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A Software Tool to support Design and Upgrade of Energy Production and Storage Systems

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Abstract

Home energy systems that can produce, store and manage electricity are efficient solutions to satisfying the growing demand of power in home installations by the exploitation of renewable sources. The design of systems that assure autonomy without oversizing the production with respect to expected requirements can be greatly facilitated by the use of tools for modelling and evaluating performances by simulation in a simple way. Here, we propose a method to model home energy systems by means of Petri Nets and, on that basis, we describe conceptually a software simulation tool, called EPSS (Energy Production and Storage Simulator), that can be used for analyzing the system's behavior and optimizing its structure with respect to autonomy and self-consumption.

Keywords:	Home energy system; Modelling and simulation; Petri Net

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1. Introduction

In the last years, variations in cost of fuels and changes in the policy of European countries led to a growth of interest for home energy systems that can locally produce, store and manage electric energy as effectively and efficiently as possible. Indeed, in the recent past, the governments massively incentivized the production of energy from renewable sources, promoting the construction of many plants [1]. After about 15 years of massive incentives, electricity produced in this way has exceeded the thresholds that were indicated as objective in development plans, causing an excess of energy fed into the grid during the peak production hours of photovoltaic plants (more than 17GW were installed in Italy at the beginning of 2013 [2]). Then, many governments changed the mechanism of incentives, in order to promote the installation of new systems, smaller and appropriately sized to maximize self-consumption and/or autonomy. Italy, in particular, has chosen to implement a hybrid policy, with tax reductions for new photovoltaic installations and a new net-metering scheme that gives credits for the energy fed into the grid, instead of money as previously done. Due to incentives, but also to other reasons, like the market availability of electric cars, the idea of achieving autonomy by means of home plants is getting more and more consensus. To-day, the design and sizing of home production and storage system must be very accurate in order to profit of the current incentives, since they are economically efficient only if the electricity produced, or available from the storage elements, equals than that required by the home appliances, devices and systems on any time period [3].

Actually, the best solution would be that of having a production and storage system that provides total autonomy, so to avoid the necessity of buying power from the grid, and whose production does not exceed the needs, so to avoid unproductive installation costs.

Design and sizing with respect to expected requirements is not easy because of the number of involved variables and difficulty increases if, together with solar photovoltaic panels (PV) for production and Lead or Lithium batteries for storage, other production and storage systems are considered (e.g. wind generators and thermal accumulators). Studies, algorithms and software tools about design and analysis of home energy systems, usually focusing on a micro-grid point of view, have already been presented for example in [4], [5], [6],[7], [8] [9] . In this paper, we propose and describe conceptually a versatile and easy to use software simulation tool, called EPSS (Energy Production and Storage Simulator), and the system modelling strategy that works behind its definition, that can be used for several different purposes in designing, virtual prototyping and analyzing home energy systems.

The EPSS can be used in the system design phase in order to determine, in a given range, the values of nominal power of the energy production devices and the values of capacity of the storage devices that better satisfy the requirements about autonomy and self-consumption with respect to an expected consumption. Practically, the EPSS evaluates the performance indices of the system with respect to different configurations (i.e. different nominal values of power production and storage) and with respect to different production and storage technologies (i.e. different dynamical models of the production and storage devices) by simulating its operations over a given time period. The results of the simulations allow the optimization of the system structure by a simple and intuitive procedure.

Although we focus in this paper on the issues of autonomy and self-consumption, it is worth noting that the EPSS, by providing a complete description of the flows of energy within the modeled home system and between this and the electric network it is connected to, produces all data on the production and consumption of electricity that, together with information on the costs of components, their maintenance and mortgage costs, the cost of energy, the environmental impact due to the construction of the system components and to their management, makes possible to evaluate and to compare the performances of different configurations with respect to a number of economic or environmental criteria.

The EPSS employs a Petri Net to model home energy systems as multi-agent systems (HAS-Sim, [10], [11], [12]) and to describe the internal energy flows. Petri Nets give the possibility to model systems of concurrent agents in a simple way and to represent intuitively the energy flow by the exchange of tokens (see [13]).

The paper is organized as follows. In Section 2, we describe the modelling methodology for home energy systems that uses Petri Nets. In Section 3, we introduce performance indices for self-consumption of the produced energy and autonomy. In Section 4, we illustrate the structure of the EPSS, we discuss its performances and we illustrate the way in which it can be used as a design tool to optimize the choice of components with respect to given criteria. Section 5 contains conclusions.

2. Modelling home energy systems by Petri Net

The home energy systems we consider include four different kinds of elements:

- *External energy suppliers* (typically represented by the Electric Company);
- *Local energy producers* (e.g. photovoltaic panels; wind generators);
- *Energy storage devices* (e.g. batteries; thermal accumulators);
- *Energy consumers or loads* (appliances; heating and air conditioning systems; systems and devices for home care, entertainment, communication, safety).

Electric energy is produced, stored or consumed according to the internal state of each involved element and, in turn, states evolve according to specific dynamics and in response to external inputs. The home energy system operates by allowing exchange of energy between the elements, according to current production and demand. It is useful to represent the behavior of the home energy system in discrete time and to quantize by multiples of e.g. 100 W the energy produced and made available, stored or consumed during each time interval between consecutive sampling instants. Exchanges of energy between producers and consumers require availability and, therefore, they may generate conflicts. In addition, they must follow rules and policies in order to assure that the system's behavior satisfies requirements of efficiency and cost. From this assumptions, it is quite natural to use a Petri Net (PN) (see [13] for basic notions on PN) to construct a model of the home energy system. In the PN model, energy is represented by *tokens* (1 token = 100 W), which at each sampling instant are moved from *places*, where they represent the amount of produced/stored energy or the amount of required energy, to places that act as counters. The presence of tokens at different places is indicated by numbers, which form the *marking* of the net at each sampling instant. Tokens move along *arcs* that connect places to *transitions* and transitions to places. The transfer of each token between two places is regulated by the *firing* of involved transition. Firing can be inhibited if there are tokens on any place that is connected to the transition by an *inhibitory arc*. If it is not inhibited, a transition can fire if it is enabled, which means that there are tokens at all places from which an arc goes to the transition. Simulating the home energy system's behavior by a PN model, we assume that all transitions that are enabled and not inhibited fire at each sampling instant, causing the marking to change.

In graphic rendering, places are represented by circles and denoted by specific names; transitions are represented by black rectangles and denoted by T#; arcs, from places to transitions and from transitions to places, are represented by arrows; inhibitory arcs, from places to transitions, are represented by dotted lines ending in small circle. Marking is represented, when needed, by numbers inside the circles that represent places.

In order to understand how the energy flow can be modelled and simulated, let us consider a simple home energy system that consists of an energy consumer L, connected to a domestic energy producer P and to an external energy supplier S (see Figure 1). The marking $E_L(t)$ of the consumer at each sampling instant t represents the (variable) load it generates in the period of time $[t, t+1)$. The markings $E_S(t)$ of the supplier and $E_P(t)$ of the producer represent the amount of energy they can make available in the same period of time. We impose by a suitable inhibitory arc that the load is satisfied primarily by the domestic producer. Assuming that the external energy supplier is able to supply 3300 W, the marking $E_S(t) = E_S$ is 33, denoting the presence in S of 33 tokens, each one corresponding to 100 W, while in P and L there are respectively $E_P(t)$ and $E_L(t)$ tokens. If $E_P(t) \neq 0$, the transition T2 is inhibited and the transition T1 fires $n = min(E_P(t), E_L(t))$ times. At each firing, one token moves from P and from L and one token is added to O1. If $E_P(t)$ is smaller than $E_L(t)$, the marking of P1 goes to 0, transition T2 is no longer inhibited and it can fire $m = min(E_S(t), E_L(t) - E_P(t))$ times. At each time, one token moves from L and from S and one token is added to O2. T2 stops firing when either the marking of L or that of S is 0. If L $\neq 0$ when firing stops, the model signals that in $[t,t+1)$ the home energy system has not been able to accomplish its basic task, namely to satisfy the load, and it must stop. Alternatively, new markings $E_S=33$, $E_P(t+1)$ and $E_L(t+1)$ are entered to restore values for the time period $[t+1, t+2)$ and operation continues. The marking of O1 and O2 keep growing since these places are counters that, at the end of the simulation, measure respectively the energy produced by P and the energy supplied by S that have been used to satisfy the load. By the same tools, it is possible to model the behavior of the elements that have been mentioned above.

External Energy Supplier

The External Energy Supplier represents an external source that provides energy to the home energy system by connection to the electric grid of an Electric Company. Its characteristic is that of making available the same amount of energy in each time interval. It is modelled by the simple net consisting of places S, L and O2 and transition T2 and by the connecting arcs already depicted in Figure 1. The marking of S represents the available energy (e.g. 3300 W). The place L connects the supplier to a load, while O2 records the amount of energy coming that has been used to satisfy the load.

Local Energy Producer

Local Energy Producers are components of the home energy system that produce energy to be used or stored within the system or, possibly, to be fed into the grid for sale. There may be different kind of producers, whose behaviour is governed by specific dynamics. A common characteristic is that the amount of energy they provide in each time interval varies according to external inputs and cannot exceed a given threshold.

Photovoltaic (PV) panels behave in that way and they are modelled by the net shown in Figure 2. The marking PV_{MAX} of PV1 represent the threshold that limit the available energy on each time interval. This is a physical characteristic of the device, which does not change over time, but can be modified to model PV's with different characteristics. The marking of PV2 represent the energy $E_{PV}(t)$ actually produced in the time period $[t, t+1)$ and it varies at each sampling instant. The places PV3 and PV4 are used to store temporarily the available energy and to separate the flows. The place PL is used to connect the PV panel to a load whose value is indicated by the marking $L(t)$ and PVO1 is the counter that records the amount of produced energy that has been used to satisfy the load. The place PVS is used to connect the PV panel to a storage device and PVO2 is the counter that records the amount of produced energy that has not been used to satisfy the load and that has possibly been stored. The place PVO3 is used to connect the PV panel to the grid and it acts as a counter that records the amount of produced energy that has not been used or stored and that has possibly been fed to the grid. Inhibitory arcs force the use of the produced energy so to satisfy primarily the load, then to charge the storage device and possibly to feed the grid. Different decoupled loads, storage devices and grids can easily be connected by replicating the corresponding connection places and priority in servicing can be set by suitable additional inhibitory arcs.

A different kind of local energy producer is the Airborne Wind Energy (AWE) system considered in [14]. Differently from PV panel, the AWE system alternatively produces and consumes energy, in such a way that the balance is positive. A Petri Net model of the AWE system can be constructed by considering it alternately as a producer (that can be modelled as the PV panel) at time t and as a load at time t+1. The length of the sampling interval, in such case, must agree with the length of the operating cycle of the AWE system.

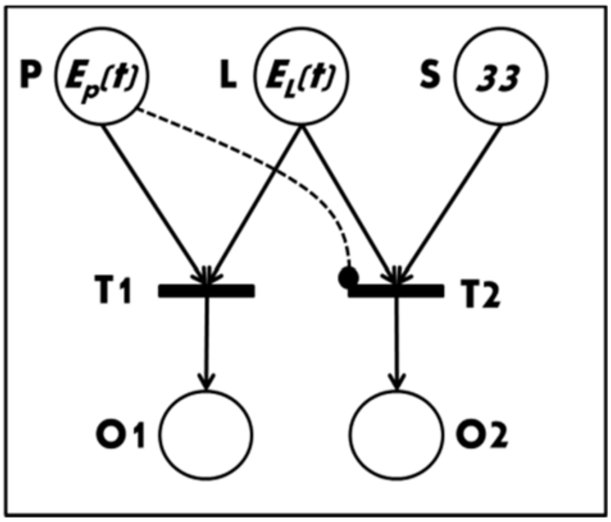

Figure 1: Simple home energy system

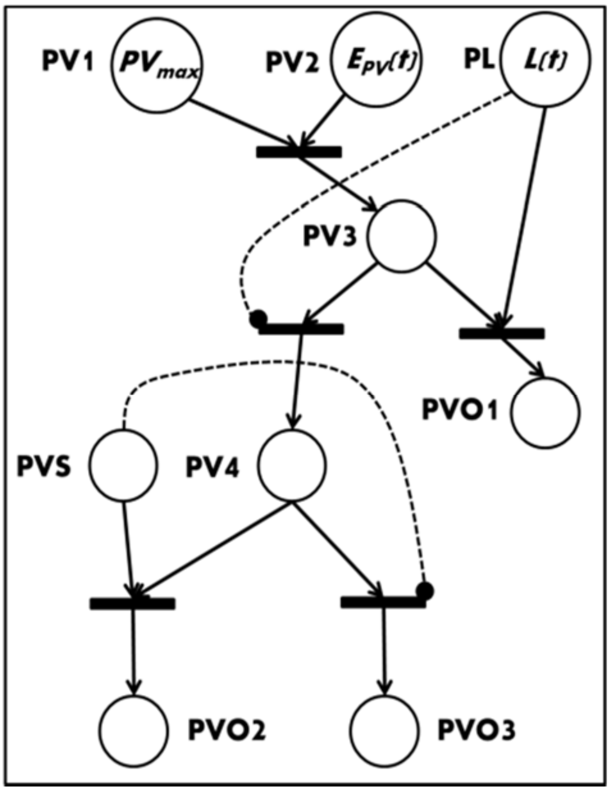

Figure 2: PV model

Energy Storage Device

Energy produced locally that is not directly consumed can be fed to grid or stored. The most common storing devices are batteries of different kind. In general, their behaviour alternates charging cycles, in which they act as loads, and discharging cycles, in which they supply the stored energy. Such behaviour can be modelled by the net of Figure 3. The marking $E_S(t)$ of PB1 represents the total energy stored in the battery at the sampling instant

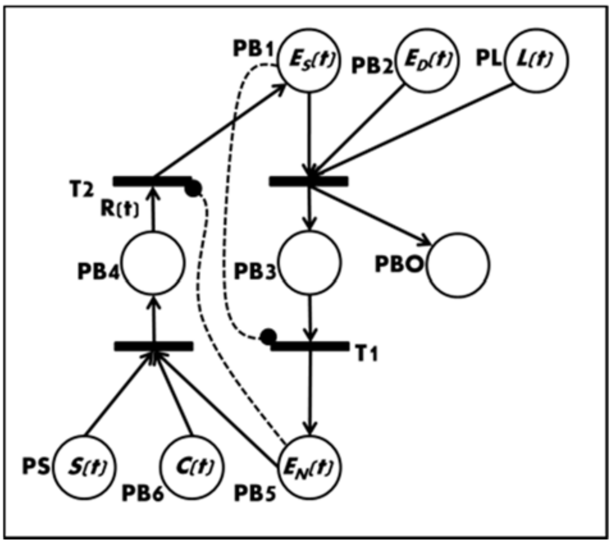

Figure 3: Battery model

t and, at *t=0*, it is initialized with the maximum value that characterize the device at issue. The marking of PB2 indicates the energy $E_D(t)$ that the device can supply in the time period *[t, t+1)* and it may vary, according to the battery status, at each sampling instant. The place PL is used to connect the battery to a load whose value is indicated by the marking *L(t)*; PB3 is a temporary counter of the energy that has been used, while the place PBO is the general counter of the used energy. When $E_S(t)$ reaches *0*, the battery cannot supply energy and a charging cycle starts. Transition T1 is no longer inhibited and all tokens temporarily stored in PB3 are moved to PB5, whose marking $E_N(t)$ (initialized as $E_N(0) = 0$) denotes the energy required to recharge the battery. The marking of PB6 indicates the energy $E_C(t)$ that the battery can absorb in the time period *[t, t+1)* and it may vary, according to the battery status, at each sampling instant. The place PS is used to connect the battery to a recharging source, which, in the time period *[t, t+1)*, can supply the amount indicated by the marking *S(t)*. The places PB4 store temporarily the absorbed energy. When the marking $E_N(t)$ of PB5 reaches *0*, the charging cycle stops and a discharging cycle may start. Transition T2 is no longer inhibited and all tokens temporarily stored in PB4 may move to PB1. The index *R(t)* associated to the arcs connecting PB4 to T2 indicates that tokens can be moved only in group of *R(t)* elements and it may vary, according to the battery status, at each sampling instant. Depending on the difference between $E_S(t)$ at the beginning of each discharging cycle and *R(t)* during the next charging cycle, some tokens may remain trapped in PB4 and this models in a simple way hysteresis in the battery's behaviour.

Electric energy can also be transformed in such a way to be more conveniently stored, e.g. by thermal accumulators. In general, they may consist of a

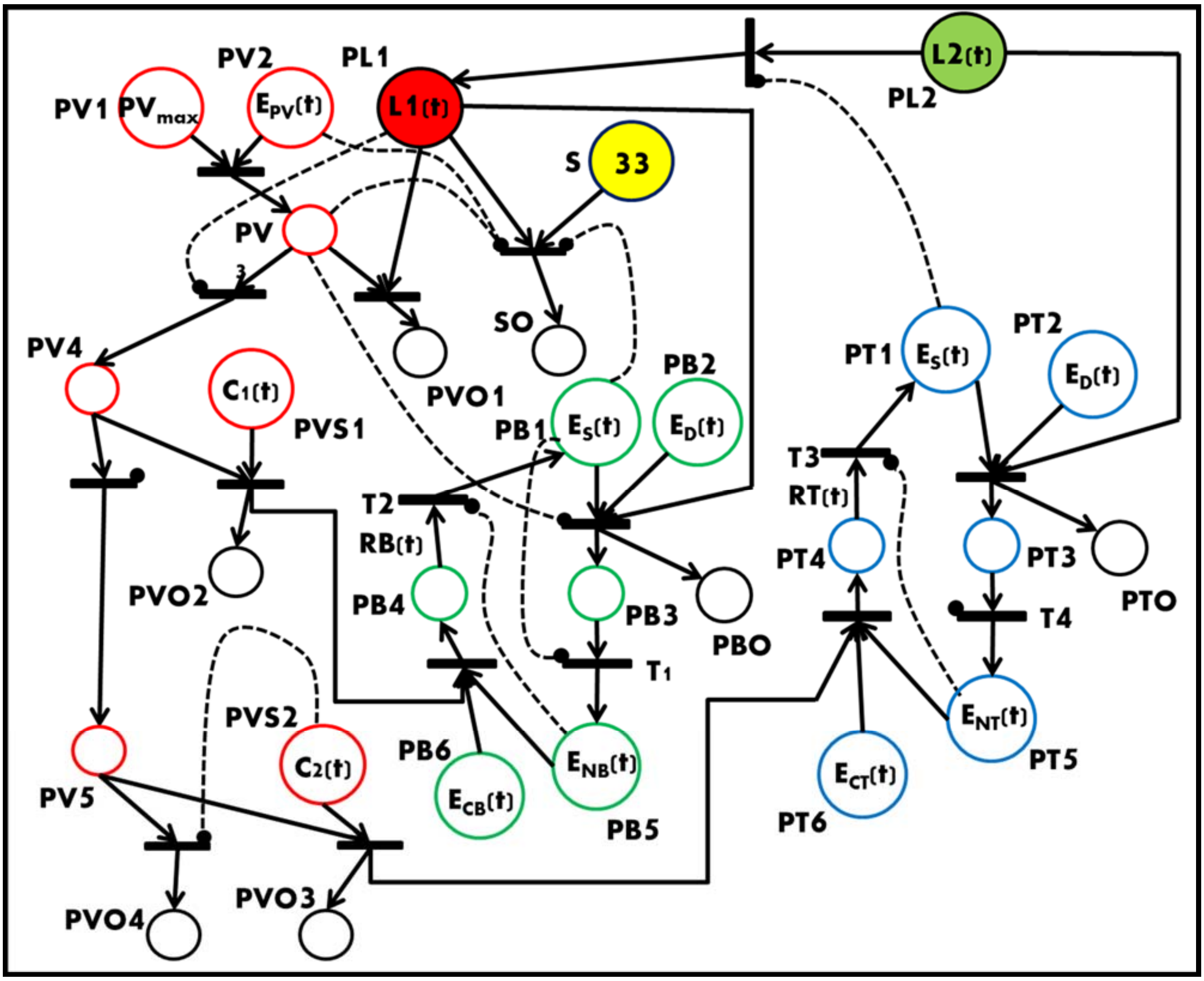

Figure 4. An example of a home energy system model

thermally insulated tank, in which water or another fluid is stored. In some installations, electric energy produced e.g. by PV during the day (or during the whole Summer) is used to heat the fluid and this, by a heat exchanger, is used to regulate the home temperature during the night (or during the whole Winter). If, instead of heating the fluid, electric energy is used to cool it, it is possible to use the stored energy to reduce the home temperature. We can consider thermal accumulators as devices that can supply the stored energy only to a Heating, Ventilating and Air Conditioning (HVAC) system, which acts as a load either for them or for a producer/supplier of electric energy. We can therefore model also this kind of storage devices as batteries, providing the only load they can be connected to is that representing the HVAC system.

Using the elements described above, it is possible to model home energy systems that contain several components. An example is given by the net of Figure 4, which describes a home energy system which integrates PV, a battery and a thermal accumulator. Load is represented by a generic load, due to all devices that require electricity to work except the HVAC system. This is represented as a special load, which can be connected either to the thermal accumulator or to other sources of electricity. Note that inhibitory arcs force a specific behaviour of the net, imposing e.g. that the generic load must be satisfied primarily be the photovoltaic production or by the battery. At the same time, the HVAC system load is primarily satisfied by the thermal accumulator. Only in case all this is not sufficient, electricity is taken from the grid. Similarly, the energy produced by PV is primarily used for satisfying the load, then for charging the battery and the thermal accumulator and only if there is no load and the storage devices are fully charged, it is fed to the grid. Inhibitory arcs can be modified, varying the structure of the net, in order to implement different policies in managing electricity.

3. Self–consumption and autonomy

To evaluate the performances of a home production and storage system, one of the most commonly used indexes is the *Self-Consumption index*. As described in literature, (for example in [4]) the Self-Consumption index (*SC*) measures the rate of produced energy that is consumed or stored locally. Let us consider a system connected to a provider grid and composed e.g. by a PV generator and a battery, in which the energy produced is used to satisfy the domestic electric load and to charge the battery. Exceeding energy is feed to the grid and, on the other hand, exceeding load is satisfied by getting power from the grid. In this case, the *SC* index is defined as

$$SC=\frac{E_{PV,L}+E_{PV,S}}{E_{PV,T}} \quad (1)$$

where

- $E_{PV,T}$ is the total energy produced by the PV generator during a given time period;
- $E_{PV,L}$ is the part of energy produced by the PV generator that is used to satisfy the domestic electric load during the same time period;
- $E_{PV,S}$ is the part of energy produced by the PV generator that is stored in the Battery during the same time period.

Obviously, *SC* cannot exceed 1 and it is lower than 1 if, during the considered period, the load, including that generated by charging the battery, is lower than the production. As it's easy to understand, maximizing *SC* without considering other constraints does not make sense, since this objective can be easily reached by keeping the production lower than the load. So, together with *SC*, it is important to consider another index, which is related to autonomy. The *Autonomy index* (*AUT*) actually measures the percentage of the consumed energy that has been provided by the production and storage system. In the case at issue, the *AUT* index is defined as:

$$AUT=\frac{E_{PV,L}+E_{PV,S}}{E_{T,C}} \quad (2)$$

where

- $E_{T,C}$ is the total energy consumed, given by

$$E_{T,C}=E_{T,L}+\left(E_{PV,S}-E_{B,L}\right) \quad (3)$$

- $E_{T,L}$ is the total energy required by domestic loads during a given period;
- $E_{B,L}$ is the total energy provided by the battery to satisfy the domestic load.

Clearly, a high value of *AUT* characterizes a system in which the domestic load is largely satisfied by the production and little or no energy is got from the grid.

Since the load is not constant, increasing the *AUT* index will generally result in a decrement of the *SC* index and conversely. The design of an efficient home production and storage system needs therefore to address a practical optimization problem that consists in maximizing both indices, while containing the costs of the various components, with respect to a (variable) expected load.

4. Simulating home automation systems

A software tool, called Energy Production and Storage Simulator (EPSS), has been developed in the NI LabView 2013 environment [15]. Basically, the EPSS implements the dynamics of the Petri Net that, as described in Section 1, models a home energy system activating the transfer of tokens.

In the simplest operating mode, the EPSS can be used to simulate the operation of a home energy system over a given time interval. The input of the EPSS consists of look-up tables that describe the behavior of the local energy producers and of the energy storage devices, together with a number of files that describe the behavior of the load(s) and of some external variables. For the PV, the look-up table indicates PV_{MAX} and the energy $E_{PV}(t)$ produced by the PV element in each time interval in correspondence of a given value of the solar radiation *S(t)* and possibly of the external temperature *T(t)*. For the battery, the look-up table indicates the initial charge $E_S(0)$; the values of $E_D(t)$, $E_C(t)$ that correspond to the actual values of $E_S(t)$ and $E_N(t)$ and that, possibly, depend also on the number of executed charge/discharge cycles and on the external temperature *T(t)*; the value of *R(t)* that possibly depends on the number of executed charge/discharge cycles and on the external temperature. A similar look-up table can be used for the thermal accumulator. The look-up tables are constructed off-line, either on the basis of experimental data or using suitable models of the considered devices.

The *load(s) file* contains the values *L(t)* of the load(s) at each sampling time. The *solar_ radiation* and the *ex_temp* files contain the values of the solar radiation *S(t)* and of the external temperature *T(t)* at each sampling time. If other variables that may influence the behaviour of the above elements are considered in the look-up tables (e.g. internal temperatures), their values are entered by means of additional input files.

Simulation is performed by executing a sequence of steps, in which each step corresponds to the time interval between consecutive sampling instants.

Marking is initialized at the beginning of each step by using the look-up tables and the input files. The EPSS gives the possibility to see the temporal evolution of the marking of the counter places, representing the energy that is produced, stored, consumed and fed to grid and it computes the self-consumption and autonomy indices. In this way, the EPSS works as a tool for analyzing the performances of the modelled home energy system, using measured or predicted data in the input files.

Energy producers and storage devices with different physical characteristics, performances and costs will correspond to different look-up tables. Therefore, any choice of the look-up tables in a given set defines a specific configuration of the home energy system. In a more complex operating mode, the EPSS can be instructed to perform a series of simulation over the same time period and with the same input files (that is: in the same conditions), changing, in a programmed way, the look-up tables (that is: the system configuration) by choosing them in a given set. Comparison of the resulting values of self-consumption and autonomy, then, gives the possibility to select the configuration of the home energy system that provides the best performances for the considered conditions. In this second operating mode, the EPSS explores the parameter space using a discretization step that can be set by the user. Procedures that search for values of the parameters that try to optimize the performances can be implemented by exploiting this operating mode of the simulator.

An example of a home system that can be modeled and simulated is given in Figure 4. The system includes a PV panel, a battery, a thermal accumulator, an external energy supplier, a generic load, a HVAC load. The set of places of the PN model which correspond to each one of these elements are identified by circles of different colors: red for the PV panel, green for the battery, blue for the thermal accumulator, solid yellow for the external energy supplier, solid red for the generic load, solid green for the HVAC load. Connections are such that the thermal accumulator can supply energy only to the HVAC system. Inhibitory arcs are such that the HVAC exploits primarily the energy stored in the thermal accumulator. If none is available, the HVAC load adds to the generic load. This is satisfied primarily by the PV, then by the battery and finally, if needed, by energy coming from the external energy supplier (Electric Company). The exceeding energy from the PV is used primarily to charge the battery or to increase that stored in the thermal accumulator (if the battery is charged) or it is fed to the grid for sale (if the battery and the thermal accumulator are charged).

To evaluate the performances of the EPSS, we compared the real behavior of a home energy system with that obtained by simulation from a model of the same system

Table 1: Real behavior vs. simulated behavior

	SC	AUT
Leaf House	49.11%	24.61%
EPSS	52.55%	27.38

with regard to the SC and AUT indices. The real system is that of the Leaf House in Angeli di Rosora, Ancona, Italy. The Leaf House is a complex of apartments, divided in energetically independent blocks. Each block is connected to a PV system with a nominal power of 6kW and to a Lithium battery with a nominal capacity of 5.8kWh. Energy production and consumptions are continuously monitored and an average value for each of them is recorded every 15 minutes. The system is governed by an inverter in such a way to maximize self-consumption. The model used in simulation is like that of Figure 4, without the thermal accumulator. Data about real loads and solar radiation have been collected for one year in 2013 and they have been used to construct the load and the solar radiation files The look-up tables for the installed PV and battery systems have been constructed experimentally. Results given in Table 1 show a substantial agreement between the real and the simulated behavior, with small discrepancies that are due to the non-ideal behavior of the real components.

As a design tool, the EPSS has been tested to find the best configuration, in terms of nominal power of the PV panel and nominal battery capacity, for the same system as above, using the same data files, with respect to a desired level of autonomy and self-consumption. In a first series of simulations, look-up tables for PV panels with nominal power between 2000 W and 10000 W (with interval of 1000W) and for battery with nominal capacity between 2000 Wh and 10000 Wh (with interval of 1000 Wh) have been used. Considering only the system configurations, in terms of PV nominal power and battery nominal capacity, that assure, for instance, values of the SC index greater than or equal to 40% and values of the AUT index greater than or equal to 45%, simulations gave, in particular, the results contained in Table 2. Simulation can also be refined, for instance considering configurations with PV nominal power between 3500 W and 4500 W with interval of 100 W and battery capacity between 3500 Wh and 4500 Wh with interval of 100 Wh, obtaining the results shown in Table 3. Then, results can be used together with information about the market prices of the PV panels and of the batteries to find the configuration that, while achieving the desired performances in terms of SC and AUT indices, minimizes the costs of one or more of those components. In this case, choosing for instance to minimize the cost of the battery irrespectively from the cost of the PV panel, the configuration corresponding to 4000W and 4000Wh resulted to be the preferable one (see [14], [15]).

Table2: Simulation results

PV nominal power	Battery nominal power	SC	AUT
4000	4000	41.69%	45.03%
3000	5000	58.17%	45.60%
4000	5000	46.76%	48.27%
3000	6000	62.70%	47.81%
4000	6000	51.73%	51.23%
5000	6000	42.18%	52.22%
3000	7000	66.44%	49.50%
4000	7000	54.29%	52.71%
5000	7000	44.07%	53.58%
2000	8000	90.69%	45.84%
3000	8000	70.52%	51.30%
4000	8000	57.37%	54.32%
5000	8000	46.91%	55.46%
6000	8000	40.21%	56.57%
2000	9000	92.00%	46.26%
3000	9000	72.71%	52.11%
4000	9000	58.99%	55.31%
5000	9000	48.54%	56.46%
6000	9000	42.78%	58.26%
2000	10000	93.28%	46.77%
3000	10000	73.65%	52.45%
4000	10000	60.48%	55.94%
5000	10000	51.18%	57.98%
6000	10000	44.54%	59.35%

Table 3: Simulation results

PV nominal power	Battery nominal power	SC	AUT
4000	4000	41.69%	45.03%
4100	4100	41.05%	45.27%
3900	4200	42.80%	45.01%
4100	4200	41.03%	45.24%
3800	4300	44.71%	45.50%
3900	4300	43.38%	45.39%
4000	4300	42.30%	45.46%
4100	4300	41.29%	45.45%
3500	4400	49.06%	45.68%
3600	4400	47.39%	45.48%
3700	4400	45.61%	45.22%
3800	4400	45.09%	45.80%
3900	4400	44.00%	45.84%
4000	4400	43.28%	46.12%
4100	4400	42.51%	46.27%
4200	4400	41.14%	46.12%
3500	4500	48.78%	45.52%
3600	4500	47.26%	45.39%
3700	4500	45.55%	45.16%
3800	4500	44.78%	45.60%
3900	4500	44.29%	45.97%
4000	4500	43.24%	46.07%
4100	4500	42.47%	46.22%
4200	4500	41.14%	46.09%

5. Conclusions

A simple and intuitive way of modelling the flows of energy in home energy systems by using Petri Net models has been illustrated. By simulating the model behaviour, components of the system can be optimized with respect to self-consumption and autonomy, facilitating the design of a cost efficient system.

Since the EPSS provides also the values of the quantities $E_{PV,T}$, $E_{PV,L}$, $E_{PV,S}$, $E_{T,C}$, $E_{T,L}$, $E_{B,L}$ defined in Section 3, which completely characterize the flows of energy in the home system and between the home system and the grid, additional information about the price of electric energy, either bought from the electric company or sold to it through the grid, and about the mortgage costs of the components can be used to analyze the performances of the home system from an enlarged economic point of view. This makes possible to find the configuration that achieves given economic objectives or that better responds to economic constraints. Analogously, information about the environmental aspects that are connected to the life cycle of the system components (PV panels, battery and thermal accumulator) and/or to the production of electric energy that the home system gets from the grid may be used to evaluate the environmental impact of different system configurations.

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