Combined (Virtual) Power Plant For A Smart Grid

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Abstract- This paper presents a simulation tool that optimizes the generation output from different renewable energy resources of a virtual power plant (VPP). A real case Study of a VPP planned to be installed in Kayathar in India is adopted in this research. The VPP is combined of a 4.4 MW wind farm, a planned solar photo voltaic plant, a biogas plant, a biomass plant, and storage. The VPP is connected to the grid, and the optimum scenarios obtained were those that imported zero energy from the grid and utilized the storage system effectively.

I. INTRODUCTION

The fast increasing penetration of distributed energy resources (DER) requires new technologies as well as new energy strategies and policies to handle the technical and the economic issues emerging due to this upward penetration. The idea of virtual power plant (VPP) arose to handle the distributed generation integration. A Virtual Power Plant, also called Combined Power Plant, is a power plant composed of small decentralized power plants, controllable loads and storage devices. Conventional as well as renewable resources are used in the VPP but mostly plants of renewable resources such as photovoltaic power plants, wind turbines or small hydro are aggregated in order to operate a unique VPP [1]. These plants are all controlled by one cloud-based remote control center which is managed by a VPP software. This VPP software effectively connects, monitors, and coordinates distributed generating sites together with the storage facilities and the controllable loads. The cloud-based control center uses information and communication technologies (ICTs) and internet of things (IOT) to control and visualize the distributed generation (DG) units as one large centralized power plant. The main goal of VPP is to make wind and solar manageable by combining various renewable energy sources to balance out fluctuations of the grid. Moreover, it aims to minimize the generation costs and the production of greenhouse gases and maximize the profits. By deployment of the VPP concept within the smart grids (SG) frame, small power plants owners get the opportunity to access the electricity market in a "collective" form via coordinated operation of power plants [2] . Figure 1 depicts the typical components of a VPP[3].

The VPP has been presented in the literature by several researchers. Reference [1] presented a literature review for different VPP definitions, components, optimization techniques for VPP structure and operation. Reference [4] also reviewed the VPP in terms of components and operation systems. References [5] and [6] proposed an operation scheduling for a VPP that is composed of intermittent renewable sources, a conventional power plant, and a storage system. A pumped hydro storage and a backup conventional power plant were used to provide flexible operation so as to settle the uncertainty of the wind and solar power generation. Reference [7] investigated the ability of a VPP consisting of a photovoltaic (PV) generation and several cogeneration devices to reduce the imbalance error of renewable generators. It was shown that the imbalance error can be reduced to up to 90% depending on the season and the rescheduling strategy. Reference [8] introduced an operational framework that maximizes the VPP profit on day-ahead and real time bases. The VPP traded energy externally with a wholesale market and traded energy and demand response internally with the consumers in its territory. Reference [9] studied the power flow control of a VPP low voltage network by controlling the voltage phase angle using an experimental device. Reference [10] considered the application of VPP in the electricity market in Greece so as to facilitate opening the retail market and simulated the day-ahead market for a duration of a year.

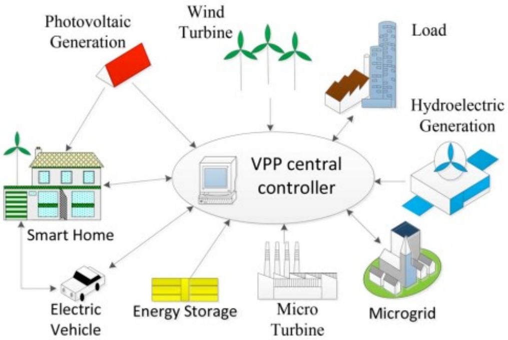


Fig. 1. A VPP Conceptual Model [3].

Reference [11] developed an economic simulation model for a VPP on the balancing market in Switzerland. Reference [12] discussed the optimal sizing of a VPP that combines wind and solar resources considering cost optimal solutions in Kenya. Reference [13] studied the integration of PV and wind generators of a VPP to the commercial grid of Pakistan, the study addressed both the technical and economic perspectives. Reference [14] investigated the static stability of an isolated VPP node with distributed energy resources at various operation modes under external disturbances. Reference [15] used Monte Carlo simulation to study the impacts of using energy storage devices into a distribution network with distributed generation and local loads aggregated as a VPP. In our work in [16] a VPP in Tamil Nadu state in India that combines a solar farm, a wind farm, a biomass plant, and batteries for storage was proposed. Two cases were adopted; the first one investigated the behavior of the system when the load can be fully supplied by the VPP generation at high wind speed. The other case assumed a larger load than the output power of the VPP during low wind speed durations. In this paper the proposed VPP is to combine a solar farm, a wind farm, a biogas plant, and a biomass plant, and other types of storage rather than the batteries that were considered in [16]. This paper focuses on the optimization algorithm that seeks the optimum capacity mix from each resource of the VPP with the storage and assuring no energy import from the grid.

Table 1. Locations of the power plants

	Latitude	**Longitude**
Solar plant	8º57’13’’	77º43’16’’
Wind plant	8º57’13’’	77º43’16’’
Pump Storage	10º24’36’’	77º2’36’’

II. Location of the Planned VPP

The VPP is planned to have different locations for each type of generation in Kayathar; which is a town in the Indian state of Tamil Nadu.

Figure 2 shows the macro location of the project and Figures 3 & 4 show the WTRS site. The approximate geographical coordinates of the sites are provided in Table 1.

A wind turbine research station (WTRS) of 4.4 MW installed capacity is located in Kayathar. It is a facility of the National Institute of Wind Energy (NIWE). The WTRS has three types of turbines installed which are:

1-MAICON-250(9x250kW),2-Suzlon(1x600kW),3-Kenersys k82(1x2MW)

Figure 5 shows the energy output of these different wind turbines in 2015. The total generation in this year was 270.22 GWh.

A solar photovoltaic (PV) power plant with 2 MW capacity is planned to be installed in Kayathar. Moreover, there are some bioenergy plants near Kayathar at different capacities which could be a part of the VPP after signing the Memorandum of Understanding (MoU). A biomass plant of 10 MW which is in operation is installed about 40km from Kayathar, it will be one of the resources of the VPP.

Fig. 2. Macro location of the project on the red zone

Fig. 3. Google Earth view of WTRS

In Fig.4a and Fig.4b it is elaborated how the site of the WTRS is completely flat, so it is not possible to develop a PHES project at this location. Mainly the PHES project depends upon the topography of the site. So based on the concept of the Combined Power Plant, it will be possible to use another plant in another location as that in Kadamparai. The main process in a pumped storage plant is that the water is pumped to a higher elevation reservoir. The stored water is released through turbines to produce electric power [23]. Table 2 shows as an example the technical data for a 2 MW plant with a 100 MWh energy storage (assuming 2 m^3/s

Fig. 4a. WTRS wind farm

Fig. 4b.

Open land available at WTRS for development

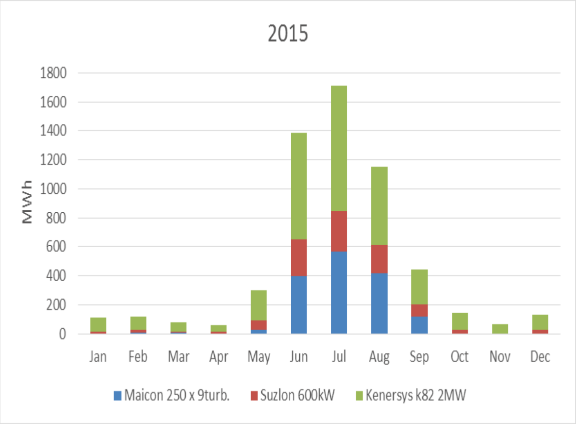


Fig. 5. The WTRS energy output in 2015[16]

II. Storage Technologies Assessment

Different energy storage technologies have been implemented in the literature [17-21]. In this study two energy storage systems are considered, the Pumped Hydro Energy Storage (PHES) system and the Compressed Air Energy Storage (CAES) system. In Tamil Nadu, there is only one pumped hydro storage plant of 400 MW in Kadamparai. This plant has been in operation since 1987 and has 4 units (100 MW each). Each unit can generate energy independently [22]. A percentage of any of the 100 MW units can be used taking into consideration all technical constraints. The CAES system will also be considered as an alternative scenario. Battery will not be considered due to the high cost for energy density.

3.1 Pumped Hydro Energy Storage (PHES)

The compressed air energy storage plants are equivalent to PHES plants when it comes to their applications. Instead of pumping water to higher reservoirs, air is compressed and stored in underground caverns under pressure. Pressurized air is heated and expanded in turbine generating electricity [24].

In Tamil Nadu, there is no CAES plant. It is proposed as an energy storage alternative that is feasible to be implemented in the flat site of the WTRS. The technical requirements for a CAES system of 5 MWh energy storage at 1 MW are presented in Table 3.

Table 2. Technical data for a 2 MW/100 MWh PHES

Flow	2 m^3/s
Head	120 m
Efficiency	85 %
Reservoir (up and down)	720,000 m^3

Possible Reservoir Size	400 x 100 x 18 m

Table 3. General data for a 1 MW/5 MWh CAES system

Container Pressure	50 Bar
Container Volume	1842 m^3
Container Size	20x20x4.6 m
Container Temperature	293 K
Energy released	18014865.9 kJ
Energy released	5 MWh
Efficiency	50

IV. Grid Connection and Control Center

Every power plant in this project can be connected to the transmission grid at different locations through a substation. They can be connected to different transmission voltages because all the transmission system of Tamil Nadu is interconnected. This allows for importing and exporting of electricity to and from the grid. When the energy production from the VPP is not enough to cover the load demand, it will be supplied by the electrical power grid. On the other hand, if electrical power produced by the VPP units exceeds the demand, this excess power could be sold to the grid. The current vision is to use one of three feeders that have 14.2 MW in total. This feeder has a maximum capacity of 5 MW, and it will be used to control and transmit the flow of the output power of the VPP plant under study. Figure 6 shows a line diagram representation of the VPP under study. As mentioned earlier units can be connected at different locations through a substation. The NIWE offices and premises in Chennai, Tamil Nadu will be the location of the control center. The control system is composed of servers connected to the cloud taking control actions based on software measurements and assessments of different variables. The logic structure and the control components are shown in Fig.7. The management of the control unit will be done using cloud computing via a cloud system. Cloud computing is providing a large-scale distributed computing services and resources to users on demand over the internet. A cloud system is comprised of hardware infrastructures as servers, storages, and networks and software resources like stand-alone operating systems [25] [26]. Cloud systems are independent systems that mostly work in parallel and need interaction in order to achieve good overall performance. Planning the availability of cloud resources is a necessity for the execution and scheduling for such power systems applications. Procedures should be set to intelligently use the available computing capacity at the cloud [27].

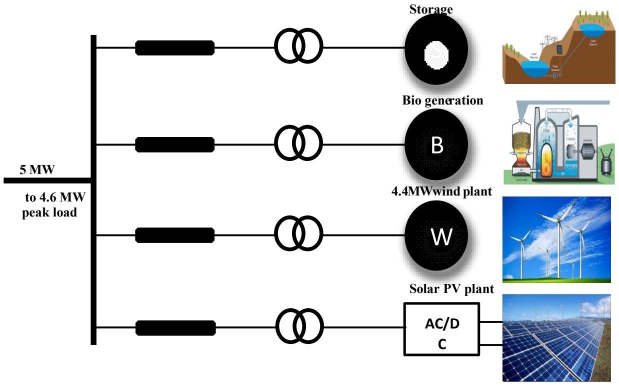


Fig. 6. Line diagram for the planned VPP

5. Problem Formulation

The objective of this study is to analyze the behavior of the different renewable energy resources when integrated together with one control unit, and to define the optimum mix of the capacities installed from each resource.

To achieve the main objective, different scenarios of VPP will be investigated with available renewable energy sources searching for the optimum scenario. In addition, the distributed renewable energy and smart grid components will be integrated together to provide a reliable power supply to the grid and the load. This will enhance existing facility and stabilize grids as well as provide proactive management of distribution network and reduce grid expansion costs. As the target is to maximize the capacities dispatched from each one of the units of the planned VPP [28, 29], let $P_{reserve,\ i}$ denotes the reserve capacity of unit i. Thus the VPP total reserve capacity is $P_{reserve}=\sum_i P_{reserve,\ i}$. The dispatched capacity from the VPP is Dispatch where Dispatch = ∑i Pundit, i , Pundit, i is the dispatched capacity of unit i.

The objective function to maximize the dispatched capacity so as to fulfill the required demand can be formulated as follows:

$$Max\ Dispatch = Max\ P\sum_{i} unit\ i, \qquad (1)$$

Subject to

$$0 \leq Pdispatch \leq \sum_{i} Preserve\ i, \qquad (2)$$

$$0 \leq P^{unit\ i,} \leq P^{unit\ i,} \qquad (3)$$

$$Pload + +P\ Pch\mathrm{export} - Pinch - Import = Dispatch \qquad (4)$$

$$10\% \leq SOC \leq 100\% \qquad (5)$$

where:

$P^{unit\ i,}$ is the maximum capacity for unit i

P_{load} is the demand power

P_{import} is the power imported from the grid

P_{export} is the power exported to the grid

$P_{ch}$is the charge power of the storage unit

P_{disch} is the discharge power of the storage unit

SOC is the state of charge of the storage unit

A simulation tool is developed to evaluate the optimum mix of the capacities dispatched from each resource.

5.1The Simulation Tool

For simulating the virtual power plant output and to select the optimum mix of installed capacities, a simulation tool was developed. This tool was developed using Mat lab® R2016a^{TM} to manipulate the values and see the results in an efficient way.

Figure 8 shows the graphic interface done for this study. The simulation tool is used for the following:

1. Hourly, daily and monthly analysis on a graphic interface
2. Input .txt files and their modification for demand, available solar energy and available wind energy
3. Manipulation of the storage and bioenergy capacities for several scenarios
4. Dispatch of the power and energy output of the virtual power plant
5. Economic analysis (planned as a future work) The simulation has the following considerations:

1. Priority dispatch sequence is solar, wind, biogas, and biomass.
2. Cutting off the generation is done by:
    a. Biogas cut down or shut down
    b. Biomass cut down is driven to the minimum (not shut down as restarting any biomass plant that uses combustion as a primary energy conversion process is expensive)
    c. Wind cut down
    d. Solar cut down

The first consideration was applied supposing that wind and solar irradiance are of zero cost. The second one was based on the wind turbines high ability to manage their active power better than solar. Shutting down the strings of the inverter to turn off or cut down the solar is not a smooth action.

5.2 Scenarios

Different scenarios were investigated for finding the optimum mix, and from all the scenarios only three were selected for the future economic analysis study. The goal for all the scenarios is to fulfill a load with a capacity of 4.6 MW peak and variable behavior depicted in Fig.9. This behavior resembles the load profile of Tamil Nadu of Kayathar and a nearby village (12.5 km away) [30]. In the following scenarios only the installed capacity of the wind plant is fixed because it is already installed. Since solar is still under planning and can be expanded to a higher capacity the study contemplates different values for the solar plant. The best suitable scenarios will be those that import zero energy and make the best use of storage. The scenarios selected are shown in Table 4. Out of several scenarios investigated, the two scenarios presented in Table 4 provided the optimum mix of installed capacities.

Afterwards, the load profile was reduced to 4 MW peak with the same behavior, and the best scenario obtained is shown in Table 5. Figure 10 presents the three selected scenarios from the previous analysis. It depicts that the first scenario dispatched 2 MW from the biomass plant, 1MW from the biogas plant, 2 MW from the solar PV plant, and the 4.4 MW from the wind farm with a PHES storage of 4320 MWh at 2MW. The second scenario dispatched 2 MW from the biomass plant, 1MW from the biogas plant, 4 MW from the solar PV plant, and the 4.4 MW from the wind farm with storage of 2160 MWh at 2MW from the PHES system. The third scenario dispatched 2 MW from the biomass plant, 1MW from the biogas plant, 2 MW from the solar PV plant, and the 4.4 MW from the wind farm with storage of 720 MWh at 2MW from a CAES system. The 3 scenarios did not import any energy/MWh from the grid. These scenarios are to be investigated from the economic point of view to settle on the optimum scenario to be implemented in Kayathar.

In order to determine an algorithm computational cost, the computational complexity can be studied according to the form of big-O notation. The algorithm adopted in this study has an inner loop with n the number of generation units and an outer loop t for the number of hours for the year. So, the time complexity is $O(n * t)$. In the experimental studies the inner loops are small ($n = 4$) and ($t = 8760$), thus the computational cost is quite inexpensive. For example, the estimated time for the VPP algorithm to compute the optimum output for a scenario was ≅38.8 seconds on average.

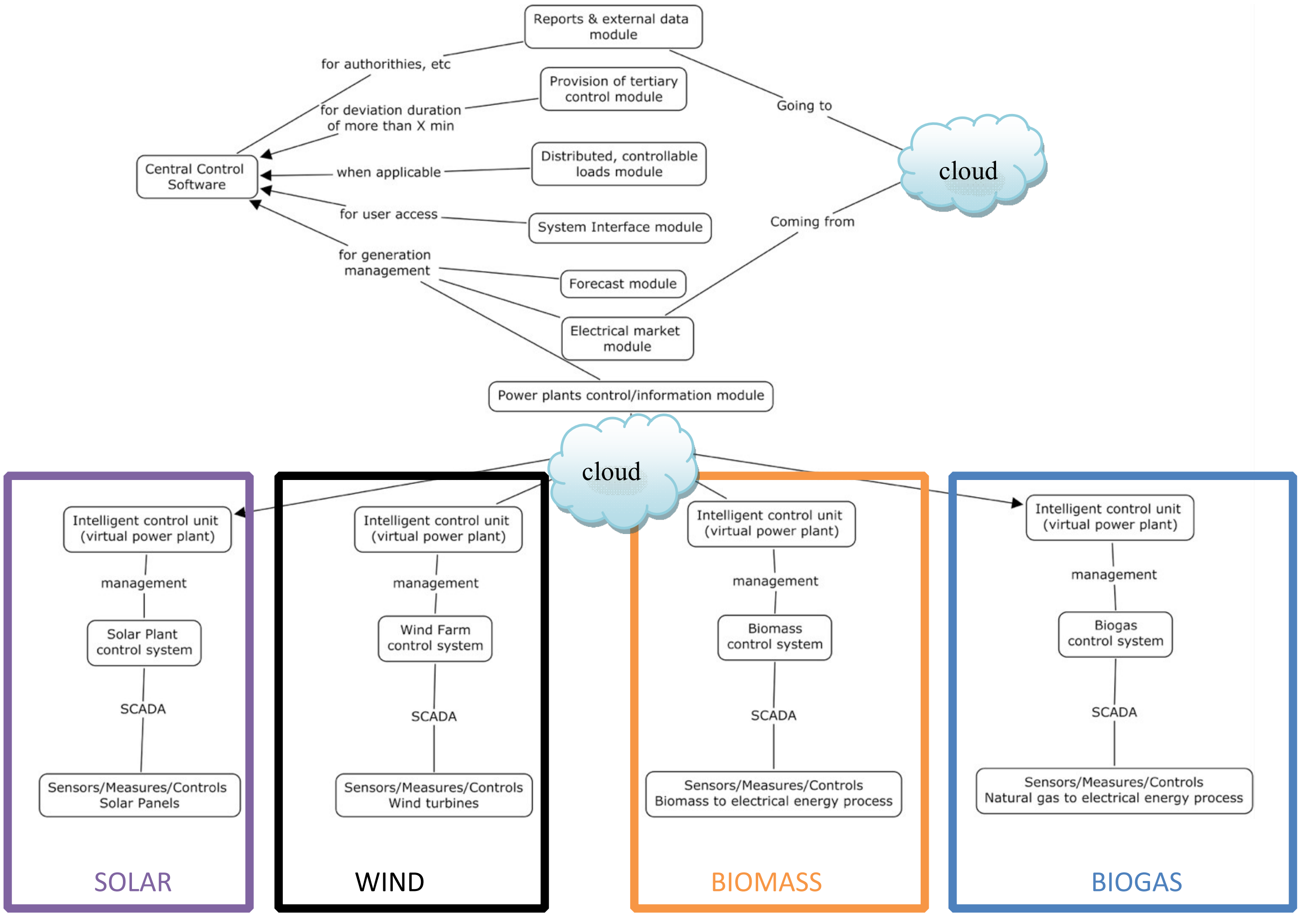


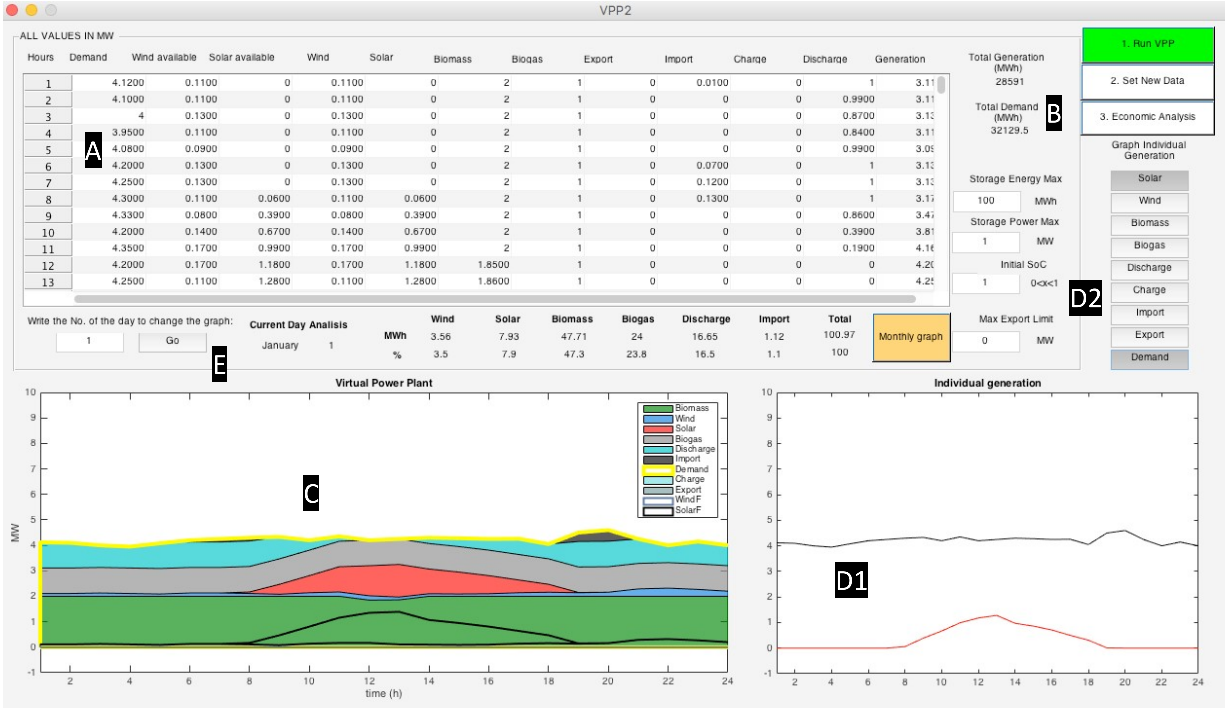
Fig. 7. Control components for the VPP

Table 4. Different Scenarios (yearly) with fixed wind generation capacity of 4.4 MW

No.	Solar MW	Biomass MW	Biogas MW	Storage MWh@MW	CUF Wind	CUF Solar	CUF Biomass	CUF Biogas	Storage cycles	Import MWh
1	2	2	1	4320@2	0.15	0.15	0.73	0.89	0.89	0.00
2	4	2	1	2160@2	0.14	0.16	0.65	0.85	1.54	0.00

Table 5. Optimum scenario for a 4 MW peak load

Solar MW	Biomass MW	Biogas MW	Storage MWh@MW	CUF Wind	CUF Solar	CUF Biomass	CUF Biogas	Storage cycles	Import MWh
2	2	1	720@2	0.13	0.15	0.61	0.82	0.79	0.00



ALL VALUES IN MW

Hours	Demand	Wind available	Solar available	Wind	Solar	Biomass	Biogas	Export	Import	Charge	Discharge	Generation
1	4.1200	0.1100	0	0.1100	0	2	1	0	0.0100	0	1	3.11
2	4.1000	0.1100	0	0.1100	0	2	1	0	0	0	0.9900	3.11
3	4	0.1300	0	0.1300	0	2	1	0	0	0	0.8700	3.13
4	3.9500	0.1100	0	0.1100	0	2	1	0	0	0	0.8400	3.11
5	4.0800	0.0900	0	0.0900	0	2	1	0	0	0	0.9900	3.09
6	4.2000	0.1300	0	0.1300	0	2	1	0	0.0700	0	1	3.13
7	4.2500	0.1300	0	0.1300	0	2	1	0	0.1200	0	1	3.13
8	4.3000	0.1100	0.0600	0.1100	0.0600	2	1	0	0.1300	0	1	3.17
9	4.3300	0.0800	0.3900	0.0800	0.3900	2	1	0	0	0	0.8600	3.47
10	4.2000	0.1400	0.6700	0.1400	0.6700	2	1	0	0	0	0.3900	3.81
11	4.3500	0.1700	0.9900	0.1700	0.9900	2	1	0	0	0	0.1900	4.16
12	4.2000	0.1700	1.1800	0.1700	1.1800	1.8500	1	0	0	0	0	4.20
13	4.2500	0.1100	1.2800	0.1100	1.2800	1.8600	1	0	0	0	0	4.25

Total Generation (MWh) 28591

Total Demand (MWh) 32129.5

Storage Energy Max 100 MWh

Storage Power Max 1 MW

Initial SoC 1 0<x<1

Max Export Limit 0 MW

Write the No. of the day to change the graph: 1

Current Day Analisis
January 1

	Wind	Solar	Biomass	Biogas	Discharge	Import	Total
MWh	3.56	7.93	47.71	24	16.65	1.12	100.97
%	3.5	7.9	47.3	23.8	16.5	1.1	100

Fig. 8. Graphic interface of the software

A: Table of results, B: Control Buttons, C: Daily Dispatch, D1: Individual Generation Graph, D2: Toggle buttons for Individual Generation Graph, E: Current Day Info Table.

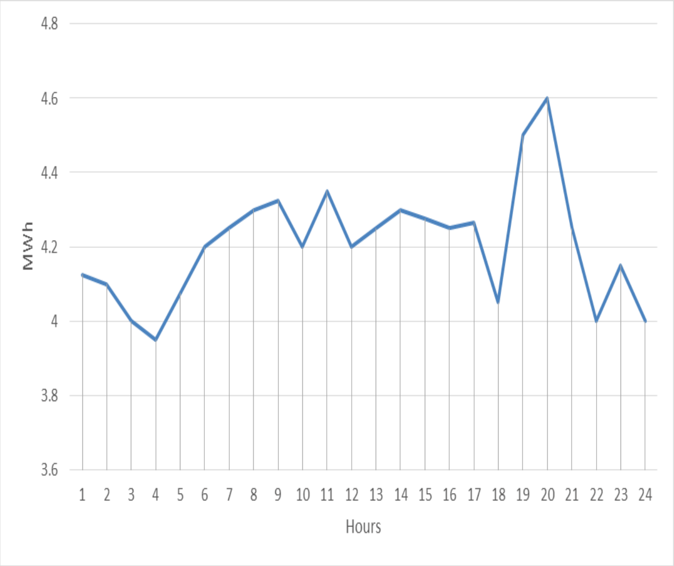


Fig. 9. Selected load profile, 32.12 GWh/year

VI. CONCLUSIONS

This study focused on the optimization of the VPP output. The main objective of this study was to analyze the behavior of different renewable energy sources when collected together with one control unit, and to define the optimum mix of the capacities installed of each resource. A simulation tool was developed using Mat lab® R2016a^{TM} for simulating the virtual power plant output and to select the optimum mix of installed capacities. This tool was implemented for a real case study of a VPP planned to be installed in an Indian town called Kayathar in the state of Tamil Nadu. Kayathar has a wind turbine research station with a capacity of 4.4 MW wind generation that already exists onsite. A solar photovoltaic power plant is planned to be installed in Kayathar. Bioenergy plants near Kayathar at different capacities were considered as a part of the VPP.

PHES and CAES systems were simulated in this study. Several scenarios were adopted and analyzed to obtain optimum solution. Optimum scenarios obtained were those that imported zero energy from the grid and utilized the storage system to the best. The computational time for the VPP algorithm to obtain the optimum output for a scenario was ≅38.8 seconds on average.

In the future work the authors intend to use evolutionary artificial intelligence techniques to solve this optimization problem as they proved to give promising results when applied to combinatorial optimization problem, and thus comparison between different solution methods would be applicable. It is also recommended to use the results and findings of this study to perform a further economic study in the future work to maximize the profit of the VPP.

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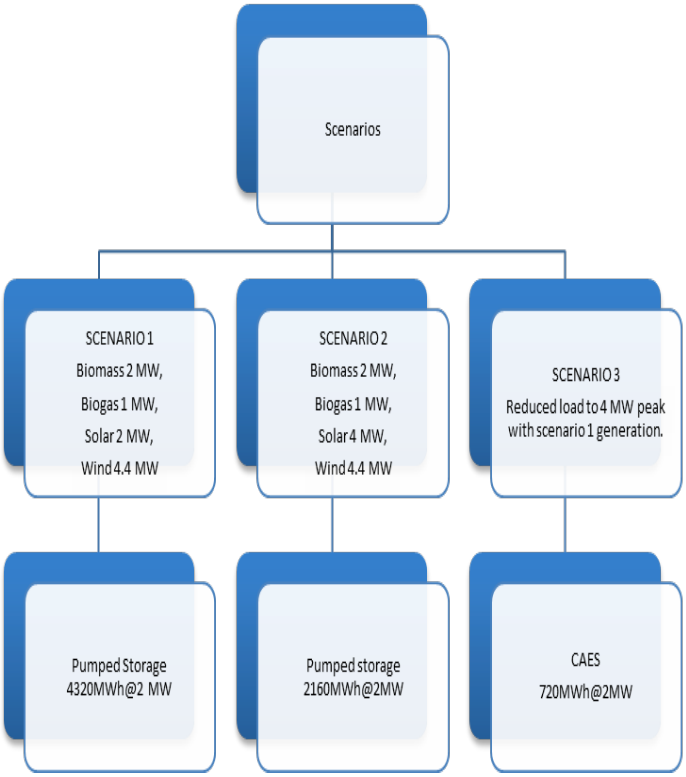

Fig. 10. Selected scenarios for the future economic study

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