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Modelling and Assessment of the HRES Discarded Energy in the Micro-grid

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Abstract: The large adoption of hybrid renewable energy systems and the increasing power requirements of residential loads brings significant challenges to the construction and operation of the micro-grid systems. In this study, the agent-based modelling methodology is proposed to proper model and assess the discarded energy in the micro-grid. With the integration of the agent-based modelling and the system dynamic approach, the proposed approach contributes to a micro-grid model that is hierarchically constituted by micro-grid management layer and component layer. The system dynamics modelling is adopted in the management layer to model the energy consumption in the micro-grid while the object-oriented agent-based modelling is adopted to generate the main components. Furthermore, this study also proposed a comprehensive micro-grid operation simulation system, through which the observation and assessment of the proposed model can be achieved. Monte Carlo simulations show that the model and system can comprehensively reflect the energy consumption and generation in the micro-grid, providing preferred quantitate assessment for the micro-grid operation economical-efficiency and security with various HRES penetrations and time scales. The proposed methodology of this study will be beneficial for the study of the micro-grid discarded energy assessment and can be further utilized to the energy management policy evaluation, electricity consumption prediction and HRES deployment optimization.

Key words: Micro-grid, HRES, discarded energy, agent-based modelling

INTRODUCTION

The worldwide constructions of the smart grid technology brings significant development to micro-grids and Hybrid Renewable Energy Systems (HRESs) technology (Rao *et al*., 2012; Venayagamoorthy, 2011). The micro-grid is an integrated energy system that consists energy resources, loads and storages. Due to the needs of distributed generation, such micro-grids have been popular over the years of development. And with the integration of HRESs including photovoltaic (PV) and wind generators as well as the battery storage devices, the micro-grids can deliver many advantages including reduced cost, renewable power generation, etc. which brings significant benefits to grid and the energy consumers (Navigant Consulting, 2006; EPRI/NRDC, 2007). However, the variations of renewable energy do not precisely match with the time distribution of electricity demand of the micro-grid load and the considerable over-sized deployment of the HRESs caused massive disgarded energy and in turn makes the design costly (Deshmukh and Deshmukh, 2008; Han *et al*., 2012a). Moreover, the increasing adoption of high energy consumption electric appliance in resident houses including EVs also brings potential challenges to the operations of the micro-grid (Han *et al*., 2012b, c; Erol-Kantarci and Mouftah, 2011) and the additional power generation might be idle for most of the time and the largely discarded energy further degrades the micro-grid efficiency and infrastructure utilization (Han *et al*., 2012d).

Condisering the mentioned problems above and the proper HRESs deployment are the keys for minimizing the discarded energy, reducing micro-grid operation cost and maximizing the utilization of the HRES power volatility. And the modelling and assessment methodology for the discarded energy in micro-grid is fundamental and critical to enable those abilities. In recent years various modelling techniques have been developed by researchers, Bazan and German (2012) proposed a hybrid simulation approach for the analysis of the domestic homes equipped with different micro generation and storage devices but the study lacks the analysis on micro-grid operations. Petermann *et al*. (2012) and Wang *et al*. (2012) proposed a multi-agent control model for micro-grid and a two-layer control system of micro-grid is built, however, the discarded energy is not considered.

Considering various characters, hierarchical components and complex interactions of the micro-grid,

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and based on the previous research work, this study develops an agent-based model on discarded energy in micro-grid which constitutes the hierarchical model to simulate different operation characters of components. And a flexible simulation system is also proposed to further assessment the impact of HRES deployment to the discarded energy.

STRUCTURE OF MICRO-GRID WITH HRES

The micro-grid consists of multiple components of HRESs and power load. The HRESs include power generation devices e.g. photovoltaic, wind energy and power storage devices such as the battery storage system. Meanwhile the multiple load of the micro-grid includes the load of industrial, commercial electric equipment and residents' home appliances, among which the residential energy consumption is the dominant section. All the components are connected together through a grid network and under the monintor of the micro-grid management center.

Without loss of generality, the schematic figure of the micro-grid system under study is shown in Fig. 1. Besides the mentioned HRES devices and load, the system consists of many power converters operating over a wide range of areas and interconnected with feeders and the grid bus. The micro-grid connects the distribution network through a single Point of Common Coupling (PCC) and operates as a single unit.

The micro-grid structure is hierarchically divided in two layers: Management layer and component layer. The management layer consists the control center and the sensors in the micro-grid. It is responsible for the communication with the electricity grid control center, monitoring and controlling the operation of the HRES on the micro-grid bus with multiple energy inflows and outflows. The component layer is formed by power generation and consumption components of the micro-grid including HRES devices and electricity consumers.

MODELLING METHODOLOGY OF HRES AND DISCARDED ENERGY

The modelling methodology in this study is based on the multi-agent theory. As a computational approach to

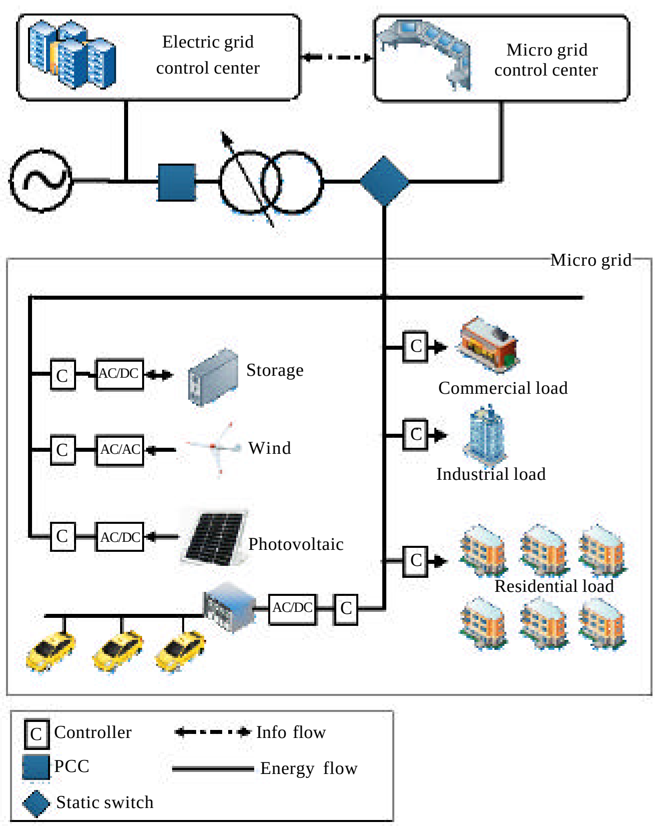

Fig. 1: Structure of micro-grid with the HRES

study Multi-Agent Systems (MASs), Agent-Based Modelling (ABM) has been a rapidly growing area for analyzing the electricity market in the past decade (Shafiei *et al*., 2012; Wang *et al*., 2012). As the objects with intelligence, the agents shall form the MAS's behavior with unique behavior and interactions. And this study adopts this character in modelling micro-grid components including HRES devices. The other advantage of ABM is that it could efficiently model the complex behavior of massive system participants which is particularly suitable for modelling massive energy consumption for residents with distinct characters and behaviors. As discreted residential energy consumption form up the majority electricity consumption in the micro-grid, they constitute a MAS which is well suited for ABS modelling. To further enhance the effectiveness of the proposed agents, the statechart is adopted in the modelling to specify their states and behaviors. The statechart is a state machine that consists simple states that containing corresponding actions and transitions that can be triggered by events. And the statecharts in this model shall graphically capture the operations and conditions of certain agents and enables a fast and convenient structuring of the micro-grid model.

The System Dynamics Modelling (SDM) are also adopted to calculate the discarded energy in the microgrid. SDM is a rigorous modelling method that enables the building of complex systems simulations and the design of more effective policies and organizations (Sterman, 2000). SDM is typically used in long-term, strategic models and has been widely used in energy industries for demand forecasting (Akhwanzada and Tahar, 2012) and energy flow modeling (Bazan and German, 2012). General system dynamics models consist of stocks and flows connected through auxiliaries depicting a system. And in this study, the SDM is adopted in the management layer to simulate the total energy consumption and generation in the micro-grid and the discarded energy can therefore be calculated.

MODELLING OF THE MICRO-GRID

Generation of HRES wind power system: Wind power is one of the most popular renewable energy sources in the micro-grid whose power output at a specific site are mainly depends on wind speed turbine characteristics. Typical hourly power output from a wind turbine can be calculated in Eq. 1:

$$P_{WD}(t)=\begin{cases}0, & V(t)\le V_{min}\\ AV(t)^3-BP_r, & V_{min}<V(t)\le V_r\\ P_r, & V_r<V(t)\le V_{max}\\ 0, & V(t)>V_{max}\end{cases} \qquad (1)$$

where, V_{min}, V_{max} and V_y are the cut-in, cut-out and rate speed of the wind turbine, V_t is the hourly average wind speed and the factors A and B can be calculated in:

$$A=\frac{P_r}{V_r^3-V_{max}^3} \qquad (2)$$

$$B=\frac{V_{min}}{V_r^3-V_{min}^3} \qquad (3)$$

Therefore, the actual total power output from a wind energy system can be calculated by:

$$P_{WE}(t)=P_{WD}(t)\,A_{WD}\eta_{WD} \qquad (4)$$

where, A_{WD} is the total turbine swept area of the wind energy system and the η_{WD} is the efficiency of the wind turbine generators and converters.

Generation of photovoltaic system: The hourly power output from the photovoltaic system with an area can be calculated by:

$$P_{PV}(t)=I_r(t)\eta_{PV}A_{PV},\ P_{PV(t)}\le P_{PVmax} \qquad (5)$$

where, I_r (t) is the total input solar radiation on unit area of the PV surface within an hour and η_{PV} is the photovoltaic system efficiency.

HRES generation statechart: The statechart of the proposed HRES generation devices can be illustrated in Fig. 2. It contains four states that describe the main conditions of a renewable generator:

- **Power generating:** The generator is generating power to the micro-grid
- **Power discarding:** The generated power is discarded
- **Shut down:** The generator is stopped for regularly maintenance
- **Failed:** The generator is temporarily out of work and needs repairs

Modelling of HRES storage components: Battery storage system is fundamental to alleviate the fluctuation of the renewable generation in the HRES. And it is therefore, sized to meet the load demand during non-availability period of the renewable energy source while absorbing the exceeded power generation in HRES. The State of Charge (SOC) of the battery storage system can be calculated by:

$$SOC_{BS}(t)=\frac{E_{BS}(t)}{E_{BSr}}\times 100\% \qquad (6)$$

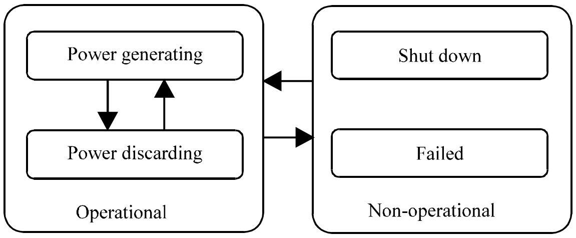

Fig. 2: State chart of the HRES generation

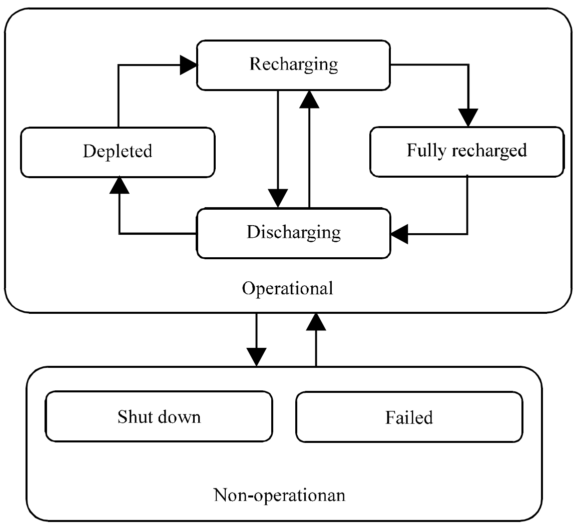

Fig. 3: State chart of the HRES storage system

where, E_{BSr} is the rate battery energy storage and the current stored energy E_{BS} (t) can be derived from Eq. 7:

$$E_{BS}(t) = EBS(t\text{-}\Delta t)(1\text{-}\sigma_{BS})+E_{C\text{ and }D}(\Delta t) \quad (7)$$

where,σ_{BS} is the hourly self-discharge rate and $E_{CandD}(\Delta t)$ is the charged or discharged energy in time period Δt and can be calculated by:

$$E_{CandD}(\Delta t)=\begin{cases}(E_{GE}(\Delta t)-E_{L}(\Delta t))\eta_{Bc}, & E_{GE}(\Delta t)>E_{L}(\Delta t) \text{ and } E_{BS}(\Delta t)\le E_{BSr}\times u_{BS\,max}\\ (E_{GE}(\Delta t)-E_{L}(\Delta t))/\eta_{Bd}, & E_{GE}(\Delta t)\le E_{L}(\Delta t) \text{ and } E_{BS}(\Delta t)\ge E_{BSr}\times u_{BS\,min}\\ 0, & \text{else}\end{cases} \quad (8)$$

where, E_{GE} (Δt) and E_L (Δt) are the total generation and load of the micro-grid system while η_{Bc} and η_{Bd} is the recharging and discharging efficiency of the battery. And $E_{c\&D}$ (Δt) is subject to the battery maximum recharging and discharging constraints:

$$E_{c\&D\,min}\le E_{CandD}(\Delta t)\le E_{CandD\,max} \quad (9)$$

The six states of the energy storage system are as follows while the corresponded statechart is illustrated in Fig. 3:

- **Recharging:** The battery storage system is being recharged by the micro-grid
- **Discharging:** The battery storage system is discharging energy to the micro-grid
- **Fully recharged:** The maximum SOC of the battery storage system has been reached
- **Depleted:** The minimum SOC of the battery storage system has been reached
- **Shut down:** The battery storage-system is stoped for regularly maintenance
- **Failed:** The battery storage system is temporarily out of work and needs repairs

Modelling of the micro-grid load: The original load of the micro-grid is mainly formed by residential, commercial and industrial load. And is mainly influenced by characters including population, electrical appliances types, energy consumption per capita, etc. In the proposed model, with the preset population and proportion of the micro-grid, static agents have been adopted to represent the residential houses, commercial and industrial buildings as well as other electricity appliances. As the massive introduction of HRES do not apparently impact the power consumption ratio and distribution of a certain area and the original load curves from residential, commercial and industrial load can be adopted to generate the load of the agents.

Modelling of the discarded energy: In the management layer, SDM is adopted in the study of the discarded energy in the micro-grid. In this model, the stock of the micro-grid energy comprises of inflows and outflows indicating energy generation and consumption and those flows are generated by the corresponding components in the component layer while under the control of the micro-grid management center. Figure 4 shows the diagram of the proposed SDM in management layer model.

Where, the E_{WD} and E_{PV} denote the energy generated by wind and photovoltaic generators in the HRES and E_{CandD} is the energy flow in or out from the battery storage system depending on its charging or discharging energy E_{BC} and E_{BD}, E_{RES}, E_{IND} and E_{COM} denote the residential, industrial and commercial consumption and E_{DSCD} is the discarded energy of the HRES. To

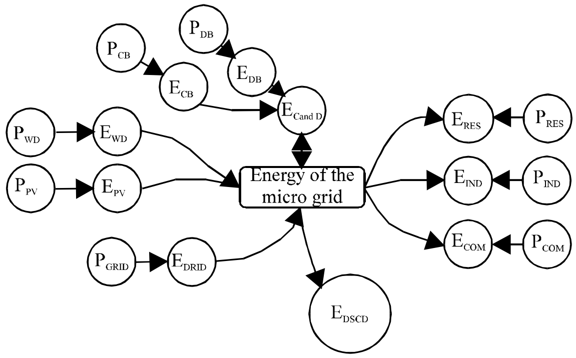

Fig. 4: Diagram of the system dynamic model

guarantee the energy balance of the micro-grid, the energy demand from the main grid can be calculated from Eq. 10:

$$E_{DSCD} = E_{WD}+E_{PV}-E_{RES}-E_{IND}-E_{COM}-E_{BC}$$
$$E_{RES}+E_{IND}+E_{COM} \le E_{WD}+E_{PV} \quad (10)$$

It should be noted that the interconnections and interactions is critical to the precise model of the discarded energy in the micro-grid. And the proper triggers between management layer and component layers are established in the proposed model to transmit the data and control message, therefore in component layer the component agent's behaviors can be controlled and their key parameters can then feedback to update the flow variables in the SDM of the management layers which enables the model to simulate the monitoring of the grid bus and the real-time control of the HRES, leading to a more accurate simulation to the discarded energy.

SIMULATION SYSTEM DESIGN FOR THE DISCARDED ENERGY

In order to support systematically in-depth exploration and assessment of the discarded energy by micro-grid operation, a comprehensive simulation system is built which enables micro-grid components to operate and interact in virtual environments, enabling a broader experimentation for the study of the HRESs in the micro-grid.

The main interface of the simulation system is implemented with the AnyLogic software, whose object-oriented model design paradigm provides for modular, hierarchical and incremental construction of large models("AnyLogic-Multimethod Simulation Software and Solutions" n.d.). In the simulation system, management layer is modelled with SDM approach in Anylogic while agents of the component layer are implemented as JAVA objects and the proposed agent behaviors, parameters and statecharts are also well constructed with AnyLogic provided functions, parameter widget and the statechart pallet. To ensure the flexibility of the model, each component agent is encapsulated to be an independent active class object and message ports as well as communication rules are also embedded on those objects to enable their interactions and communications among different agents and between different layers.

To make the system visual and interactive, many charts and graphics are adopted in the model. Animations including elementary graphical shapes as well as various types of indicators and graphs are developed to enable real-time illustration of the operation data. The user interaction is also considered in the simulation system. Interactive elements such as sliders, buttons and text inputs are used to control the model's execution at run time while the control panel and user interfaces of them are well-designed. Moreover, the simulation system also prepares the open architecture and sockets for the database connection. Thus enables the real-time data exchange to the other softwares, databases and micro-grid utilities.

With the reusable active objects, visual interactive elements and function to import database and GIS data, the constructed simulation system is visual, flexible and extensible and besides the dicarded energy model, the component-based design of the system allows it for the efficient creation of new case studies including centralized/decentralized control design, micro-grid islanding mode, dynamic power flow computing, etc.

COMPUTER SIMULATION AND ANALYSIS

The Monte Carlo simulation is carried out to verify the effectiveness of the proposed model and simulation system. The electricity grid load consults from the real load of Electric Reliability Council of Texas (ERCOT) (FERC, 2005). As an isolated electricity system, ERCOT manages the flow of electric power to 23 million customers in Texas (Rachakonda, 2010) while the latest residential electricity consumption is 37.6%. The study then reasonably assumes a micro-grid covering a community with one thirty-thousandth Texas population, i.e., 2300 residents in Austin, TX and with several industrial and commercial loads. The main information of HRES components used in the simulation is given in Table 1. The environment characters of Austin is acquired from the System Advisor Model (SAM) provided by the National Renewable Energy Laboratory (NREL).

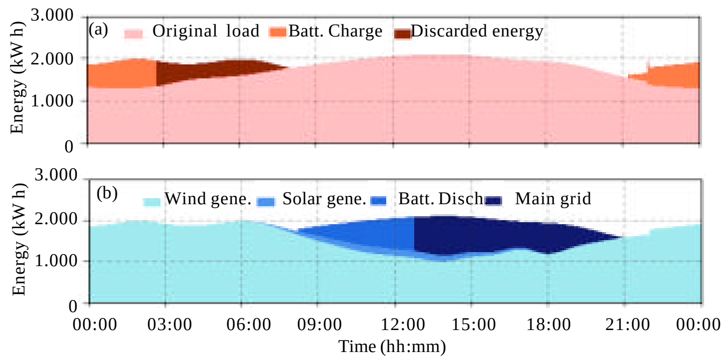

Fig. 5(a-b): Real-time energy generation and consumption in Type I Micro-grid

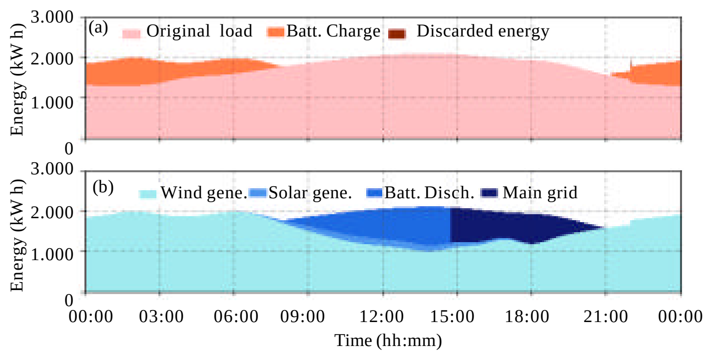

Fig. 6(a-b): Type I HRES with additional battery storage

Table 1: HRES Parameters in the micro-grid

Component	Type	Rate power (kW)
Wind turbine	Endurance E3120	50
Solar panel	Sharp ND-62RU1	1.1
Battery storage	Hoppeche 600	0.2

Table 2: Configurations of HRES in the Micro-grid

Types	Wind turbine	Solar panel	Battery storage
I	50	200	2000
II	10	1000	2000

To minimize the operation cost, the micro-grid model tries to operate in the island mode and wind turbines as well as photovoltaic panels are firstly enabled to feed the energy consumption and extra generation can be absorbed by unfulfilled battery storage system. And the main grid shall supply insufficient energy when the total required energy goes beyond all the HRES generation in the micro-grid.

To model different HRES systems based on different micro-grid areas, two types of HRES configurations are adopted to the proposed system, as are shown in Table 2. Type I stands for the area with prefered wind resource and Type II is suited to the area with more solar radiations.

The real-time micro-grid energy generation and consumption is shown in Fig. 5a, b. It is obvious that the wind generation mismatches the original load which forms the largest micro-grid energy consumption. Due to the shortage of energy storage, the energy at night is largely discarded while the energy requirements at peak hours can not be satisfied by the HRES. To further verify this conclusion, the simulation of Type I HRES with additional 3000 batteries in HRES is shown in Fig. 6a, b. And it denotes that the discarded energy after midnight is totally absorbed while the peak requirements at noon is largely satisfied. And the little energy provided by the main grid might be reduced with additional wind generation depending on the cost of wind system construction and main grid electricity price.

The simulation result of micro-grid with Type II HRES is shown in Fig. 7a, b. The massive solar energy at noon conducts a severe fluctuation to the energy generation and caused the discarded energy at noon while the night energy suppliment is insufficient from the HRES. And the simulation with additional 3000 batteries is shown in Fig. 8a, b which donates that the discarded energy can be well absorbed by the plenty of batteries. And the energy requirement at early night can therefore be satisfied with the stored solar energy. However, the remained energy shortage should be offered by the main grid, or through the construction of larger solar systems based on the

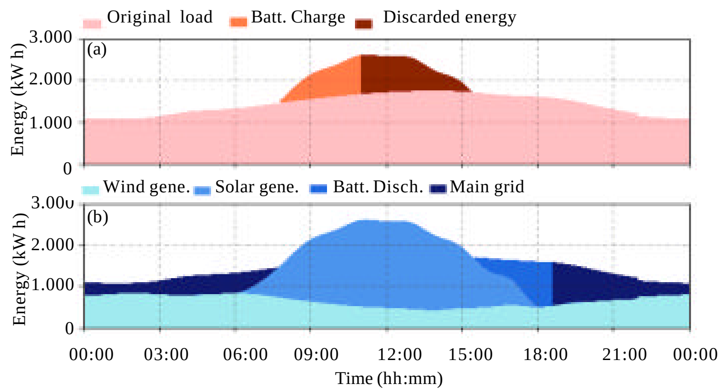

Fig. 7(a-b): Real-time Energy Generation and Consumption in Type II Micro-grid

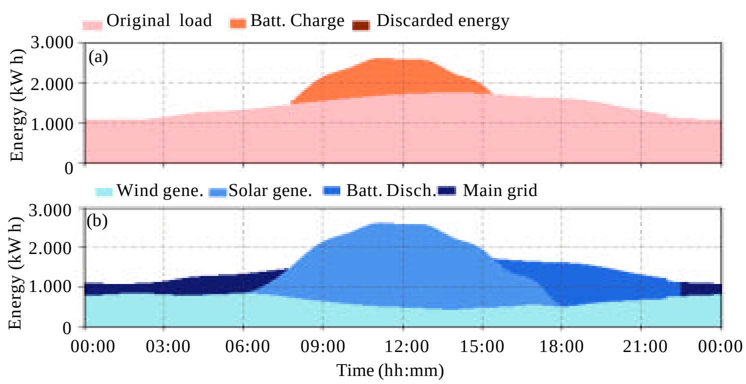

Fig. 8(a-b): Type II HRES with additional battery storage

further study of profit and cost. An a further configuration optimization is needed with the proposed modelling and simulation system.

CONCLUSION

To model and assess the discarded energy of HRES in the micro-grid systems, this study proposes an agent-based integrated modelling methodology while developing a comprehensive simulation system. A hierarchical micro-grid structure is proposed and with the integration of ABM and SDM, the modelling methodology for each layers and componenets are proposed and the discarded energy is derived. Furthermore, a visual, flexible and extensible micro-grid simulation system is designed to verify its effectiveness. The simulation examples indicate that the proposed model can well reflect the discarded energy in the HRES in the micro-grid and the configuration defects can be revealed, then help to optimize the proper construction of the HRES. Besides, with the establishment of the proposed model and combining with the actual grid data of the grid, the impact of various parameters imported by the energy policy, weather and climate, population and personal behaviors can be tested in risk-free space at a very low cost which will help to strategize the HRES and load management and shall eventually help with a better planning of future micro-grids.

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