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 residential energy management systems (EMSs) 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, stoves, dish washers, cloth washers, dryers, lights, pool pumps, and refrigerators, whose models are validated with actual measurements. Wind and solar power generation as well as battery sources are also modeled, and the impact of different variables such as ambient temperature 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 sources can be determined for a 24-hour horizon. This freeware platform is a useful tool for researchers and educators to validate and demonstrate models for energy management and optimization, and can also be used by residential customers to model and understand energy consumption profiles in households. Some simulation results are presented to demonstrate the performance and application of the proposed simulator.**

***Index Terms*—Appliance modeling, home energy management, household energy consumption, smart grid, smart loads, smart houses.**

I. Introduction

SMART grids coupled with renewable energy resources can yield significant economic and environmental benefits. The smart grid's ability to improve 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 [1]. These grids are growing fast, but if this growth 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 near 20% of the electrical energy demand in Ontario, Canada in 2016 [2]; also, residential energy consumption in the US was 22% of the total consumed energy in 2015 [3], and similar values were reported for the European Union in 2016 [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 [2]–[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 on 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 conditioner and water heaters (WH) is proposed in [7]; a mixed integer linear programming model is developed to minimize the energy cost and maximize customers' comfort while taking into account the influence of price signals on the household. Some projects focus on scheduling the HVAC and/or water heater by making use of wireless thermostat technology to optimize costs and thermal comfort, as in [8].

References [9]–[15] explore different ways of creating appliance-level load models for load management purposes, based on statistical data to predict the load-shape of the demand. Several models and simulators have been developed to model HVAC systems and buildings. For example, the EnergyPlus software [16], which models thermal energy in buildings, allows analyzing the impact of HVAC and lighting systems in buildings from a thermal perspective, but it has not been designed for determining electrical load profiles of households, including the impact of appliances and other building loads and local sources on its electricity demand. The Commercial HVAC (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 analyze thermal performance and energy use of buildings [18].

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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 simulators 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 EMSs, which is the main purpose of the work presented here. The presented simulator allows computing load profiles of buildings that could be used by other simulators such as Homer [19], where electric load is used as an input for the design of hybrid diesel-renewable microgrids.

This paper presents a novel toolbox, entitled the Smart Residential Load Simulator (SRLS), with a user-friendly graphical interface to simulate optimal on/off decisions of residential appliances to study residential energy profiles on a 24-hour horizon, which can be used, for example, to develop home EMSs. Local power generation such as photovoltaic and wind generators together with battery energy storage are considered in the simulator. The developed SRLS can be used to study, demonstrate, and evaluate different energy management strategies for residential households, and it can also be used as an educational tool that is available to the research community as open source code at: https://uwaterloo.ca/power-energy-systems-group/downloads/smart-residential-load-simulator-srls.

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 the proposed simulator in Section IV. Finally, the main conclusions and contributions of the presented work are provided in Section V.

II. The Smart Residential Load Simulator

The developed SRLS 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 ambient temperature, which play an important role in energy consumption of a household, are considered as user-defined inputs to the SRLS. Other inputs are electricity time-of-day 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 the appliances shown in Fig. 1 are modeled in the SRLS and can be simulated individually or as a group. Observe in Fig. 1 that the simulator allows to define the characteristics of the family, i.e., number and ages of the people in the household, so that the residents' activity levels can be represented in the relevant appliance models such as the water heater and the house thermal model.

Fig. 2 shows the interface for plotting the simulation results, where consumed and generated power by appliances and sources are 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, which are inputs to the model, can be also depicted. Moreover, the interface provides consumption and generation tables where the cost of consumed energy by appliances and sources during off-, mid-, and on-peaks price periods are detailed. Finally, gas consumption and its costs can also be shown in the interface. The models of the appliances and energy sources considered in the SRLS are explained next.

A. 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, defined by the size and the numbers of rooms, which are assumed to be from 1 to 4, modeled using the average of length, width and height of walls and windows. The thermostat is assumed to be placed in one of the rooms. Fig. 3(a) shows the graphical interface to represent the house, where the user inputs the required information.

Fig. 3(b) depicts the circuit model used to represent a single room, which considers the outside temperature T_{amb}, the thermal characteristics of the room (i.e., thermal resistance of walls R_w and windows R_c, and thermal capacitance of the wall C_w, and indoor air C_{in}), and the Air Conditioner (AC) or furnace system, which are represented by the Q_{ac_ht} thermal source. Using this model, the wall's temperature T_w, room's temperature T_{in} and power consumption, and the corresponding cost of consumed energy can be calculated. The following equations representing the indoor temperature dynamics can be obtained from this figure [20], [21]:

$$\begin{aligned} \frac{dT_w}{dt} &= \frac{Q_s}{C_w} + \frac{T_{amb}}{R_w C_w} + \frac{T_{in}}{R_w C_w} - \frac{2T_w}{R_w C_w} \\ \frac{dT_{in}}{dt} &= \frac{(Q_{in} - Q_{ac_ht})\, S(t)}{C_{in}} - \frac{T_{in}}{C_{in}}\left(\frac{1}{R_w} + \frac{1}{R_c}\right) \\ &\quad - \frac{T_w}{R_w C_{in}} \end{aligned} \tag{1}$$

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

B. Air Conditioner (AC)

The AC is often specified by its cooling capacity in terms of British Thermal Unit (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 6,000-18,000 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 9,000-60,000 BTU. Fig. 4(a) shows the graphical interface of the AC in the SRLS, where the user can select the capacity of the equipment.

The modeling of the AC is represented schematically by the heat flow diagram in Fig. 4(b). The Energy Efficiency Ratio (EER) denotes the amount of cooling effect provided by the AC as follows:

$$EER = 3.412\frac{Q_{in}}{W_{in}} = 3.412\frac{Q_{in}}{Q_{out} - Q_{in}} \tag{2}$$

Fig. 1: Graphical interface of Smart Residential Load Simulator (SRLS).

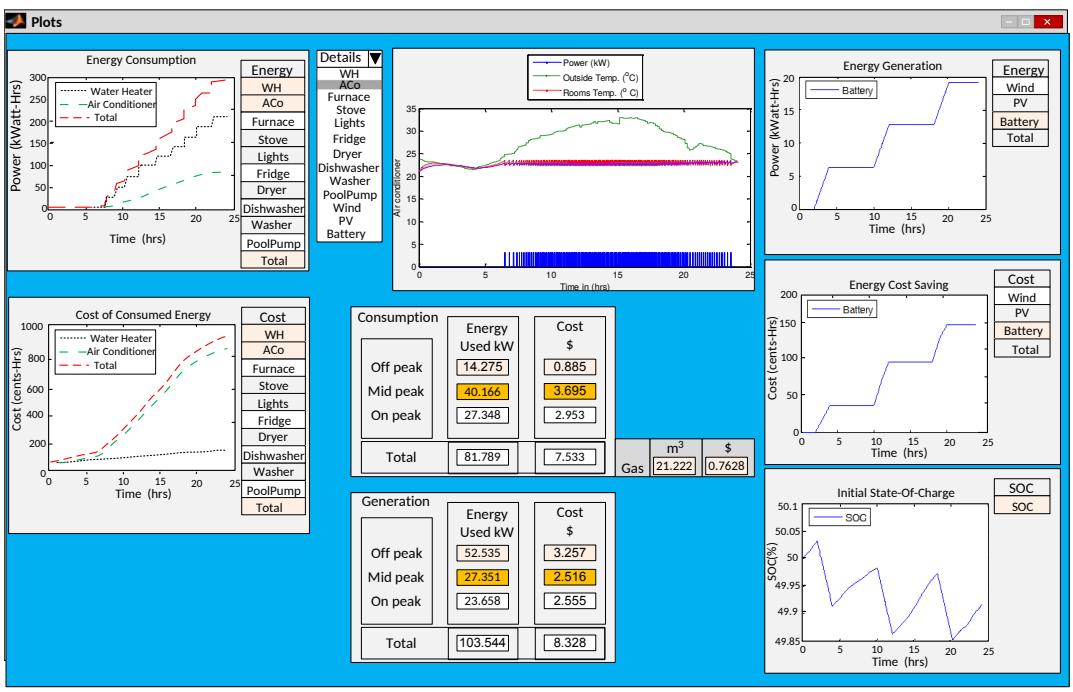

Fig. 2: Graphical interface that presents simulation results.

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.

C. Furnace (HT)

Central gas furnaces are normally used in households to inject hot air into the rooms. The most common type in Canada and the US is a natural gas fired furnace inside an enclosed metal casing, which injects and distributes heated air in the house [22]. The graphical interface of the furnace is shown in Fig. 5(a), where only the capacity and Annual Fuel Utilization Efficiency (AFUE) values are needed as inputs.

The heat flow diagram of the furnace is depicted in Fig. 5(b), where the efficiency is known by the furnace AFUE rating. The following equation represents the thermal model of the furnace:

$$AFUE = 3.412\frac{Q_{in}}{Q_{ht}} = 3.412\frac{Q_{in}}{Q_{in} - Q_{out}} \tag{3}$$

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

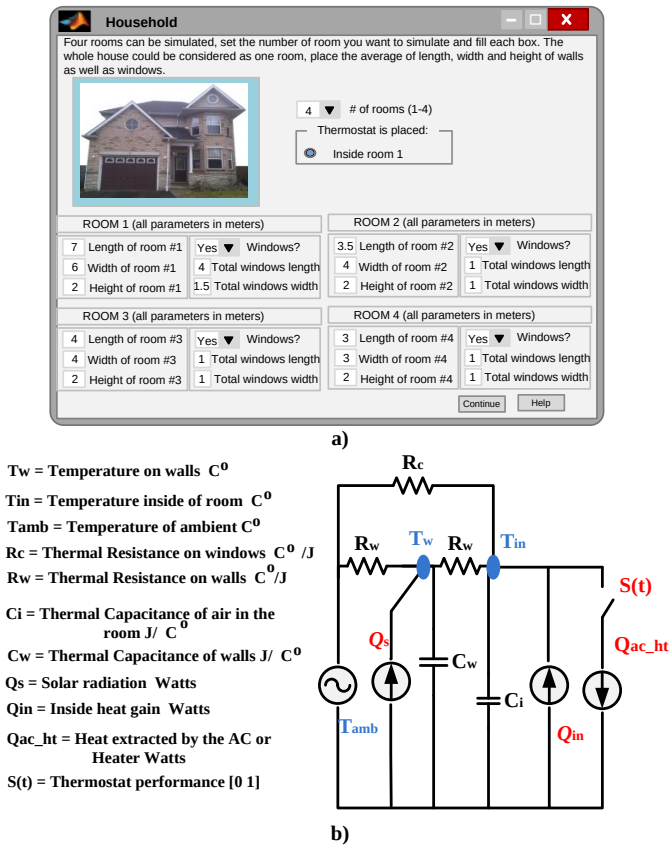

Fig. 3: House model: (a) graphical interface, and (b) thermal circuit model of a room.

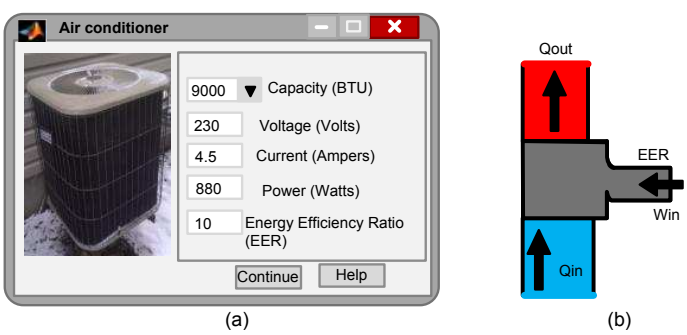

Fig. 4: AC model: (a) graphical interface, and (b) Carnot machine representation of AC.

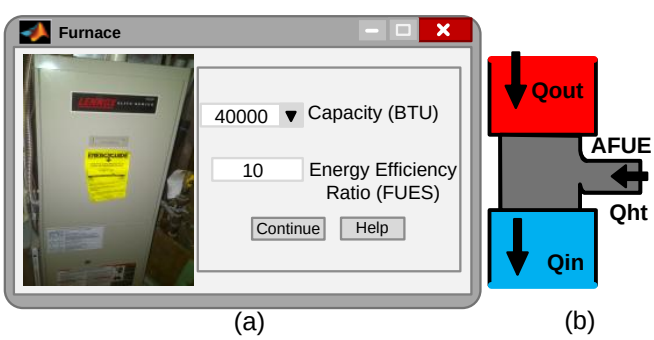

Fig. 5: Furnace model: (a) graphical interface, and (b) Carnot machine representation of HT.

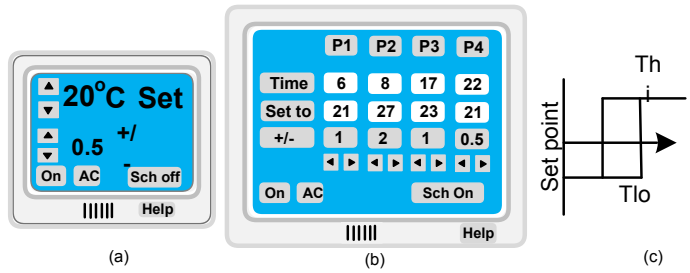

Fig. 6: Graphical interface for (a) conventional and (b) programmable thermostat, and (c) on/off decision logic to represent the thermostat delay.

D. Smart Thermostats

Programmable thermostats are used in most households with central AC and/or HT [23]. Such thermostats are 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 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. Fig. 6(a) illustrates a conventional thermostat, where the user has to select the desired temperature. Fig. 6(b) depicts a programmable thermostat where the user can specify four time periods, as well as upper and lower temperature set points. Fig. 6(c) illustrates the thermostat model used in the simulator, where T_{hi} and T_{lo} are the upper and lower temperature limits, respectively, within which the thermostat maintains the house temperature. These values are set by the user pressing the $+/-$ button.

E. 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 [24], [25]. 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.

Fig. 7(a) 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 for inlet water and ambient temperatures are provided as default, corresponding to values applicable in southern Ontario, Canada. Generally, the efficiency of electric WHs are in the range of 85-94%, while for gas WHs is 50-65% [26].

Fig. 7(b) 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 power (Q_{e_gh}), and the efficiency (η) [24]. The following equation represents the energy flow in the WH that is used to implement the model:

$$\frac{dT_w}{dt} = \frac{mC_p}{C_w}T_{inlet} + \frac{UA}{C_w}T_{amb} - \frac{UA + mC_p}{C_w} + Q_{e_gh}\eta \quad (4)$$

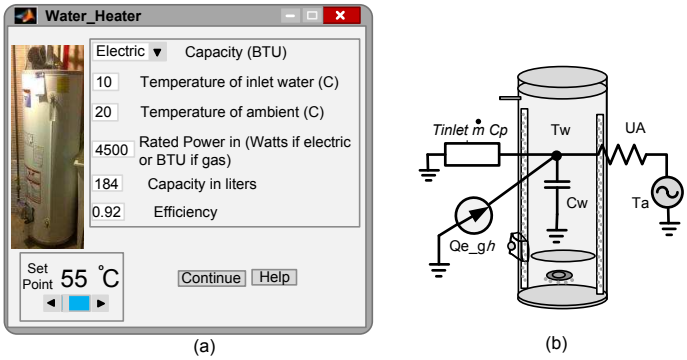

Fig. 7: Water heater model: (a) graphical interface, and (b) thermal circuit model.

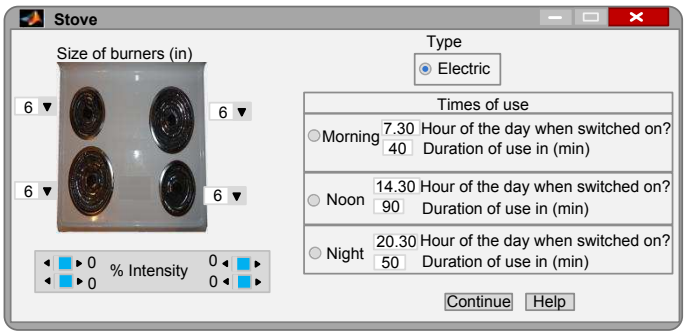

Fig. 8: Graphical interface for stove.

where T_w is the temperature of the tank's 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 [27], which depends on the number and age of the household occupants.

F. Stove

Normally, gas or electricity stoves are used in residential houses. About 87% of families in the US use electric range-ovens for cooking [3], and similarly in Canada [28]; 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. 8, 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.

G. Lighting

The most common types of lights used in residential houses are the traditional incandescent bulbs, Compact Fluorescent Lights (CFL), fluorescent tubes and recently Light Emisor Diode [22]. 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. Fig. 9 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 input in this interface, from which their energy consumption can be readily calculated.

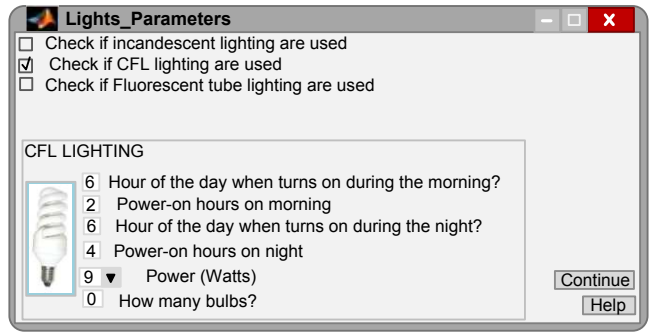

Fig. 9: Graphical interface for lighting.

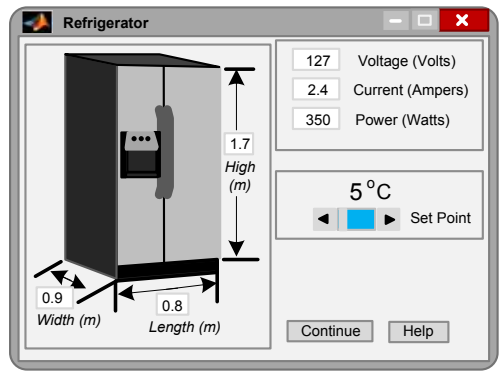

Fig. 10: Graphical interface for refrigerator.

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 [20]. Fig. 10 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 [29]. Electrical dryers are commonly used in North America, and hence only these are considered in the SRLS. Fig. 11(a) shows the interface for the dryer, where the user can select up to three loads per day and the corresponding duration of use. An example of the energy consumption pattern of a dryer is shown in Fig. 11(b) [30], 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 rating of 2,000 W is assumed for the first 60 minutes of use, and 500 W for the remaining period.

J. Dishwasher (DW)

The DW represents a small share of residential appliances' energy consumption. However, DWs draw high power during short periods of time, which makes them relevant for peak demand programs [31]. Fig. 12 shows the graphical interface and 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; it then provides electric heating, increasing

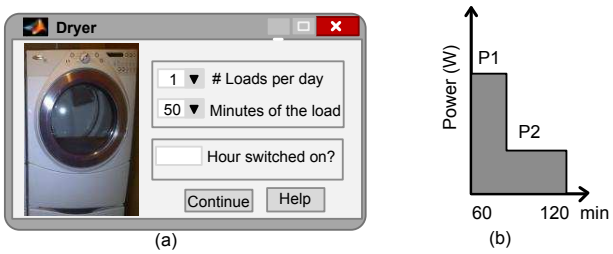

Fig. 11: Dryer model: (a) graphical interface, and (b) power consumption cycle.

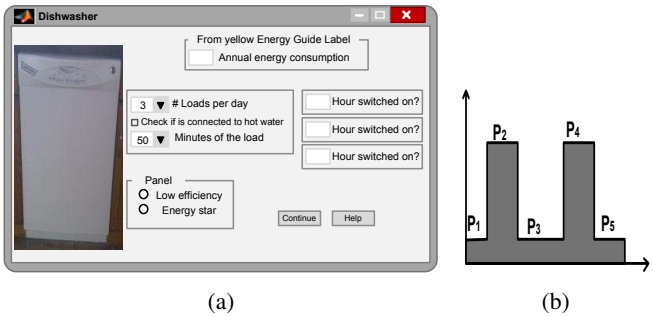

Fig. 12: Dishwasher model: (a) graphical interface, and (b) power consumption cycle.

its power to P2 for a time period that depends if it is connected to hot water or cold water [32]. After that, hot water and detergent are sprayed over the dishes, draining and refilling alternatively with rinse water; this consumes power P3. The dishes are dried using first an electric resistance element consuming P4 power, and then hot air remaining in the DW, consuming P5 power. According to [32], 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 the curve in Fig. 12(b) to the Yellow Energy Guide under standard conditions, and the specifications provided by the user in the graphical interface shown in Fig. 12(a). Three loads per day, including duration and time of use, can be entered by users.

K. Cloth-washer (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 [31], [33].

Fig. 13(a) shows the graphical interface for the CW in the SRLS. The number of loads per day, time and duration of use, water temperature, and efficiency can be input by the user. An example of the CW power demand profile is shown in Fig. 13(b), where the P1 and P4 denote the powers corresponding to the filling and draining of rinse water, and P2 and P3 correspond to heating the water. The model developed in the SRLS determines this powers from the Yellow Energy Guide and the user defined inputs.

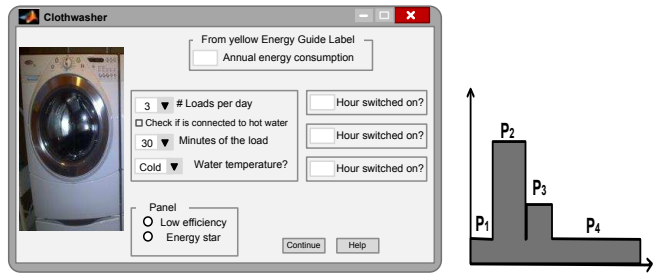

Fig. 13: Cloth-washer model: (a) graphical interface, and (b) power consumption cycle.

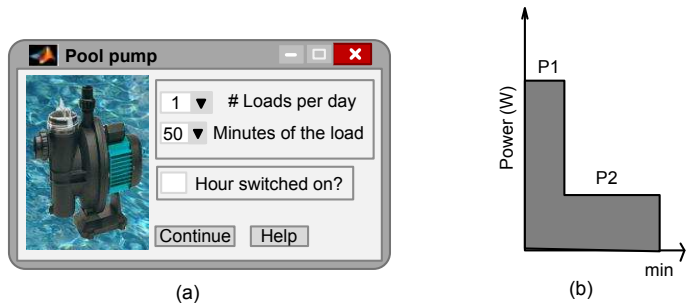

Fig. 14: Pool pump model: (a) graphical interface, and (b) power consumption cycle.

L. Pool Pump

Considerable amount of energy is needed for heating and maintaining the water temperature in pools, in addition to the energy used by the pool pump to circulate and filter the pool water. Pool water heating can be accomplished with solar power, 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 [34].

Fig. 14 presents the interface for the user to define up to three loads per day, specifying the time and duration of use. A typical pool pump consumption pattern is shown in Fig. 14(b). Generally 200-500W single-phase pumps are used for 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, pool pumps are controlled by electro-mechanical or electronic on/off clock timers with start- and end-times manually selected by users.

M. Local Generation Resources

Wind and solar photovoltaic (PV) power generation are considered as local power sources supplying residential loads. These power sources are not dispatchable and vary during the day; 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. Besides being expensive, batteries have limited capacity; thus,

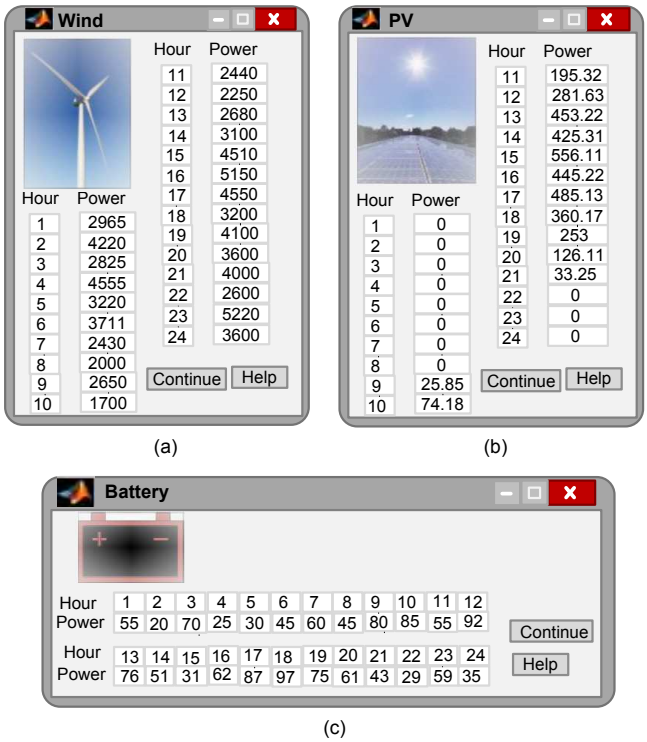

Fig. 15: Graphical interface to define local power generation profiles: (a) wind, (b) solar PV, and (c) battery.

if there is a surplus of energy produced by, for example, a domestic PV system, this extra energy could be sold to the local grid.

Fig. 15 depicts the interfaces for the user to define wind, PV, and battery systems, using a simple modeling approach of defining output profiles. In Fig. 15(a) and Fig. 15(b) different power outputs per hour are defined for wind and PV generations. Fig. 15(c) shows the 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 could supply the load or the surplus could be injected into the grid.

III. Results and Discussion

Several examples of applications and appliance model validation of the developed simulator are presented and discussed next to demonstrated the usefulness and accuracy of the SRLS.

A. House Load Profile

An 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 application of 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. 3. Fig. 4 illustrates how the user should input the AC parameters in the simulator. The thermostat is set at 23°C with a $+/-$ 0.5^{o}C tolerance, as in Fig. 6(a). Fig. 7 shows the information required to model the gas WH. A stove, pool pump, and lighting loads, as well

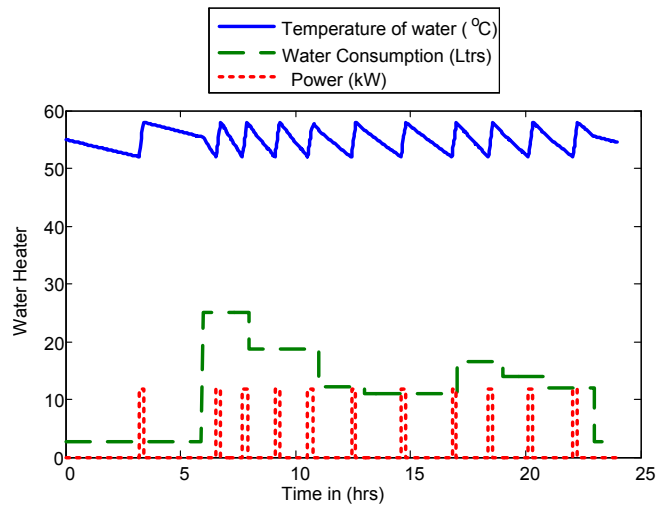

Fig. 16: Water heater results.

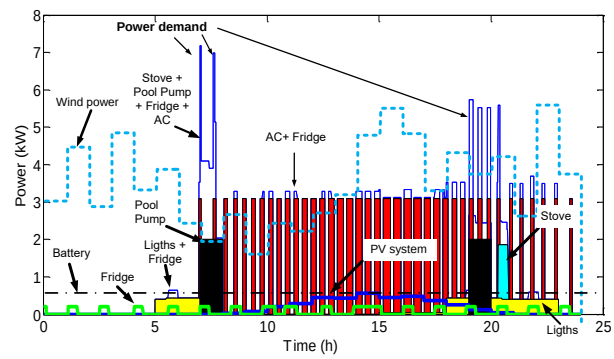

Fig. 17: Power demand profile.

as wind, solar PV, and battery sources are also included in this simulation; the washers and dryer are not considered here.

The simulator takes approximately 20 s to solve the model equations, with time intervals of 24 s, generating data for the user to analyze the behavior of the simulated appliances. Fig. 2 shows the consumed and generated energy by some of the loads and local generation sources, respectively. The WH and AC loads and the corresponding total consumed energy are shown along with the battery output. The cost of energy used by the AC and WH, and the cost of energy saved from battery 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. Fig. 16 shows the hot water temperature and consumption, and power generated by the SRLS for the water heater, and Fig. 17 illustrates the household demand profile, together with all considered appliances and sources.

B. Validation of the SRLS models

Measurements were taken on October 12, 2016, for an AC of 12000 BTU (Mirage Absolute X brand) cooling a 4x4x2 m^3 room in a coastal city in Mexico. The ambient temperature

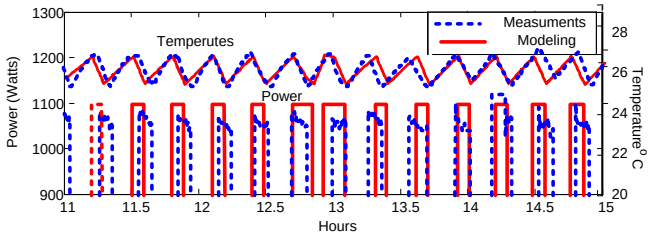

Fig. 18: AC model validation.

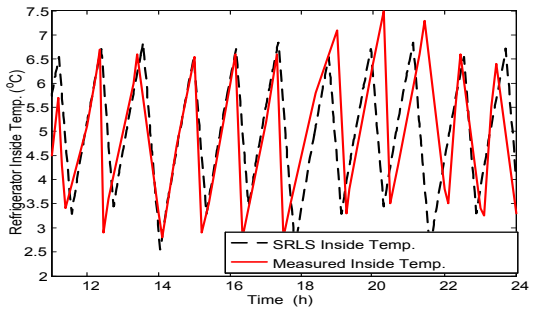

Fig. 19: Refrigerator model validation.

and solar radiation were taken from a forecasting public website, and the appliance set point was fixed at 26^oC. The room temperature was obtained using a data logger Amprobe TR 300, and power was measured with a power quality analyzer FLUKE 434. Fig. 18 shows both the measurements and simulation results obtained by the SRLS, which clearly validate the AC model.

Similar results were obtained for a small refrigerator, as shown in Fig. 19, where the similitude of the temperature variations inside the fridge obtained with the SRLS and measured using a dataloger clearly validate the model [34].

Finally, the cloth washer, dryer, dishwasher, and stove models are discussed in [30], where it is mentioned that the models were obtained in cooperation with manufacturers of appliances and electric utilities, and that the appliances' demand were discussed with experts familiar with regional case studies in selected European countries.

C. SRLS applications

The simulator has been applied to generate residential energy profiles for various studies. Thus, in [35], it was used to generate data for the development of neural network models of existing urban residential smart loads to represent these loads in a Distribution system Optimal Power Flow (DOPF) for feeder optimal control. In [36], the simulator was used to create thermal energy profiles of remote residential loads to study the application and impact of thermal energy storage on remote hybrid microgrid operation and control. These two SRL applications are discussed next in more detail.

1) Peaksaver Plus Modeling: Smart loads include various appliances controlled through an EMS, smart meters, and two-way communication connections among appliances, the Local Distribution Company (LDC), and/or external data sources (e.g., weather stations and energy prices) [37]. Since customer behavior may vary by location, preferences, and time of usage, information on customer preferences and the activity level of their appliances are important. However, the only measurement available to LDCs from most residential houses is the energy consumption data derived from their smart meters. These measurements vary widely across households; however, as the load profiles are aggregated, they become smoother, with less variations, thus allowing to better model the load at the feeder level. In order to reduce the peak load at the feeder level, LDCs may send peak demand cap or temperature setpoint signals to HVAC systems to modify the load profiles and reduce the customers' peak demand, as in the case of the Peak Saver Plus (PS+) program [38].

To study the effect of controllable smart residential loads in distribution feeder optimal operation, power consumption of different houses with realistic data for all appliances, for all days in July 2013, was modeled in the SRLS. For each house, every appliance was defined in the SRLS considering their usage; the household ambient temperatures and Time Of Use (TOU) tariffs were also input in the simulator. The consumption and generation profiles of each appliance and energy source for each household were obtained with the SRLS, together with the energy costs at different times of the day. The load profiles were obtained for two different cases: normal AC operation without receiving a PS+ signal, and operation with PS+ signals that increase by 2°C the thermostat set point.

As shown in Fig. 20, the residential load dataset from each house, including the characteristics and time of use of each appliance, was modeled in the SRLS, and the obtained load profiles from a group of houses were then added to obtain an aggregated model of the load at a phase and node in a distribution feeder. These results were then used to create a Neural Network (NN) model of the aggregated loads, which was integrated into a DOPF model. This DOPF with the NN load model of PS+ loads was used to obtain the optimal dispatch of a practical distribution feeder with 41 nodes, assuming certain percentage of PS+ controllable loads, and thus evaluate the impact and relevance of PS+ on the optimal operation of distribution feeders.

2) Thermal Demand Modeling: The SRLS was used to determine the thermal load profiles of typical Canadian houses in remote communities, to be utilized as the thermal output of an Electric Thermal Storage (ETS) system to maintain temperature in residential homes. An ETS model was developed with the help of the thermal profiles obtained with the SRLS, and integrated into a microgrid EMS to study the application and impact of ETS systems on the operation of remote microgrids.

The thermal profiles of microgrid households were obtained based on the number and dimensions of rooms and windows. For the kinds of households in remote communities, four large rooms with typical window dimensions were used. In the SRLS, the furnace is considered as a heating source during winter, based on its BTU and AFUE, yielding its thermal output in kW. The smart thermostats model was used in the simulator to define temperature set points and upper and lower temperature limits. Ambient temperature profiles for an average winter day were used. With all these information, the

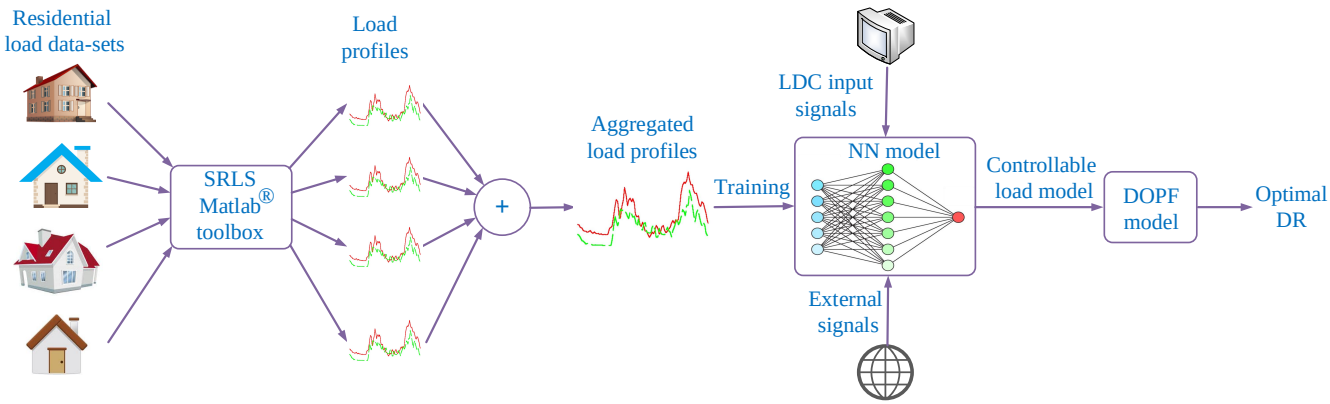

Fig. 20: Approach to modeling controllable smart loads for their integration into a DOPF based on the SRLS simulator.

thermal demand of the house in kW, which is the output of furnace, was obtained using the SRLS for a typical household in these communities.

IV. Conclusions

A new toolbox based on Matlab-Simulink has been developed to model residential energy consumption and local generation resources. 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. The main objective of the proposed simulator is to allow studying, demonstrating, and teaching energy management of residential households, and this tool can be useful for researchers to validate their models for energy management and optimization, and can also be used by customers and educators to understand and explain residential energy demand and supply. The simulator is open source code available for the interested reader at: https://uwaterloo.ca/power-energy-systems-group/downloads/smart-residential-load-simulator-srls.

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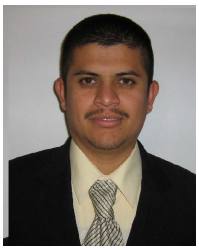

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