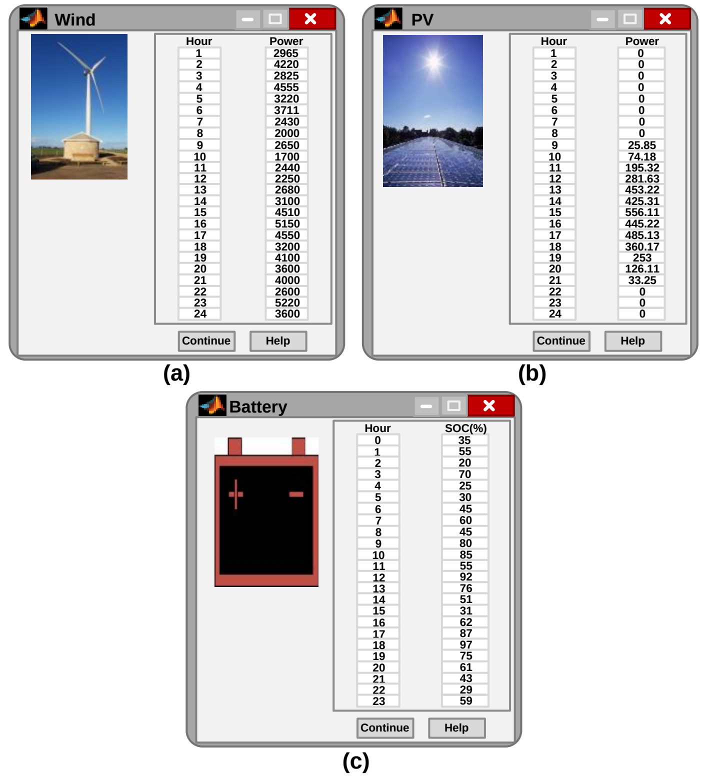

Fig. 23. Graphical interface for local power generation resources: (a) Wind, (b) PV, and (c) Battery.

These power sources are not dispatchable and are available at periods of low demand; therefore, they are typically integrated with some storage devices, such as batteries, to store the generated energy for a certain period of time, releasing it when demand increases. However, besides being expensive, batteries have limited capacity; thus, if there is a surplus of energy produced by, for example, a domestic PV system, this extra energy is sold to the local grid.

Figure 23 depicts the window interfaces for the user for wind, PV, and battery systems. In Fig. 23(a) and Fig. 23(b) different power outputs per hour are defined for wind and PV generations. Figure 23 (c) shows the window interface for the battery, where the user can select the kWh rating and SOC hourly profile for the day. The sum of these three power sources is assumed to supply the load or be injected into the grid.

III. RESULTS AND DISCUSSION

The AC and gas WH are considered here as an example of residential loads, and solar PV and a battery are selected as sources of local power to illustrate the SRLS. Thus, an AC with 48,000 BTU is used to cool the air in a house comprised of four rooms, inputting the required information for the rooms as shown in Fig. 5. Figure 7 illustrates how the user should input the AC parameters in the simulator. The thermostat is set at 23^{o}C with a $+/-$ 0.5^{o}C tolerance, as in Fig. 10 (a). Figure 3 shows the information required to model the gas WH.

The simulator takes approximately 20 seconds to solve the model equations, generating data for the user to analyze

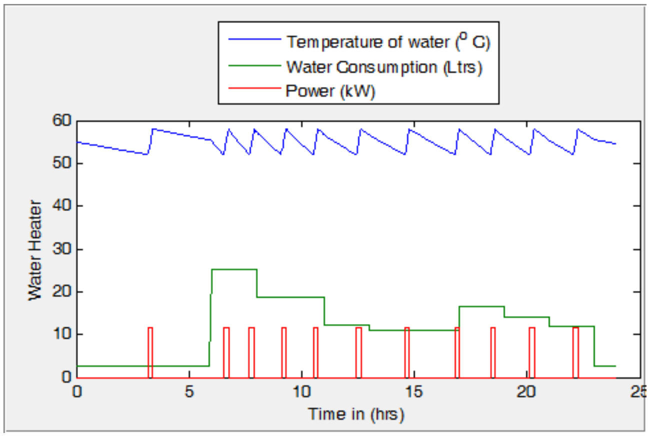

Fig. 24. Water heater details.

the behavior of the simulated appliances. Figure 2 shows the consumed and generated energy by the loads and local generation sources, respectively. The WH and AC loads and the corresponding total consumed energy are shown along with the battery and the solar PV output. The cost of energy used by the AC and WH and the cost of energy saved from local sources are also illustrated. The defined SOC of the battery and the inside house temperature, outside temperature, and AC power are also shown in this figure. The Consumption and Generation tables in the figure illustrate the value of consumed electricity and gas, and the generated energy by the local generation, during off-, mid-, and on-peak hours, respectively. Finally, Fig. 24 shows the hot water temperature and consumption, and water heater power generated by the SRLS.

IV. Conclusions

A new toolbox based on Matlab-Simulink has been developed to model residential energy consumption and local generation resources. The main objective of the proposed simulator is to allow the study, demonstrate, and teach energy management of residential households. The simulator has been described together with the models and graphical interfaces of the main residential energy consuming appliances and local generation, and an example illustrating its performance and application has been presented. This tool can be useful for researchers to validate their models for energy management and optimization, and can also be used by costumers and educators to understand and explain residential energy demand and supply. The simulator is available for the interested reader at www.power.uwaterloo.ca.

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