MODELING AND SIMULATION FOR THE ANALYSIS OF A DISTRIBUTED GENERATION SYSTEM FOR BUILDING CLUSTERS

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Overview

This study aims to model and simulate a distributed generation system with photovoltaic panels to supply the demand of a building cluster of five residencies with a Discrete Event Simulation tool. The model was built on the software Ururau and took into consideration the electricity generated by the photovoltaic cells and consumed by basic domestic equipment and lighting. The simulation analyzed the energy balance for one year with a roof photovoltaic system of both 20m² and 30m² and for a set of basic equipment and lighting, responsible for the energy consumption. The results also showed that discrete event simulation performs satisfactorily when calculating the energy balance of a group of buildings, as it allows the quick replication of a model – in this case, one residency. However, a building energy software would offer a more detailed verification when simulating a single residency.

Keywords – Grid-connected photovoltaics; Energy; Discrete Event Simulation.

1. Introduction

Among the various human activities, energy generation represents one of the main sources of greenhouse gas (GHG) emissions. Every year, the emissions related to energy generation are approximately 4.5 tons per person. However, the rapid expansion of power generation through renewable sources allowed the emissions to stay flat from 2013 to 2015 (IEA, 2016a). The 21ª Conference of the Parts (COP21) might have contributed to this expansion due to its policies related to energy safety, pollution and climate benefits (IEA, 2016b).

Of all renewable energy sources, photovoltaic (PV) energy is one of the most promising as it is the only technology for renewable electricity generation that can be widely integrated in the urban environment (DÁVI et al., 2016). Thus, buildings – responsible for consuming 40% of the world's energy – will be able to generate energy to supply their own demand (KOLOKOTSA, 2016). Moreover, with the expansion of the technologies for renewable power generation there is the need to improve the tools and methods to analyze their effect and perform forecasts, as the energy supply is intermittent (BATALLA-BEJERANO; TRUJILLO-BAUTE, 2016).

Therefore, this work aims to evaluate the feasibility of utilizing Discrete Event Simulation (DES) as a tool to perform the modeling and analysis of a photovoltaic electricity generation system for a building cluster. Although there are other methods and software, as TRNSYS (Transient System Simulation Tool) (BECKMAN et al., 1994) e EnergyPlus (CRAWLEY et al., 2001), able to perform detailed building simulation, authors as Frances, Escriva e Ojer (2014) believe that the formalism of DES may present advantages worth being explored in this field of application.

This paper begins with the collection of worldwide and Brazilian data on distributed energy generation using PV systems. The focus is on the residential sector, in which the concept of net zero energy buildings is approached. Then, the system was defined and limited in order to build the conceptual and simulation models. The results were analyzed for the number of replications necessary, the electricity consumption of each residency and the final balance between energy consumed and generated. Ultimately, considerations were made on the DES tool's performance while solving a non-trivial problem.

2. Background

2.1 - Distributed Power Generation with Solar Photovoltaic Systems

Solar energy is, among all renewable energy sources, the most abundant and it is available in both direct and indirect forms. The Sun emits energy at a rate of 3.8 x 10^{23} KW, of which 1.8 x10^{14} KW is intercepted by the Earth (THIRUGNANASAMBANDAM et al., 2010). Electricity generation using photovoltaic cells is appealing because, if 0.1% of this solar energy intercepted by the Earth was converted at an efficiency of 10%, the output would be approximately 12000 GW – more than double of the world's installed power capacity in 2012 (5550 GW, according to data from the U.S. Energy Information Administration - EIA). Furthermore, the photovoltaic systems have simple design, require low maintenance and are stand-alone systems, operating without the user's intervention.

At the end of 2014, the PV capacity installed worldwide was at least 177 GW (IEA, 2015a). Figure 1 shows the evolution of the installed capacity of solar photovoltaic systems, in GWh, of the top five countries.

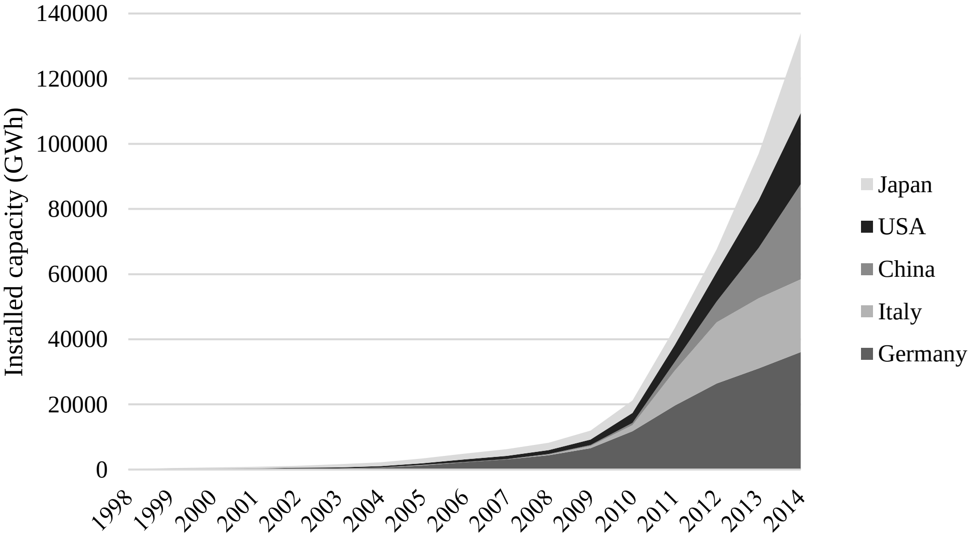

Figure 1 - Evolution of the installed capacity of solar photovoltaic systems of the top five countries, from 1998 to 2014.
Source: Own elaboration with data from IEA.

Since 2012, the largest increase in the installed capacity of photovoltaic systems has been concentrated in the Asia-Pacific region. China was placed on the top of the list in 2013 regarding all-time PV installations, followed by Japan and the USA. On the other hand, markets such as Germany or Italy have exchanged the two first places from 2010 to 2012 (IEA, 2015b).

Brazil has started to include PV in auctions for new power plants and more than 1048 MWh were granted in 2014. Although the participation of photovoltaics in the country's energy matrix is not significant yet (1.09 MW of installed capacity in 2011, according to the World Energy Council), its high radiation index due to the country's geographical position grants it with favorable conditions to PV generation (IEA, 2015b). Also, the government has set a goal to expand its installed capacity to 3.5 GW in 2023.

In the residential sector, the use of PV systems, or any other compact source of clean energy, for distributed generation on site has its benefits. They include the reduction of energy-related greenhouse gas emissions, the provision of a clean energy source for isolated areas and a low-cost option for customers subjected to higher rates during peak hours (EL-KHATTAM; SALAMA, 2004). However, the grid might not be prepared for the process of receiving electricity from residencies, with the possibility of damaging equipment. Furthermore, the residencies not connected to the grid may not fulfill their energy needs on days of low generation on site.

Thus, the need of protecting the system by controlling the voltage fluctuations, to control the process itself and to be able to store energy (BAYOD-RÚJULA, 2009) is leading to a better prepared power grid. These smart grids accommodate the distributed power generation by using state-of-the-art technology to monitor and manage energy transport and storage (IEA, 2011), creating the proper environment for net zero energy buildings (NZEBs) to operate.

2.2 - Net Zero Energy Buildings

NZEBs are efficient buildings, with low energy demand, that can generate at least as much power as it takes from the grid over a year through renewable sources. They are commonly divided into four categories: net zero site energy, net zero source energy, net zero energy costs and net zero energy emissions (TORCELLINI et al., 2006).

A net zero site energy building produces on site as much energy as it uses, sending back to the grid at least the same amount of energy as it takes from it. The definition of a net zero source building is similar; however, the building also has to produce extra energy to offset what was lost by the source during transmission and distribution. A net zero energy costs building receives as much credit for exporting electricity to the grid as it pays for the electricity imported from it. The limitation of this definition is the fluctuations of rates, making it hard to achieve grid parity (SARASA-MAESTRO; DUFO-LÓPEZ; BERNAL-AGUSTÍN, 2016). Ultimately, a net zero emissions building produces as much energy through emission free renewable sources as it takes from emitting sources.

In addition to the definitions previously presented, authors such as Hernandez and Kenny (2010) also include the embodied energy of the building components for a life cycle net zero energy building. Furthermore, buildings can also be categorized as net plus energy if it exports more energy to the power grid than it imports from it, as in the model proposed by Dávi et al. (2016).

3. Methodology

The modeling and simulation of the system were performed utilizing DES, tool commonly used for the analysis of dynamic and stochastic systems, as the one proposed in this study. Thus, it may also be resourceful for the simulation of PV electricity generation and the energy consumption by equipment and lighting of a residency, as they are all intermittent events.

The system idealized consists in a small residential condominium with five houses of 250m² each. The electricity is generated in a distributed way by a PV system of 20m², at first, installed on each roof. Furthermore, the electricity consumption is given by the use of basic domestic equipment and lighting. The number of occupants per residency was set randomly, considering the average number of 3.03 occupants/house for the state of Rio de Janeiro, according to data from IBGE (2010).

On days of low PV generation, the total energy consumed (P_{PL}) is the sum of the PV energy generated and directly consumed by the residency ($P_{PV\to L}$) and the energy imported from the grid (P_{IMP}), as shown on Equation 1 (DÁVI et al., 2016).

$$\int_{\tau_1}^{\tau_2} P_{PL}\ (t)dt = \int_{\tau_1}^{\tau_2} P_{PV\to L}\,(t)dt + \int_{\tau_1}^{\tau_2} P_{IMP}\ \ (t)dt \qquad (1)$$

In an ideal situation, however, as show on Equation 2, the PV energy generated (P_{PV}) is enough to supply the residency's demand ($P_{PV\to L}$) with an extra share that can be exported to the grid in exchange for financial credits (P_{EXP}) (DÁVI et al., 2016).

$$\int_{\tau_1}^{\tau_2} P_{PV}\ (t)dt = \int_{\tau_1}^{\tau_2} P_{PV\to L}\ (t)dt + \int_{\tau_1}^{\tau_2} P_{EXP}\ (t)dt \tag{2}$$

The delimitation of the system, followed by the construction of the model, had the intention of demonstrating the relevance of utilizing DES for the analysis of PV systems in a building cluster. Hence, the electricity consumption by equipment was better detailed when compared to the electricity generation itself. Variables such as the roof area available for PV mounting and the tilt angle of the panels were not considered. The electricity generation was simplified as its main purpose was to provide a calculation basis for the energy balance of the residencies.

The balance between electricity generated and consumed was performed by the DES software Ururau (PEIXOTO et al., 2017), following the steps proposed by Banks et al. (2010). The verification of the simulation model was done according to the methodology of Sargent (2013). Each residency's model differs only on the number of equipment and time of usage. Figure 2 shows the conceptual model of house number one.

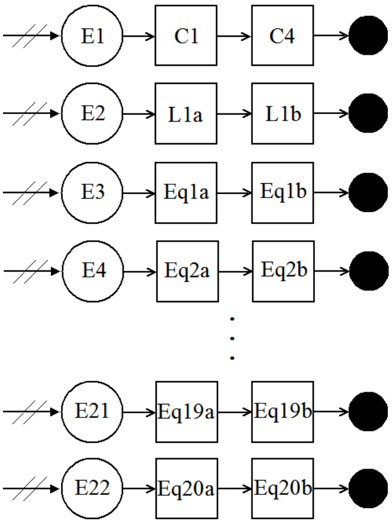

Figure 2 – Conceptual model of residency number one, using the IDEF-SIM technique.
Source: Own elaboration.

The modules C1 and C4 account for the electricity generated by PV cells and the total consumption of equipment and lighting, respectively. The consumption is given by the sum of entities E2 to E20, which represent the electricity consumed by lighting (L1a and L1b) and equipment (Eq1a/b to Eq20a/b). The modules with the tag "a" use a discrete type function to determine the time of usage of each equipment and lighting. The modules with the tag "b" calculate the energy consumed according to the average power consumption of the equipment/lighting, the time of usage set by the module tagged with "a" and the number of this equipment in the house. The average power consumption of equipment used in this simulation is presented on Appendix A and the complete simulation model is shows on Appendix B, with all the parameters properly detailed. The solar radiation data were obtained from the software EnergyPlus, considering 20m² of solar panels with 20% efficiency.

All five simulation models – one for each house – are similar and based on the list of basic equipment from Appendix A. Table 1 shows the configuration of each house and the equipment suppressed when compared to house number one.

Table 1 – Configuration of each residency.

House Identification	Basic Configuration	Occupants	Equipment Suppressed
01	According to Appendix A	Couple with two children of opposite sex	-
02	According to Appendix A	Couple with two children of same sex	3 air conditioners
03	According to Appendix A	Couple with one child	1 air conditioner 1 ceiling fan 1 laptop
04	According to Appendix A	Couple with no children	2 air conditioners 2 ceiling fans 2 electric showers 2 laptops
05	According to Appendix A	One person	2 air conditioners 1 TV 3 laptops 3 ceiling fans 2 electric showers

Source: Own elaboration.

The familiar configuration of the residencies and equipment suppressed were randomly set to observe the variation of energy consumed.

4. Results and Discussion

To determine the number of replications necessary for the convergence of results, the simulation model of house number one was executed on Ururau. The PV energy generated was used as the variable of control. It has been set a precision of 2 KWh. Thus, a pilot sample was considered with 10 replications to determine the half-width, as shown on Equation 3.

$$h = t_{n-1,1-\alpha/2}\,\frac{S_x}{\sqrt{n}} \tag{3}$$

In which:
h = half-width or precision achieved (KWh);
$t_{n-1,1-\alpha/2}$ = percentile of $(1-\alpha/2)$ of the distribution *t* from *Student* with α = 0,05 (2,26);
S_x = standard deviation of the sample (KWh);
n = number of replications.

Thus, the precision achieved was 3.52 KWh. Since this number is higher than the one required, Equation 4 was used to find a new number of replications that would allow a precision of 2 KWh.

$$n^* = n\left(\frac{h}{h^*}\right)^2 \tag{4}$$

In which:
n^* = number of replications necessary;
h^* = precision required (KWh).

The new number of replications necessary, found with Equation 4, was 31.03. Therefore, it was used 35 replications for each simulation model. The simulation length was set for one year, or 8760 hours, with an average time of 9 minutes of simulation time in computer with an Intel Core i5 processor and 4 GB of RAM. The results for each residency are shown on Table 2.

Table 1 – Simulation results found by using 35 replications.

	Consumption of lighting (KWh)		**Consumption of equipment (KWh)**		**PV Generation (KWh)**		**Energy balance (KWh)**	
	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
House 1	244.4	3.7	14957.4	239.3	5145.3	8.4	-10055.4	238.3
House 2	244.4	3.7	8342.2	304.1	5145.3	8.4	-3439.9	304.7
House 3	243.4	5.5	12943.6	269.6	5146.2	8.1	-8039.4	268.6
House 4	243.4	5.5	7598.1	128.2	5146.2	8.1	-2694.3	126.1
House 5	244.4	3.7	7045.7	93.7	5145.3	8.3	-2144.2	92.9

Source: Own elaboration.

Table 2 shows the mean values and the standard deviation of energy consumption, PV generation and final energy balance of each house. The balance was obtained by subtracting the the consumption from the energy generated. The negative results indicate that the energy consumption was higher than what was generated by the PV cells, therefore representing the amount of electricity that should be imported from the grid to supply the house's demand.

Houses number 1 and 3 had the highest energy consumption due to the number of equipment and the use of air conditioner. It has been verified that this equipment in particular is the biggest responsible for the high energy consumption in a residency. Figure 3 shows the consumption of each house, divided into equipment and lighting.

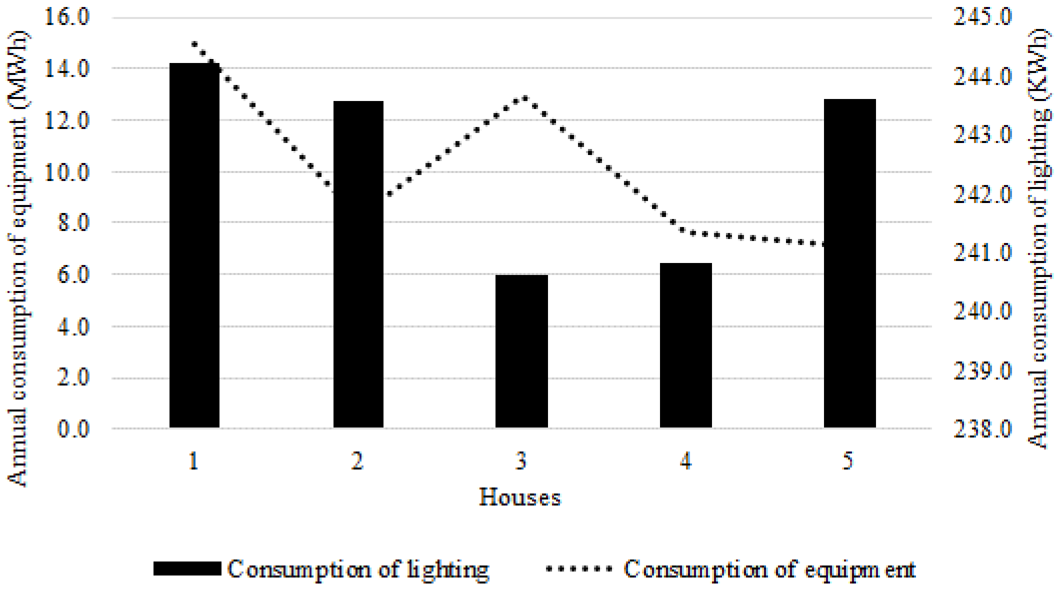

Figure 3 – Annual consumption of equipment and lighting of all five houses.
Source: Own elaboration.

Figure 4 illustrates the energy balance of the five residencies, in which the axis zero represents the net zero energy status (i.e. same amount of energy generated and consumed over a one-year period).

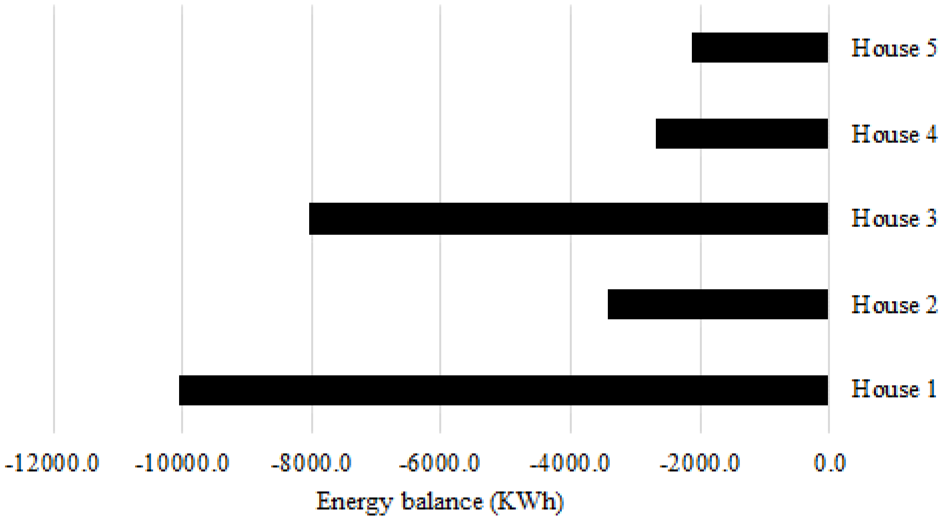

Figure 4 - Energy balance of each residency by using a 20m² PV system on each roof. Source: Own elaboration.

Thus, it is noticeable that in each residency, the annual electricity consumption is higher than what the PV system is able to generate in the same period. Nonetheless, houses number two, four and five consumed less electricity than the others did. Still, they have not achieved the net zero goal.

The electricity consumption of equipment in residencies number one and three was significantly higher, as shown on Figure 4. This high consumption can be explained by the use of the air conditioner. The other equipment, however, did not promote a significant fluctuation in the consumption.

Therefore, the area of PV panels was raised in 50%, adding 10m² of panels to the existing system. The new results of energy balance for a 30m² PV system is shown on Figure 5.

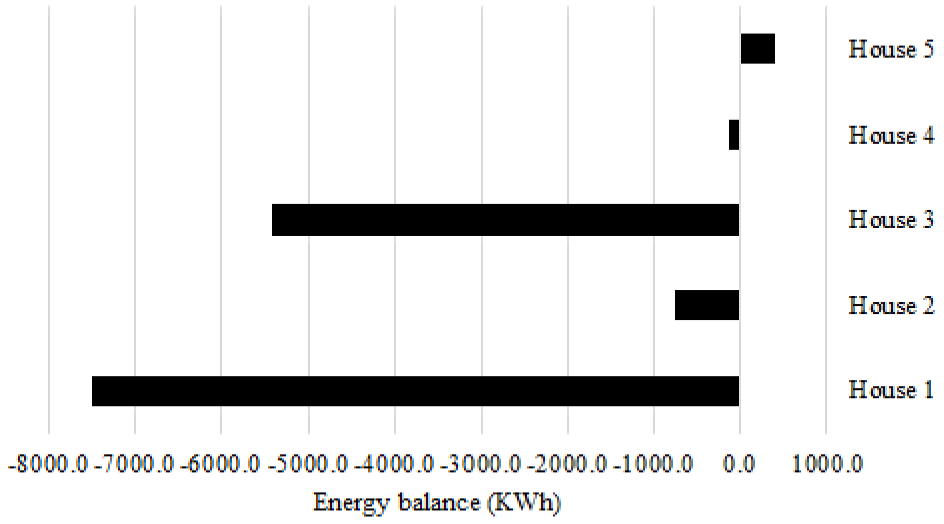

Figure 5 - Energy balance of each residency by using a 30m² PV system on each roof. Source: Own elaboration.

In this new scenario, all residencies had a lower energy balance due to the bigger area of PV panels. Houses number one and three still have their consumption higher than the electricity generated, resulting in a negative balance. House number four is the closest to net zero energy while house number five has reached the net plus energy status, being able to export the extra share of electricity to the grid.

5. Final Considerations

This study had the objective of evaluating the feasibility of utilizing discrete event simulation for the modeling and simulation of a distributed electricity generation system for a building cluster. Thus, a five-house condominium was idealized and analyzed for its balance between energy generated and consumed over a one-year period using the software Ururau.

The results showed that the discrete event simulation tool performed the simulation of energy generated and consumed in a satisfactory way, as they are both intermittent events. Furthermore, it allowed the quick replication of the model – in this case, one residency is a model – for the analysis of the cluster. However, for the study of a single house, it does not offer the same level of detail as a building energy software would.

As a suggestion for future work, this research may be extended to a comparison between a discrete event simulation software and another specifically designed for the simulation of photovoltaic systems. Also, this type of energy generation can be employed in industrial plants, as they are typical environments for the application of discrete event simulations. Ultimately, the simulated system can be compared to a real one in order to find the discrepancies between them.

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APPENDIX A – Average energy consumption of equipment/lighting and the amount of each of them in the house number one. Source: PROCEL.

Quantity	Equipment	Average Consumption	Time of Usage
11	LED Light bulb	12 W	5 h
02	Television (42’’ LED)	203 W	3 h
03	Air conditioner (10000 Btu)	756.67 W	8 h
01	Video game console	24 W	2 h
04	Laptop	80 W	4 h
01	Printer	15 W	20 min
04	Ceiling fan	73 W	4 h
02	Electric shower	5500 W	40 min
01	Hairdryer	347.33 W	20 min
01	Electric shaver	10 W	10 min
01	Stereo	110 W	1 h
01	Fridge	55 W	24 h
01	Electric stove	2285 W	1 h
01	Electric oven	500 W	1 h
01	Microwave	1398 W	20 min
01	Coffee machine	218.67 W	15 min
01	Vertical freezer	75 W	24 h
01	Exhaust hood	166 W	1 h
01	Washing machine	293.33 W	2 h
01	Clothes iron	600 W	30 min
01	Vacuum cleaner	717 W	20 min

APPENDIX B – Parameters of the simulation model of house number one.

Code	Description	Parameter
E1 to E22	Discretization of energy	1 unit of energy per hour
C1	Photovoltaic energy generated	total_gen +4.82*NORM(6,1)/24
C4	Total energy generated by PV minus total energy used	total_gen - (total_ilum+total_equip)
L1a	Lights on/off	DISCRETE(0.79,0,0.21,1)
L1b	Electricity used by lighting	total_ilum +0.012*on*11
Eq1a	TV on/off	DISCRETE(0.875,0,0.125,1)
Eq1b	Electricity used by TV	total_equip +0.203*on*2
Eq2a	Air conditioner on/off	DISCRETE(0.66,0,0.33,1)
Eq2b	Electricity used by air conditioner	total_equip +0.75667*on*3
Eq3a	Videogame on/off	DISCRETE(0.917,0,0.083,1)
Eq3b	Electricity used by videogame	total_equip +0.024*on
Eq4a	Laptop on/off	DISCRETE(0.833,0,0.167,1)
Eq4b	Electricity used by laptop	total_equip +0.08*on
Eq5a	Printer on/off	DISCRETE(0.9861,0,0.0138,1)
Eq5b	Electricity used by printer	total_equip +0.015*on
Eq6a	Ceiling fan on/off	DISCRETE(0.84,0,0.16,1)
Eq6b	Electricity used by ceiling fan	total_equip +0.073*on*4
Eq7a	Electric shower on/off	DISCRETE(0.972,0,0.027,1)
Eq7b	Electricity used by electric shower	total_equip +5.5*on*2
Eq8a	Hairdryer on/off	DISCRETE(0.9861,0,0.0138,1)
Eq8b	Electricity used by hairdryer	total_equip +0.34733*on
Eq9a	Electric shaver on/off	DISCRETE(0.9930,0,0.0069,1)
Eq9b	Electricity used by electric shaver	total_equip +0.010*on
Eq10a	Stereo on/off	DISCRETE(0.958,0,0.041,1)
Eq10b	Electricity used by stereo	total_equip +0.10*on
Eq11a	Fridge on/off	DISCRETE(0.001,0,0.999,1)
Eq11b	Electricity used by fridge	total_equip +0.055*on
Eq12a	Electric stove on/off	DISCRETE(0.958,0,0.041,1)
Eq12b	Electricity used by electric stove	total_equip +2.285*on
Eq13a	Electric oven on/off	DISCRETE(0.958,0,0.041,1)
Eq13b	Electricity used by electric oven	total_equip +0.500*on
Eq14a	Microwave on/off	DISCRETE(0.9862,0,0.0138,1)
Eq14b	Electricity used by microwave	total_equip +1.398*on
Eq15a	Coffee machine on/off	DISCRETE(0.9861,0,0.0138,1)
Eq15b	Electricity used by coffee machine	total_equip +0.21867*on
Eq16a	Vertical freezer on/off	DISCRETE(0.001,0,0.999,1)
Eq16b	Electricity used by vertical freezer	total_equip +0.075*on
Eq17a	Exhaust hood on/off	DISCRETE(0.958,0,0.0416,1)
Eq17b	Electricity used by exhaust hood	total_equip +0.166*on
Eq18a	Washing machine on/off	DISCRETE(0.9166,0,0.0833,1)
Eq18b	Electricity used by washing machine	total_equip +0.29333*on
Eq19a	Clothes iron on/off	DISCRETE(0.979,0,0.02083,1)
Eq19b	Electricity used by clothes iron	total_equip +0.600*on
Eq20a	Vacuum cleaner on/off	DISCRETE(0.9792,0,0.0208,1)
Eq20b	Electricity used by vacuum cleaner	total_equip +0.717*on