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Energy Sharing in a Grid: Cellular Automata Approach

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Abstract: This study proposed a new Cellular Automation (CA) model for decentralized energy management in P2P micro grids. The model is made in python programming language and validated by real data, collected during the two weeks of the Solar Decathlon Middle East competition. The model concerns energy sharing in a network that is modeled on the CA approach. The proposed CA determines the users state based on the energy supply and demand of the microgrid. Any excess energy is automatically shared without intermediaries (distribution system operators or market operators). The status of each user is defined by a number of parameters such as energy production, consumption, and storage. The numerical model was validated using real data collected during the two weeks of the Solar Decathlon Middle East competition 2018. Simulations and experimental results illustrating the current approach are presented. Based of the findings, valuable recommendations for practitioners and future research directions for scholars are highlighted.

Keywords: *Cellular automata, micro grid, peer-to-peer sharing, photovoltaic systems, solar decathlon*

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I. INTRODUCTION

In recent years, the power systems of most developed countries have undergone a process of integration of renewable energies. Many factors are at the origin of this transformation, mainly: The commitment of governments to implement energy efficiency programmes in response to the threat of climate change [1]; The drastic reduction in the cost of renewable energy.

In fact, these technologies represent a cost-effective solution for small-scale electricity generation by individual users, which hosts a variety of distributed energy resource units and different types of energy consumers [2, 3]. However, due to the intermittent nature of DER generation (e.g., solar panels and wind turbines), makes this solution complex to manage. At the scale of a group of buildings or a district (residential microgrid), there could be a significant gap between the supply and demand for electricity, especially when the microgrid is operated in island mode and disconnected from the main grid. One possible solution to this challenge is the principle of power sharing. The objective is to allow an exchange between buildings with an excess of energy and those with an energy deficit. This enables consumers with an energy deficit to purchase renewable energy at a more advantageous price from a neighbor with an energy surplus [4, 5, 6, 7].

In recent years, considerable academic research on the P2P energy trade has been conducted. Most of this research concerns the design of mechanisms for P2P energy. They can also be classied into two models: centralized [1, 8, 9, 10, 11] and decentralized (A review summarizes and discusses these projects) [2]. In the case of a cen-

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tralized system, a Distribution System Operator (DSO) is necessary. to interact with the peers and cover responsibilities such as operating and organizing resources to achieve the benefits of each individual user. These peers submit their offers to the DSO and receive the price and quantity of traded electricity after the end of the bidding time window [12]. However, carrying out P2P energy sharing with a DSOposes a practical problem which lies in the difficulty of guaranteeing convergence of offers between different prosumers [12]. For this reason, most P2P projects developed or under development around the world are decentralized models. Piclo in the United Kingdom [13], Vandebron in the Netherlands and Sonnen Community in Germany [14]. On the other hand, The decentralized model, is based on information storage and transmission technology (Blockchain). The energy is numbered and automatically stored in the blocks of the blockchain as a contract. The first blockchain implementation in the P2P energy trading sector was held in Brooklyn in April 2016 [15].

In this context, due to the possibility of assimilating a microgrid to a regular structure of connected cells (prosumers and consumers), the cellular automata can be a very useful choice to decentralize P2P electricity sharing. To our knowledge, no model based on CA for peer-to-peer networks has been reported in the literature. Cellular automata are discrete models of cells; each cell has a set of neighborhood cells each with their own states. The systems evolution in time is governed by a set of local rules related to the state of each cell as well as to its neighborhood. These models have a very wide range of applications and in our case their properties give them significant potential for the management of energy distribution in micro-grids menu.

In this work,a new decentralized model for the management of energy distribution in a microgrid is derived. The model is made using CA approach, which determines the status of the user based on the energy supply and demand of the microgrid. The numerical model was validated using SDME 2018 reports data [16]. The solar village of Solar Decathlon Middle East competition UAE 2018 is a perfect example of a microgrid where each house has energy production capabilities.

The rest of the document is structured as follows. We begin with the generalities in section 2, including the definition of CA in general, followed by P2P energy sharing architectures and a description of the CA method for P2P sharing. In section 3, we describe the proposed CA model.

GENERALITIES

This section begins with a brief overview of cellular automata to provide basic information for the rest of the document. Then, the P2P energy sharing structure is presented, this is followed by a general concept of cellular automata in the management of energy in a microgrid.

A. *Cellular Automata*

A CA is defined by the quadruplet A plus the boundary and initial condition [17].

$$A = (\mathrm{L}, \mathrm{N}, S, \mathrm{F}) \tag{1}$$

Where L is lattice, S is a set of states, N is a neighborhood, and F is a function of transition. Below is a description of the CA structure:

1) Lattice: Is a grid that consists of a paving of the n-dimensional space R^n, $n = 1$, 2 or 3 consisting of cells C_i, $i \in N$

2) Neighborhood: The neighborhood of a cell is the set of cells surrounding it. If we consider a two-dimensional domain $n = 2$ and a radius $r > 1$ the most common neighborhoods are:

•Von Neumann neighborhood

$$\mathbf{N}(ij) = (C_H; |k-i| + |l-j| \leq 1)$$

•Moor neighborhood

$$\mathbf{N}(ij) = \{C_{\mathrm{x}l}; |k-i| \leq 1, \quad |l-j| \leq 1\}$$

•Generalized Von Neumann neighborhood

$$\mathbf{N}(ij) = \{C_{kl}; |k-i| + |t-j| \leq r\}$$

•Generalized Moore neighborhood

$$\mathrm{N}(ij) = \{C_{nl}; |k-i| \leq r, \quad |t-j| \leq r\}$$

3) Set of States Represents the number of states that any cell can take on.

$$S = \{S_1, S_2, S_3, \ldots S_k, k = \mathrm{card}\, S\} \tag{2}$$

4) Transition function: The CA evolves in a discrete time horizon where the incrementation +1 corresponds to a time step (seconds, minutes, hours ...). The transition function governs the dynamics of the cell. It specifies the state of a cell at time $t + 1$.

5) Initial Conditions: The starting point of an evolution is an initial configuration defined for all cells (a state $S(C_{ij}, t+1)$). This configuration can be considered random, given by a known function or estimated.

B. *P2P Energy Sharing Architecture*

We consider an electrical grid consisting of connected members exchanging energy with one another. Members can be consumers or prosumers and can represent residential users (homes, apartments or villas). The prosumers are equipped with a standard solar panels with battries. If the microgrid is operating in on-grid mode, members are connected to the main grid as shown in Fig. 1. The transfer of energy between users is done through the traditional distribution grid. In islanding mode, users are connected via a universal power interface that, with some logic, can transfer energy bidirectionally between any combination of its connections. Via this interface, each users AC output is connected to the nearest neighbors AC input to form a power-sharing microgrid structure, as shown in Fig. 1. The arrows in Fig. 1 indicate the directions of allowed power flows for all component connections.

1) Cellular automata for energy management: CA are widely used to model many systems in different fields such as physics, chemistry, biology and computer science. The application of cellular automata to the energy management of the microgrid system is a new area of study and, as noted in the introduction, cellular automata have great potential for solving problems associated with the microgrid system. Our CA model includes a number of cells (residential users) arranged in a microgrid, which naturally corresponds to a two-dimensional lattice. All cells are interconnected to their nearest neighbours via the power lines, either by conventional lines or universal interfaces. The energy balance between demand and supply is automatically ensured without the need for intermediation thanks to clearly defined transition rules and conditions.

We therefore propose 5 states reflecting the energy user status of the residential user in real time (Demand satisfied+, Demand satisfied-, Excess power, Power deficit, Grid connexion). The dynamic state change depends on three main parameters; the solar power generation, the load profile, the battery bank state and the microgrid's total energy balance. A detailed description of the components of the proposed CA model is given in the following section.

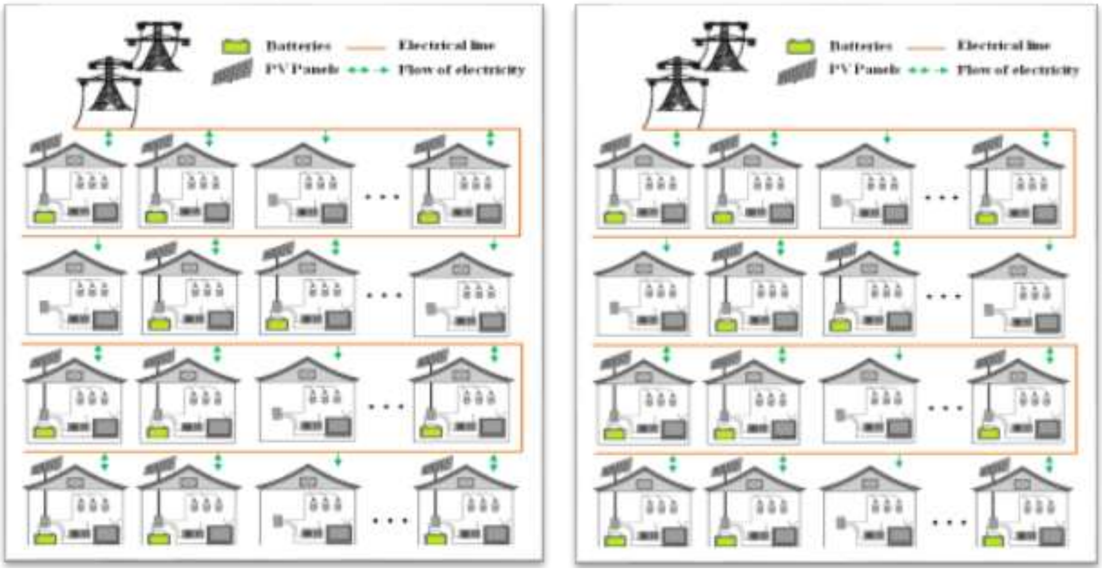


Fig. 1. P2P energy sharing architecture. a) Connected grid mode b) Islanding mode

II. DESCRIPTION OF THE PROPOSED CA MODEL

Our CA model is similar to the one we proposed and was reported in a conference proceeding [18]. We will now describe the model in more detail.

A. *Lattice and Neighborhood*

The study area is microgrid structure, which consists of n residential users (cells). These cells are energy consumers and prosumers arranged in a two-dimensional lattice as shown in Fig. 2. Since all residences are connected via the power lines, we assume that they are arranged in a regular space. Similarly, for a good discretization of our lattice, the actual physical space between the members of the microgrid is not taken into account. We therefore consider a network of cells, each cell being a residential user as shown in Fig. 1. The lattice is:

$$\mathrm{L} = \left\{C_{ij}; i, j \in \mathrm{N}; i = 1, 2, \ldots n_i \text{ and } j = 1, 2, \ldots n_j\right\} \tag{3}$$

with n_i and n_j the number of residential users.

The neighborhood of a cell C_{ij} is the Generalized Moore neighborhood with a dynamic radius r to search the nearest user with the desired state as shown in Fig. 2.

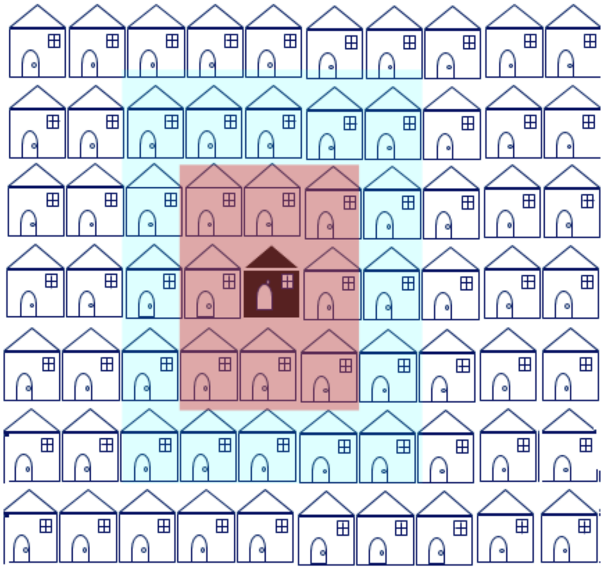


Fig. 2. CA neighborhood

The size of neighborhood is defined as ∈3,5,8 according to the boundaries.

The neighborhood is:

$$\mathbb{N}(ij)=\{C_{kl}:|k-i|\leq r,|l-j|\leq r\},C_{ij}\in\mathscr{L} \qquad (4)$$

B. Set of Possible States

1) State values: At each time step, the energy balance between supply and demand is based on the determination of the state of the cell. The state of a cell C_{ij} will be given by a combination of 3 parameters, namely the amountof energy generated P_{pv}^{t}, consumed P_{c}^{t} and stored Q_t. Furthermore, the model allows us to identify the state of the node according to four defined states

$$s=\{1,2,3,4,5\} \qquad (5)$$

With

- State 1: Demand satisfied+,
- State 2: Demand satisfied,
- State 3: Surplus power,
- State 4: Power deficit,
- State 5: Grid connexion.

1. Demand satised+:The power produced by solar panels is sufficient and surplus energy is then used to charge the batteries.
2. Demand satised: The power produced by solar panels is not sufficient to cover the required load. The priority is to use the energy stored in the batteries.
3. Surplus power: Same as case 1, but the surplus energy produced by solar panels is greater than the need for the load and batteries. Consequently, the surplus energy is transferred to the neighbours in this case.
4. Power Decit: The energy produced by the solar panels is not sufficient to cover the required load and the battery bank is also used up. In this case, the load and the batteries are powered by the surplus energy of the other homes.
5. Grid connexion: Same as case 4 but the surplus power of other homes is not sufficient to cover the required load. The power is drawn from the grid.

2) State transition and factors: The state of each cell depends on a set of attributes and parameters as summarized in Tab.1. A comprehensive description of such parameters will be provided along the transition rules. The configuration of the proposed CA state is given by Eq.6:

$$S=\begin{cases}\langle 1\rangle & \text{if } Nl^{t}(i,j)>0 \text{ and } \mathrm{Soc}^{t}(i,j)\leq\alpha\,\mathrm{Soc}^{t}_{\max}(i,j)\\ \langle 2\rangle & \text{if } Nl^{t}(i,j)<0 \text{ and } \alpha\,\mathrm{Soc}^{t}_{\max}(i,j)<\mathrm{Soc}^{t}(i,j)\leq\mathrm{Soc}^{t}_{\max}(i,j)\\ \langle 3\rangle & \text{if } Nl^{t}(i,j)>0 \text{ and } \alpha\,\mathrm{Soc}^{t}_{\max}(i,j)<\mathrm{Soc}^{t}(i,j)\leq\mathrm{Soc}^{t}_{\max}(i,j)\\ \langle 4\rangle & \text{if } Nl^{t}(i,j)<0 \text{ and } \mathrm{Soc}^{t}(i,j)\leq\alpha\,\mathrm{Soc}^{t}_{\max}(i,j)\\ \langle 5\rangle & \text{if } Nl^{t}(i,j)<0 \text{ and } \mathrm{Soc}^{t}(i,j)\leq\beta\,\mathrm{Soc}^{t}_{\max}(i,j)\end{cases} \qquad (6)$$

where $Nl^{t}(i,j)$ is the net load of the *(i,j)* cell at the time t, defined as the difference between the PV generation power $P_{pv}^{t}(i,j)$, and the power consumption $P_{c}^{t}(i,j)$ (Eq.7). $Soc^{t}(i,j)$ is the state of charge of the (i,j) battery at time t, $Soc_{max}^{t}(i,j)$ and the maximum allowable state of charge. A description of these parameters is given in the next subsection. α and β are two specified coefficients, which guarantee battery storage balancing and safety.

C. Transition Rules

From the state of a cell at time t, we evaluate the energy sharing processes between peers which take place between times t and $t+1$, while respecting the neighborhood of each cell. This makes it possible to calculate the dynamic parameters of a C_{ij} at time $t+1$ Eq. 10. Thus, the state of the cell at time $t+1$ is determined by means of the configuration Eq.6.

The transition function F is identified with the mutual action between three mechanisms which take place between two instants t and t + 1:

$$Nl^t(i,j) = P_{pv}^t(i,j) - P_c^t(i,j) \tag{7}$$

$$F \equiv \text{ production} \oplus \text{consumption} \oplus \text{storage} \tag{8}$$

where $\oplus$ refers to mutual action. We consider two influences; the state of charge Soc and the net load power

$$\begin{aligned} F: Sm \rightarrow S \mid \\ St(N(C_{ij})) \rightarrow S_{t+1}(C_{ij}) = F \;\; St(N(C_{ij})) \end{aligned} \tag{9}$$

$$F \;\; \mathrm{St}(N(C_tj j)) = \{\mathrm{Soc}_{t+1}(i,j), \quad Nl_{t+1}(i,j)\} \tag{10}$$

1) Battery State of Charge (BSC): The battery is a necessary component of the PV system, it is connected in parallel with the load and PV panels and the universal interface to allow them to receive or transmit energy with neighboring households. The BSC value is the ratio of the charge at a given time to the maximum capacity of the battery. The expression of Soc respectively, at time *t* and *t+1* are the following:

$$\mathrm{Soc}^t(i,j) = \frac{Q^t(i,j)}{C_n(i,j)} \times 100\% \tag{11}$$

$$\mathrm{Soc}^t(i,j) = \mathrm{Soc}^t(i,j)\left(1 - \sigma^t(i,j)\right) + \Big(P_c^{[t]}(i,j)\eta_c^t(i,j) + P_d^{[t]}(i,j)\eta_d^t(i,j)\Big) \tag{12}$$

where Q^t is the stored energy by the battery at the time of interest t and Cn is the battery nominal capacity. $P_c^{[t]}$ and $P_d^{[t]}$ are the charging and discharging power at time η_c^t and η_d^t are the charging and discharging inefficiencies.

2) Charge and discharge power: The charging and discharging power at time *i*, are given respectively by Eq.13 and Eq.14.

$$P_c^{[t]}(i,j) = P_{cpv}^{[t]}(i,j) + P_{im}^{[t]}(i,j) \tag{13}$$

$$P_d^{[t]}(i,j) = P_{dl}^{[t]}(i,j) + P_{tr}^{(\mathrm{t})}(i,j) \tag{14}$$

Where $P_{cpv}^{[t]}$ is the charging battery power by solar panels. It is equal to the surplus PV power generation. $P_{im}^{[t]}$ is the power imported from the neighborhood, $P_{dl}^{[t]}$ the discharging battery power by load and $P_{tr}^{[t]}$ the power exported to the neighborhood lacking electrical energy. The amount of energy shared between the cells (transmitted or received) is defined according to Jains fairness index Eq.18 expressed by:

$$\text{fairness} = \frac{\left(\sum_{i=1}^n x_i\right)^2}{n\sum_{i=1}^n x^2} \tag{15}$$

Where x_i is the allocated shares to agent i.

TABLE 1
DYNAMIC PARAMETERS OF A CIJ

At Time *T*	Between *t* and *t+1*
$P_{pv}^t(i,j)$: PV generation power	$P_{la}^{[T]}$ *(i,j)*: Surplus power
$P_c^t(i,j)$: Power consumption by electrical load	$P_s r^{[T]}(i,j)$: Deficit power
$Q^t(i,j)$: Batteries energy storage	$P_c^{[T]}(i,j)$: Charging battery power
	$P_d^{[T]}$ *(i,j)*: Discharging battery power
	$P_{im}^{[T]}$ *(i,j)*: Power imported from neighborhood
	$P_t r^{[T]}$ *(i,j)*: Power exported to the neighborhood

Lets respectively call T_d^t and T_s^t the total energy demanded by the microgrid and total available surplus energy at time t. If $T_d^t < T_s^t$, the cells with the lack of energy are totally compensated by the surplus energy of the nearest cells. In this case the system works in a safe energy balance. On the other hand, if $T_s^t < T_d^t$, the sharing of the available surplus energy in the microgrid is minimized in accordance with Jains fairness. According to Eq.15, the quantity of energy transmitted $P_{tr}^{([t])}$ and imported $P_{im}^{[t]}$ are the following:

$$P_{im}^{[t]}(i,j) = \begin{cases} 0 & \text{if} \quad S(C_{ij},t) = 1 \\ 0 & \text{if } S(C_{ij},t) = 2 \\ 0 & \text{if } S(C_{ij},t) = 3 \\ \frac{P_{lm}^{[t]} \min(T_d^t, T_s^t)}{T_s^t} & \text{if } S(C_{ij},t) = 4 \text{ and} \\ & \exists S(\mathbb{N}(C_{ij},t)) = 5 \end{cases} \tag{16}$$

$$P_{im}^{[t]}(i,j)=\begin{cases} 0 & \text{if} \quad S(C_{ij},t)=1 \\ 0 & \text{if } S(C_{ij},t)=2 \\ \frac{P_{sr}^{[t]}\min(T_d^t,T_s^t)}{T_s^t} & \text{if } S(C_{ij},t)=3 \text{ and} \\ & \exists S(\mathbb{N}(C_{ij},t))=4 \\ 0 & \text{if } S(C_{ij},t)=5 \end{cases} \tag{17}$$

in which $P_{la}^{[t]}$ and $P_{sr}^{[t]}$ are respectively the demand and surplus energy of a cell during the lengthy period time.

3) Maximum charge and discharge power: In practice, for a correct modeling of the battery Soc, we would have to comply with the following conditions:

$$\mathrm{soc}_{\min}(i,j)\leq \mathrm{soc}^t(i,j)\leq \mathrm{Soc}_{\max}(i,j) \tag{18}$$

$$0\leq P_c^t\leq P_{c\_max}^t, 0\leq P_d^t\leq P_{d\_\max}^t \tag{19}$$

where Soc_{min} and Soc_{max} are the minimum and maximum allowable Soc, $P_{(cmax)}^t$ and $P_{(dmax)}^t$, are the maximum charging and discharging power. They are calculated using the following equations Eq.18:

$$P_{C\_max}^t=\frac{kq_1e^{-kt}+q_0kc\left(1-e^{-kt}\right)}{1-e^{-kt}+c\left(kt-1+e^{-kt}\right)} \tag{20}$$

$$P_{c\_max}^t=\frac{-q_{max}kc+kq_2e^{-kt}+q_0kc\left(1-e^{-kt}\right)}{1-e^{-kt}+c\left(kt-1+e^{-kt}\right)} \tag{21}$$

Substituting Eq.18 and Eq.19 into Eq.13 and Eq.14 gives:

$$P_c^{[t]}(i,j)=\begin{cases} P_c^{[t]}(i,j) & \text{if } P_c^{[t]}(i,j)<P_{c\_\max}^{[t]}(i,j) \\ P_{c\_max}^{[t]}(i,j) & \text{if } P_c^{[t]}(i,j)>P_{c\_\max}^{[t]}(i,j) \\ 0 & \text{if } \mathrm{Soc}^t(i,j)=\mathrm{Soc}_{\max}(i,j) \end{cases} \tag{22}$$

$$P_c^{[t]}(i,j)=\begin{cases} P_d^{[t]}(i,j) & \text{if } P_d^{[t]}(i,j)<P_{c\_\max}^{[t]}(i,j) \\ P_{d\_max}^{[t]}(i,j) & \text{if } P_d^{[t]}(i,j)>P_{d\_\max}^{[t]}(i,j) \\ 0 & \text{if } \mathrm{Soc}^t(i,j)=\mathrm{Soc}_{\max}(i,j) \end{cases} \tag{23}$$

4) Net load power: PV generation power; The PV installations are composed of PV modules connected to inverter. The PV generation profiles vary between users due to the differences in installed power. In our work we consider a power PV installation size P_{sz} to be between 5 Kwp and 12 kwp. The prediction of power generation P_{pv}^t of a cell *(i,j)* is a function of climatic factors such as ambient temperature and solar radiation. It can be obtained by using Eq.24 proposed by Menicucci and Fernandez [19].

$$P_{pv}^t(i,j)=P_{sz}(i,j)\frac{I^t(i,j)}{t_{ref}(i,j)}\left[1+\lambda(i,j)\left(T_c(i,j)-T_{ref}(i,j)\right)\right] \tag{24}$$

P_{sz} is the nominal capacity of the solar power system under standard test conditions [KW], I^t solar radiation incident on the photovoltaic panels [1kW/m^2], I_{ref} and T_{ref} are respectively the irradiation and temperature at standard conditions. λ is the temperature factor for power [% °C]. Table 2 lists λ for different types of PV modules.

- Households electricity consumption: To simulate the operation behavior of the PV systems, time series of electrical load profiles are required $P_c(i,j)$, as part of the input data of our CA model.

D. *Initial and Boundary Conditions*

The initial conditions of our CA model provide the initial charge state of the batteries and power consumption. The batteries begin the simulation fully charged.

$$\mathrm{soc}_{t\_0}(t,j)=100\% \tag{25}$$

The matrix of power consumption at the beginning of the simulation depends on the start time of the numerical simulation. Once we launch the simulation, we upload the load data of the considered hours from our text file.

$$P_c^{(t_0)}(i,j)=f(h,tf) \tag{26}$$

We consider a fixed boundary, where the concerned houses cannot share electricity with houses of the external domain. The quantity of energy transmitted and imported are nul, i.e.,:

$$P_{tr}^{[t]}(i,j)=0, P_{re}^{[t]}(i,j)=0, Cij\in\partial L \tag{27}$$

III. SIMULATION

To study energy sharing in a grid, we have developed an application by using the Python programming language. We used the python tkinter library to run the script in real time in GUI mode. The simulation was performed on a workstation; Intel Core i5-6500 processor at 3.20 GHz, 4 GB RAM, HD Graphics 530. The Fig. 3 presents an overview of the principle of our application. The numerical model was validated using a real data collected during the two weeks of the Solar Decathlon Middle East competition (SDME).

TABLE 2
AVERAGE VALUES OF THE TEMPERATURE COEFFICIENT OF POWER

PV Modlr Type	Avg. Value of λ(%/°C)
Polycrystalline silicon	-0.48
Monocrystalline silicon Thin film	-0.46
Amorphous silicon	-0.20
Thin film CIS	-0.60

A. *Application Case*

1) Solar decathlon event: The Solar Decathlon is an international environmental building competition, organized by the U.S. Department of Energy, which challenges university teams to design, build, and construct solar-powered homes [20]. The first Solar Decathlon competition was held in Washington in 2002 and has since been held in different areas including the U.S, Europe (2010, 2012, 2014, 2019), Africa (2019), China (2013, 2018), Middle East (2018, 2020) and Latin America (2015, 2019). Solar Decathlon Middle East is the Middle Eastern version, launched for its first edition in The United Arab Emirates (UAE) through an agreement signed between the Dubai Supreme Council of Energy, Dubai Electricity and Water Authority, and the U.S. Department of Energy. The SDME 2018 was held in Dubai at the Al Maktoum Solar Park from November 14 to 29, 2018. SDME 2018 participating teams presented 15 solar-powered houses in the competition site as shown in Fig. 5.

2) Study area: The studied area is the competition site of the SDME 2018, where the houses are assembled (see Fig. 5). The site is located south of the the city of Dubai at the Solar Park UAE (24.7547 °N 55.365 °E). It is a micro-grid system composed of 15 solar houses connected to a local electrical network system that ensures bi-directional transmission of AC power. All houses operate on grid-tied system with AC service of 50 Hz, 230V single phase with neutral. According to SDME rules;

- The photovoltaic installation size (kWp) is not limited
- The maximum battery storage capacity is 15 kWh
- The allowed AC power of the grid tie inverters is limited to 8 kW.

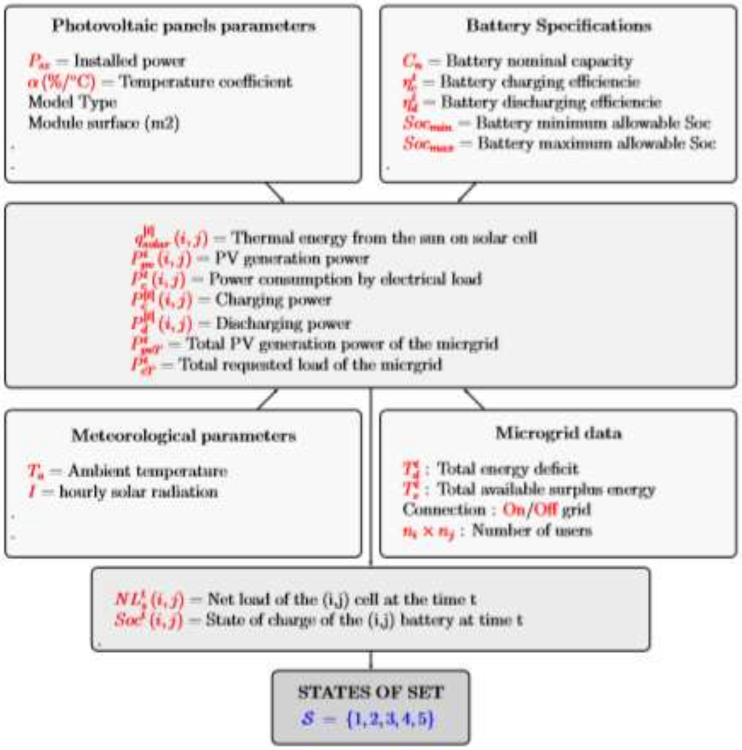


Fig. 3. P2P energy sharing architecture. a) Connected grid mode b) Islanding mode

TABLE 3
DYNAMIC PARAMETERS OF A CIJ

Teams	Power output kwp	Photovoltaic modules
1. AUD 10.62	10.62	Mono, 74 m2
2. BX	08.96	Mono, 46 m2
3. NCT	09.92	Poly, 71.84 m2
4. HW	07.82	Poly, 108 m2
5. UOW	09.60	Mono, 62 m2
6. UOS	18.00	Mono, 98 m2
7. AUR	05.00	Polu, 31 m2
8. NYU	07.48	Mono, 60 m2
9. TUE	10.56	Mono, 64m2
10. VT	09.42	Mono, 53 m2
11. SUR	08.96	Poly, 64 m2
12. USI	10.40	Mono, 74 m2
13. BU	15.00	Mono, 42 m2
14. AST	07.10	Mono, 32 m2

Table 3 presents the photovoltaic system description of the 15 teams houses. An energy monitoring system is available to constantly collect and measure the information and data provided by the electrical energy systems of each house.

3) Data management: The objective of using SDME 2018 energy data is to ensure that our numerical CA model converges to an energy equilibrium state. The energy management of SDME houses is similar to the states of our CA model. During daylight, the solar power is used to cover the required load and the surplus energy is injected into the grid if the batteries are full.

When The PV and batteries cannot satisfy the load; the power deficit is covered by the grid. One might consider that when an SDME house injects or recovers electricity into the grid, it is in the corresponding states number 3 and 4 of the CA model, respectively. At each step of the simulation, two main parameters of the SDME data are used as input values of the numerical model; the output PV power and household consumption power. The dynamics of the CA states during the simulation are compared to the actual energy curves of the SDME houses. The comparison allows us to verify if the power flow and the power transfer in the micro-grid meet the demand and converge to the same energetic state as that of the experimental scenario. To highlight our approach, we considerthe SDME rules as conditions for numerical model simulation:

- The solar power is the only source of electrical energy used in the home
- The size of the photovoltaic installation and the capacity of the batteries are different for each user due to the differences charge of each house. We consider the data of Tab.3
- The PV generation power and power consumption processed in the simulation are data obtained during the two weeks of the Solar Decathlon Middle East competition (SDME)

B. *Simulation Results*

In this section, we compare the simulation results of the CA model studied (Fig. 7) with the actual data sets of the SDME houses (Fig. 6) to examine model performance. We consider 15 prosumers in connected network mode, with fully charged batteries for the initial configuration. The second day of the SDME contest period 18-9-2018 was chosen to apply the model. The data set presented in Fig. 6 includes; solar energy production, demand profiles, grid consumption, grid excess power injection. We consider a time step of 30 minutes and the following color connotation:

🟦 State 1 🟦 State 2 🟩 State 3 🟥 State 4 ⬛ State 5

Fig. 4. Color connotation

At Iteration 0 (12:00 am) it appears in Fig. 6 that the power produced by the PV panels and the power sent to the grid are both null. The load is powered by batteries, except for houses that are not equipped with them (2, 5 and 10), in which case the charge is drawn from the grid as illustrated in Fig. 6 This situation is confirmed by the simulation as is shown in Fig. 7, in which all cells are in state 2,except for the three houses with no storage banks (state 5).

Fig. 5. SDME solar village

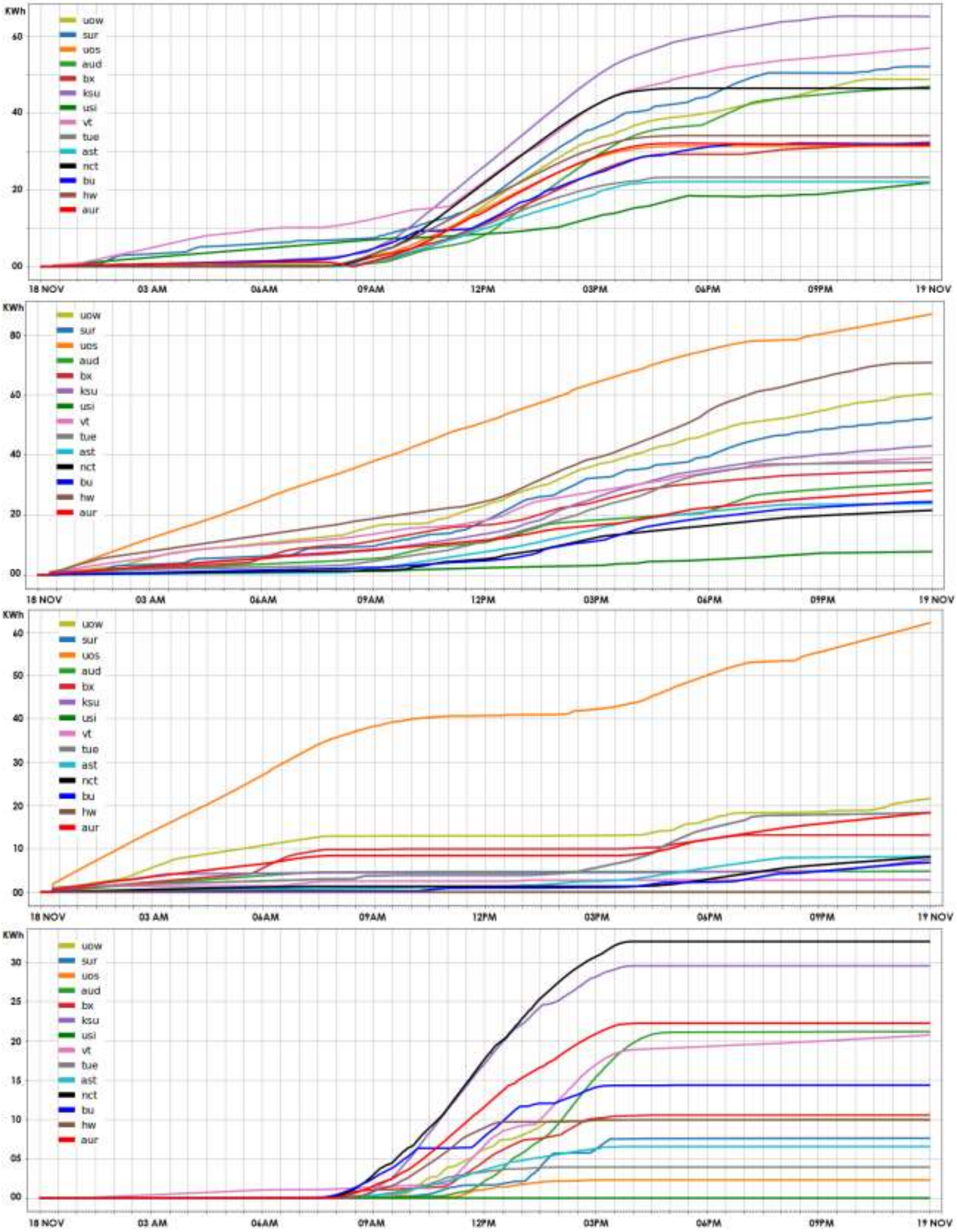
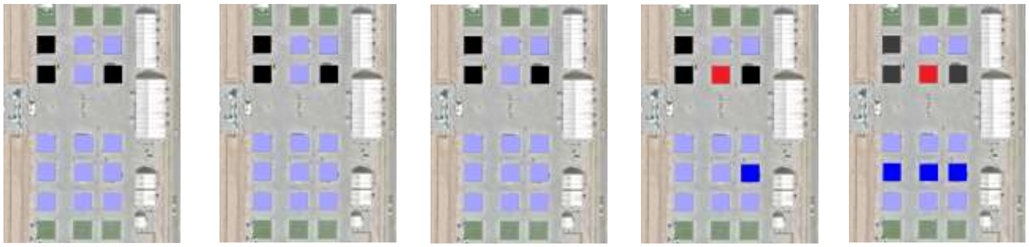
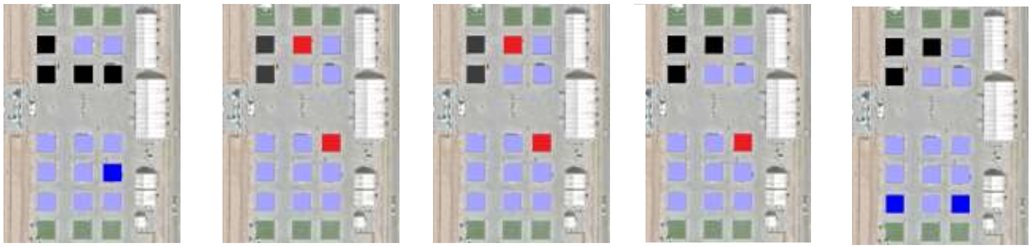
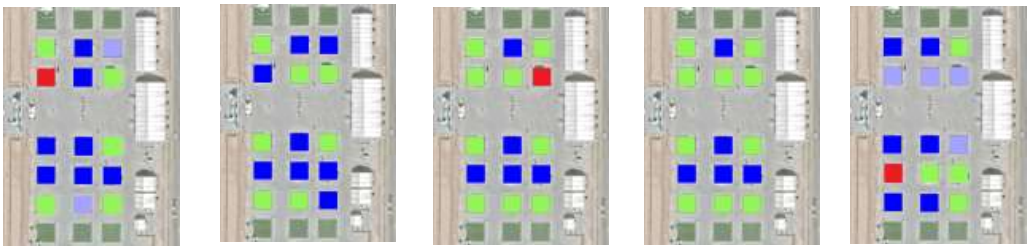
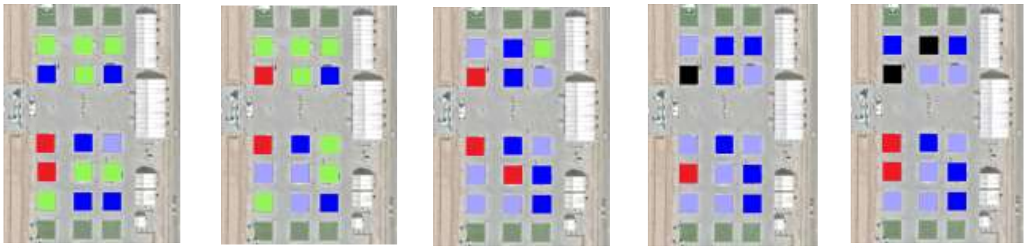


Fig. 6. Collected electrical data of a typical day during the contest period (18-09-2018). a) Electricity generated by the PV panels (EG) b) Electricity consumed by house loads (EC) c) Houses electrical energy sent to the grid (ES) d) Houses electrical energy drawn from the grid (ED)


(a) Iteration 0 (b) iteration 2 (c) iteration 4 (d) iteration 6 (e) iteration 8


(f) iteration 10 (g) iteration 12 (h) iteration 14 (i) iteration16 (j) Iteration 18


(k) iteration 20 (l) iteration 22 (m) iteration 24 (n) iteration 26 (o) iteration 28


(p) iteration 30 (q) iteration 32 (r) iteration 34 (s) iteration 36 (t) iteration 38

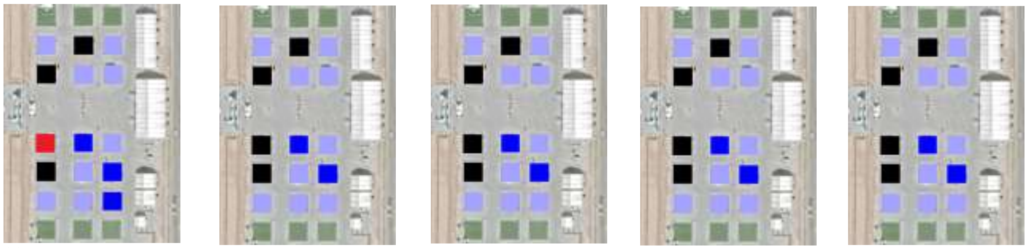

(u) iteration 40 (v) iteration 42 (w) iteration 44 (x) iteration 46 (y) iteration 48

Fig. 7. Evolution of stat of cells in a typical day during the contest period (18-09-2018)

The cells maintain the same states for the next five iterations until iteration 6 (3:00 am), when two houses change their state. House number 5 reports a lack of energy (state 4) and house number 10 changes to state 1, meaning that team HWs batteries are down to less than 40% and that team VTs house has started producing its own energy. The experimental data confirms this state change; team VT generated a cumulative power equal to 5 kWh in that period (Fig. 6). Due to the early sunrise in Dubai (06:05 am), houses with east-facing solar panels such as VT, VQ and USI started producing electricity at 06:00 am. These three houses are shown in blue in the simulation (Fig. 7). The other teams covered their power deficit either through the grid (BXN, CT, HW and UOW) or using batteries (all the remaining teams). For the next four hours (from 4:00 am to 8:00 am), the loading profile is generally stable. The supply and demand for battery-equipped teams is well balanced.

The total power consumed during the night is 85 kWh and the total capacity of the battery banks is 102 kWh. The loads of the houses is therefore satisfied. Additionally, for the three houses without batteries (BX, UOW, VT), electricity is drawn from the grid. P2P sharing of electricity up to iteration 18 does not yet work, no energy exchange takes place between neighbors due to general lack of excess energy in the microgrid. At iteration 22 (11:00 am), the solar radiation on site is greater than 700 w/m2, the cumulative power produced (EG) varies between 4.5 kWh (AUD team) and 15 kWh (VT team). The power produced by PV systems is greater than the consumption, so all houses have a surplus of energy. 8 teams have used this surplus to recharge their batteries and the rest have fed it into the grid. 60 minutes later, due to significant variations in the load, house number 4 declares its energy needs as shown in fig Fig. 7. Here we see the CA in action as neighbors with excess energy automatically meet these needs and begin to share the energy demanded. These simulation results are validated by the actual data presented in Fig. 6, in which there is a significant increase in the amount of electricity produced by photovoltaic panels and the electrical energy sent to the grid. The principle of CA also appears clearly in the next iterations, in which energy exchange between teams is possible due to the excess energy available in the microgrid.

In iteration 30, the TUE and USI teams are displayed in red, their batteries are down to less than 40% of capacity and, thanks to the automation of energy sharing, they have connected to the microgrid to benefit from the available excess energy. 30 minutes later, at iteration 31, the USI changes to state 2 after charging its batteries, but the TUE is still receiving power. The rest of the houses are in a balanced energy state. The energy exchange is stopped at 7pm, because there is no more solar radiation. Thus, for the rest of the iteration, teams that cannot meet the requested charge and teams without batteries draw the required power from the grid.

IV. CONCLUSION AND RECOMMENDATIONS

In this research, a new CA model has been proposed for decentralized energy management in P2P micro grids. The model is made in python programming language and validated by real data collected during the two weeks of the Solar Decathlon Middle East competition. This method confirmed the potential of cellular automata to provide solutions to problems concerning the energy efficiency of micro-grids. The comparison between simulation results and experimental data has shown a convergence of supply and demand decisions towards a state of energy equilibrium. This work can be improved and developed to be adapted to a wide variety of other electrical systems that include multiple energy sources and loads.

Declaration of Conflicting Interests

No known conflict of interest is present in this work.

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