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Implementing agent-based emissions trading for controlling Virtual Power Plant emissions

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ABSTRACT

A methodology was developed and tested for controlling the emissions from a group of micro-generators aggregated in a Virtual Power Plant. The methodology is based on the EU Emissions Trading Scheme. A multi-agent system was designed and simulations were performed. The operation of the system was demonstrated experimentally using micro-generation sources installed in two laboratories. Two days of experiments were performed. Results show that system emissions have been controlled with a good accuracy, since only small deviations between desired and actual emissions output were observed. It was found that Virtual Power Plant controllability increases significantly by increasing the number of participating micro-generators.

1. Introduction

Aggregation of Distributed Energy Resources (DER) has been considered as a promising solution for mitigating issues related with DER grid integration, such as network constraints, controllability, or resource intermittency [1–4]. Two aggregation concepts have been proposed [5]: (i) the micro-grids and (ii) the Virtual Power Plants (VPP). Emission Trading Schemes (ETS) have been adopted by several countries as a means to regulate carbon emissions, the most prominent of which is the European Union ETS [6]. This scheme allows the cost-efficient reduction of CO_2 emissions among its participants. Allowances are issued by the regulator, in the form of transferrable Carbon Credits, representing one tonne of CO_2 emissions [6]. The method of "cap and trade" is used, issuing fewer allowances than the participants actually need. Hence, the participants with the lowest cost of emissions reduction are given incentive to balance the emissions of the more costly participants. This results in a cost-efficient way of matching the total emissions to a desired value. The total emissions are controlled by the total amount of Carbon Credits supplied to the participants by the regulator (the European Commission). In this paper, a method for the control of carbon emissions induced by a group of aggregated micro-generators is presented. The purpose of this work was to test this methodology by performing simulations and an experimental demonstration of an agent-based implementation. This methodology is based on the EU ETS scheme, as presented in Section 2. A multi-agent system has been developed for implementing the methodology and is presented in Section 3. The methodology was demonstrated with a simulated and an experimental case study, presented in Sections 4 and 5, respectively. Results are presented in Section 6 and conclusions are given in Section 7.

2. Control methodology

2.1. The Environmental Virtual Power Plant (EVPP)

In [7], the operation of Virtual Power Plants is characterised by two aspects: the Commercial Virtual Power Plants (CVPP) and the Technical Virtual Power Plants (TVPP). This classification was made based on the orientation of aggregation towards markets or power system operation, respectively. Following the CVPP and TVPP classification, the category of Environmental Virtual Power Plants (EVPP) is proposed. The EVPP can also be described as a sub-category of a CVPP, since it operates by simulating the EU Emissions Trading Scheme [6]. Micro-generators are too small to participate

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individually in the EU ETS, since there is a lower limit of 20 MW in thermal capacity, which is closer to a typical market participant size [6]. The main benefit of the proposed regulation system is that it enables the participation of micro-generator sources in electricity and emissions markets, potentially increasing their revenue compared to standalone operation. The micro-generation resource is expected to be a sizeable asset, so depending on the size of the aggregator portfolio and the business model, it can bring significant economic benefits to the aggregator as well [5,8].

2.2. EVPP aggregator Carbon Credits

In the EU emissions market, the Carbon Credits allow specific quantities of carbon dioxide equivalent ($CO_{2\text{-}e}$) emissions to be released by the holding party [6]. One Carbon Credit represents one tonne of $CO_{2\text{-}e}$, and it is transferrable, i.e. the market participants can trade Carbon Credits between them [6]. In an EVPP, the Carbon Credits are issued by the EVPP aggregator. The EVPP aggregator creates internal Carbon Credits and distributes them to the micro-generators through the intermediate micro-grid aggregators. The Carbon Credits are received by the micro-generators that participate in the EVPP, who can trade Carbon Credits between them according to their needs, thus creating an emissions market. These internal EVPP Carbon Credits are different from the Carbon Credits in the EU emissions market. The amount of $CO_{2\text{-}e}$ that the internal EVPP Carbon Credits represent (e.g. 1 kg $CO_{2\text{-}e}$ or 1 g $CO_{2\text{-}e}$) depends on the size and emission rates of the generators. The EVPP aggregator is effectively acting as a translator between the EU emissions market Carbon Credits and the internal EVPP Carbon Credits. The EVPP aggregator records and controls the flow of Carbon Credits to and from the micro-generators, but not between them. The micro-generators exchange Carbon Credits between them, autonomously, to match their needs. The concept is illustrated in Fig. 1(i).

2.3. EVPP control policies

The amount of Carbon Credits that are created and fed into the internal market at each trading period is defined by the control policy that is followed by the EVPP aggregator. Three control policies were considered in this work, to reflect the Environmental and Commercial aspects in an EVPP. Technical issues were also considered in terms of micro-generator operational limits. When the EVPP aggregator creates the Carbon Credits, it evaluates the current grid emission factor, or electricity price, or both. It uses fuzzy logic inference techniques (i.e. fuzzification–fuzzy associative matrix–defuzzification) to infer the number of Carbon Credits that it will feed into the internal agent market, based on the indicator that is being assessed.

(i) **Emissions policy [*Goal*:** to reduce the overall emissions resulting from EVPP components/***Indicator***: grid emission factor]. Domestic loads are considered to be included in the EVPP area. As the emission factor of the grid is not taken as constant, the EVPP directs the micro-generators to generate more when the grid emission factor is higher, by supplying more Carbon Credits during these times. Thus, more carbon-intensive grid electricity is displaced and the overall emissions are reduced. Since it is cost-effective for the micro-generators to match their emissions with their Carbon Credits, the overall EVPP output is thus regulated.

(ii) **Cost policy**: [***Goal***: to increase the revenue of the EVPP when it is participating in the wholesale electricity markets/***Indicator***: electricity market price]. The micro-generators are driven to generate more when the electricity price is higher, by supplying more Carbon Credits during these times. The emissions output is proportional to the energy generation. The micro-generators produce more energy and emissions to match the Carbon Credits and this energy is traded by the EVPP.

(iii) **Mixed policy (Cost and Emissions)**: [***Goal***: a multi-objective combination of the above/***Indicator***: grid emission factor *and* electricity market price].

2.4. EVPP operation

The Emissions Trading Scheme was used as the basis to design the EVPP operation. An internal EVPP market is created. An EVPP aggregator, acting as the regulator, distributes Carbon Credits to the micro-generators, through intermediate micro-grid aggregators. The Carbon Credits are essentially unique character strings and they are sent as lists through communication links. The micro-generators trade Carbon Credits to cover their emissions. This process is periodic and has 4 stages [also see Fig. 1(ii)]: (i) the beginning of the trading period, (ii) the trading period, (iii) the end of the trading period and (iv) the penalties allocation. A high-level algorithm of the EVPP operation is presented in Fig. 2. It should be noted that the settling periods between internal EVPP operation and external emissions markets are likely to be different. The EVPP aggregator acquires Carbon Credits from the external emissions market (e.g. once daily) and regulates the internal EVPP Carbon Credits accordingly (e.g. every 15 min).

3. A multi-agent system for the environmental virtual power plant

Intelligent agents are defined as autonomous programmes and multi-agent systems (MAS) are systems which contain more than one agent [10]. A hierarchical structure was used to design the proposed MAS, similar to [3] and [9]. Aggregation was realised at two levels: (i) micro-grid and (ii) EVPP level. The intermediate micro-grid level was introduced to reduce the communicational burden and complexity when large numbers of micro-generators are aggregated by a single entity. The Java Agent DEvelopment framework (JADE), a Java-based platform, was used to develop the MAS [10,11]. It implements standard communication protocols designed by the Foundation for Intelligent Physical Agents (FIPA) [12]. Fuzzy logic techniques were applied for the decision-making processes of the agents, since they are adaptive and allow decisions based on incomparable variables. Agents were developed for each of the proposed entities, as described below:

- **The Environmental Virtual Power Plant (EVPP) Aggregator** agent draws the strategy of the EVPP. It creates and distributes the Carbon Credits to the micro-generators, based on control variables such as the grid emission factor.
- **The Micro-grid Aggregator** agent is a transitional layer between the EVPP and the micro-generators. It does not host any intelligence. Its function is to transfer Carbon Credits and aggregated information.
- **The Micro-generation** agent is responsible for the micro-generation operation. It is located in the micro-generator controller. It has access to the information which influences the micro-generation operation and measurements of the local electrical and thermal demand. Every micro-generator agent is trading Carbon Credits based on its own objectives.

4. Simulated case study

A simulation of the MAS operation was performed, in order to test its behaviour. The agents have been initiated using JADE, as in a practical implementation, but on a single computer. The

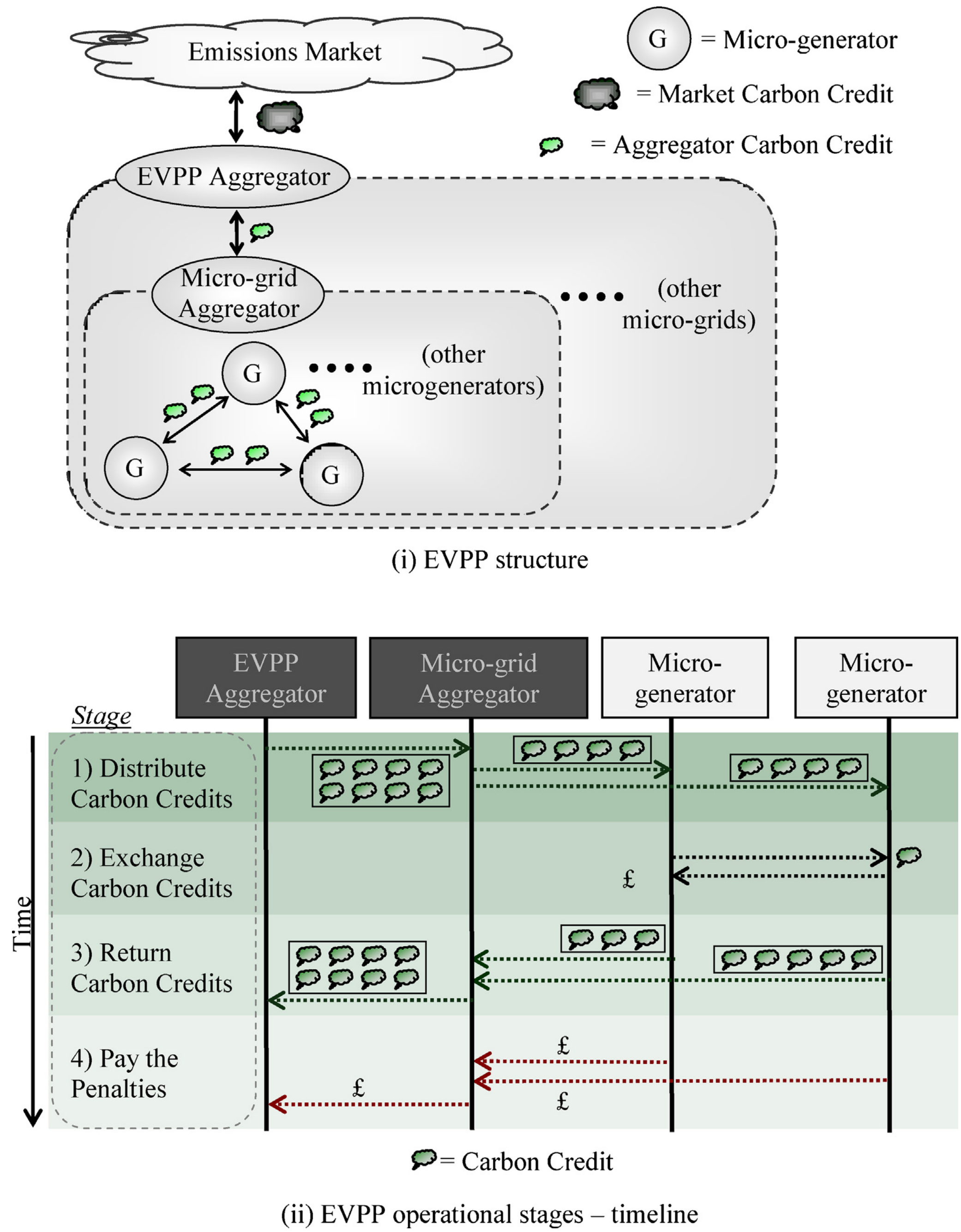

Fig. 1. Carbon credits trading.

main difference from a real implementation was that the agent input data and outgoing commands were not fed from and to real devices.

4.1. Input data

The input data that were used were grid real-time emission factor data [13], electricity market price data [14], thermal demand data [8], electrical demand data [15] and renewable generation data [16]. To reproduce the variation in demand and renewable generation between customers, each of the data points in these profiles was multiplied with a randomisation factor, according to the method described in [17].

Table 1
Micro-generation sources for the two experiments.

Source type	Experiment I		Experiment II	
	NTUA	CRES	NTUA	CRES
Wind Turbine-Battery (2.5 kW)	–	–	4	4
Photovoltaic-Battery (1.1 kW)	1[a]	1[a]	12[a]	12[a]
Microturbine (3 kW)	–	–	10	6
Fuel Cell (1.9 kW)	–	1[a]	5	5[a]
Diesel engine (12 kW)	–	1[a]	–	1[a]
Total sources	1	3	31	28
Total installed power (kW)	1.1	15.0	62.7	62.7

[a] One of them is a real installed micro-generation source.

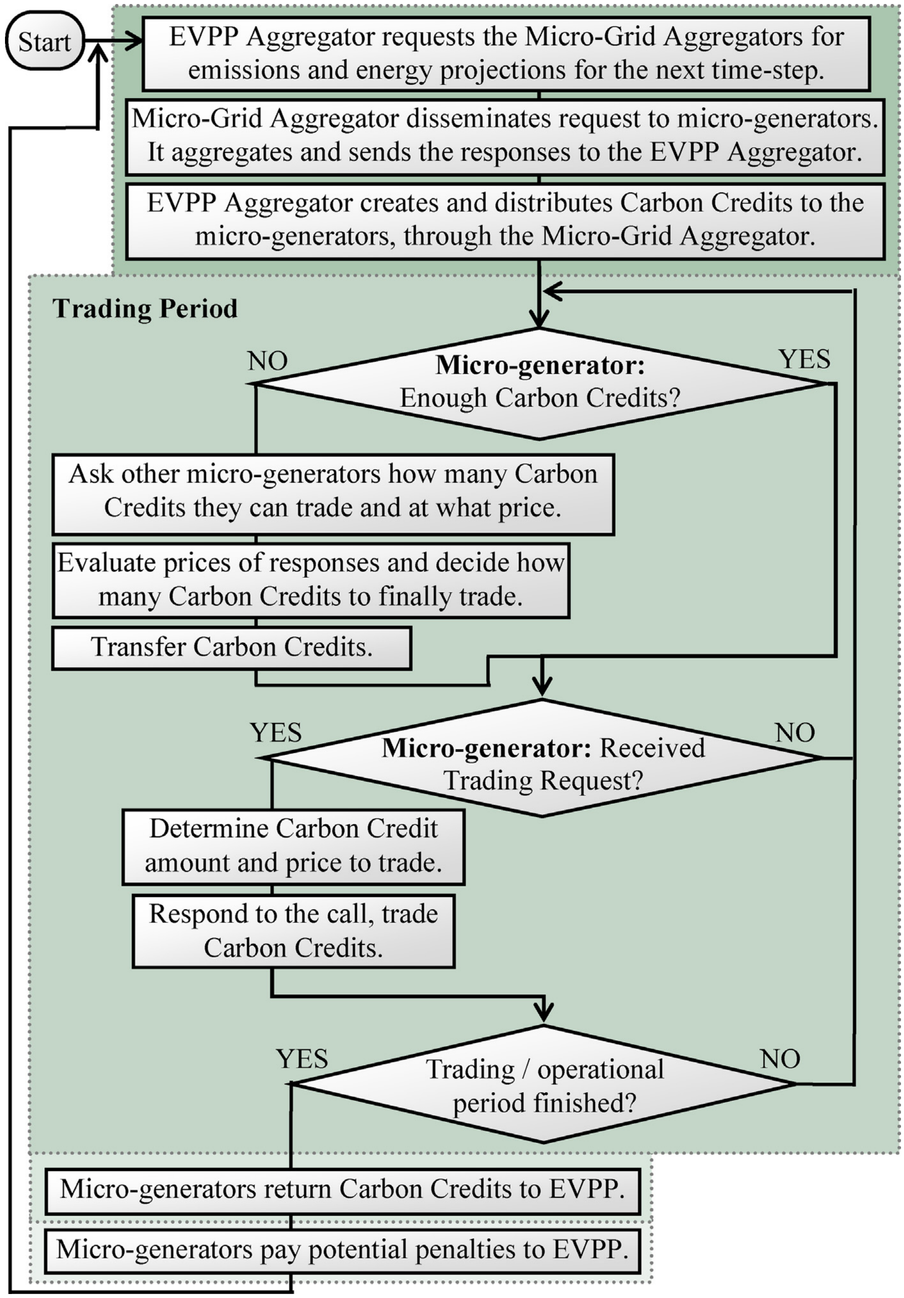

Fig. 2. Environmental Virtual Power Plant algorithm.

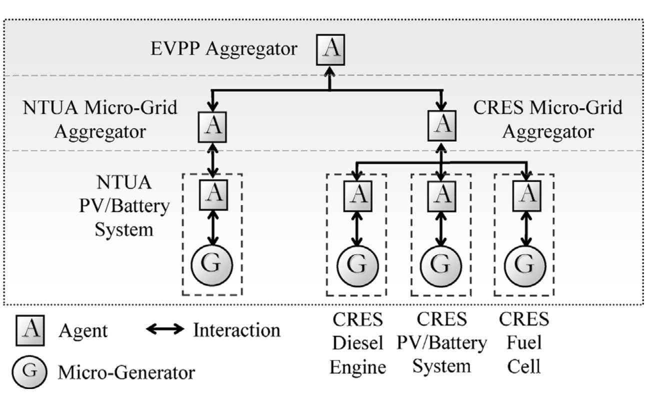

Fig. 3. Structure of the experimental EVPP.

4.2. Simulated EVPP

The number of agents that were simulated is based on the case described in [18]. Two micro-grids were simulated, each of them containing the following agents: 4 Wind Turbine agents, 2 Photovoltaic agents, 2 Microturbine agents, 3 Fuel Cell agents and 13 Stirling Engine agents. In total, 48 micro-generators were simulated. The life-cycle carbon emissions of wind turbines and photovoltaics were also considered [18]. This provided an emission factor for these sources as well. All other micro-generators were considered to be capable of Combined Heat and Power (micro-CHP) operation. Part-load micro-CHP emission curves were derived from literature data [18–21] and used by the agents to determine their projected emissions according to their loading. Electrical storage capacity of 20 kWh_e was considered for wind turbines and photovoltaics and thermal storage capacity of 20 kWh_{th} for the

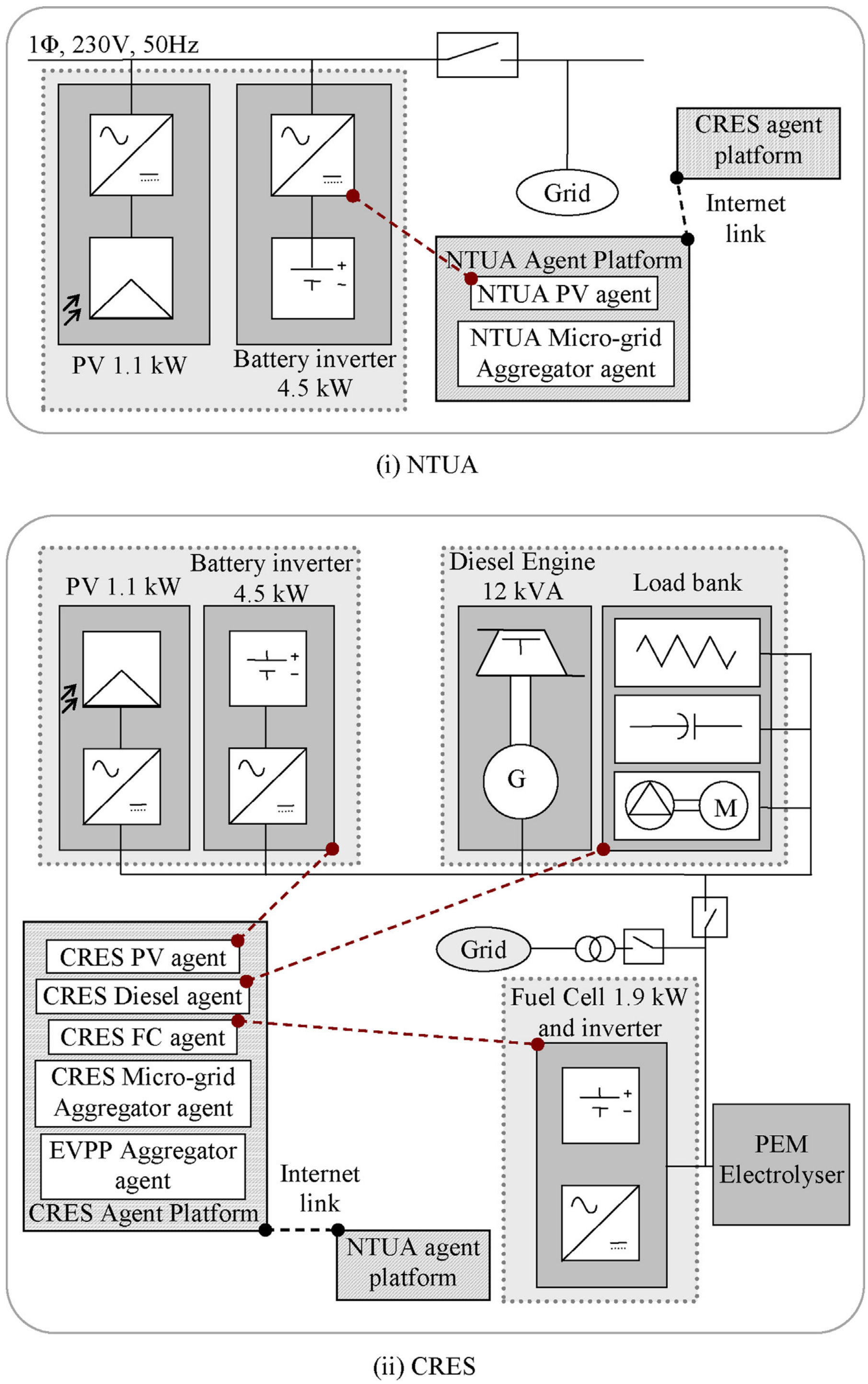

Fig. 4. Laboratory setup in (i) NTUA and (ii) CRES.

micro-CHPs. One Carbon Credit was considered to be equal to 1 g CO_2. Results from the simulations will be presented later in the paper (see Section 6).

5. Experimental case study

5.1. Experimental setup

The experimental EVPP comprises two micro-grids, installed in different laboratories. The one is located in the Centre for Renewable Energy Sources (CRES) and the other in the National Technical University of Athens (NTUA). The agents communicate between the laboratories via the Internet. A diagram of the EVPP is presented in Fig. 3. The agent platform is run on one dedicated computer, which also hosts the EVPP agent. The other agents were attached to this host platform through the Internet, utilising JADE functionality [11].

5.2. Laboratory components

The laboratory equipment that was utilised at NTUA include a 1.1 kWp photovoltaic installation, battery energy storage and a controlled interconnection to the local LV grid. Both the battery unit and the PV generators are connected to the AC grid via fast acting DC/AC power converters. The components that were utilised in this study from the CRES laboratory are a 1.1 kWp photovoltaic installation, battery storage, a 12 kVA Diesel genset and a 5 kW Proton Exchange Membrane (PEM) fuel cell (operated at 1.9 kW). Micro-CHP operation and Natural Gas reforming for extracting H_2 were simulated. A diagram of the laboratory components utilised is shown in Fig. 4.

5.3. Input data

The example data that were used as inputs were grid real-time emission factor data from the Greek power system [22], marginal electricity price data from the Greek power system [22], thermal demand data [23], electrical demand data [15], a wind generation profile [16] and photovoltaic generation measured at the CRES PV installation. For the photovoltaics, a life-cycle emission factor was derived [18]. Part-load emission curves were measured for the CRES Diesel engine and Fuel Cell, which were used by the agents to determine their projected emissions according to their loading. Actual emissions were estimated by using the measured actual energy output of each of the micro-generators. Using the emission characteristics of the micro-generator, the actual emissions were then calculated.

5.4. Experimental procedure

Two days (8 h per day) of measurements were successfully completed:

Experiment I: One day with the four sources operational and
Experiment II: One day with the four sources plus 55 additional simulated sources with their corresponding agents.

The purpose of the Experiment II was to determine if the EVPP proves to be more stable and controllable by increasing the number of sources that are participating. The penetration scenario for Experiment II was based on the benchmark micro-grid in [24]. Table 1 shows the configuration in both experiments. The control policy that was followed by the EVPP aggregator agent was the Mixed Policy, which takes into account both the electricity price and the grid real-time emission factor.

6. Results

Fig. 5 presents a comparison of the actual EVPP output relative to the Carbon Credits provided by the EVPP aggregator for (i) the simulated case, (ii) Experiment I and (iii) Experiment II.

6.1. Simulation results

A simulation of the system was performed using the Emissions Policy for 3 simulated days. The micro-generators follow closely the EVPP requirements set by means of the Carbon Credits – see Fig. 5(i). Minor deviations occur: (i) immediately after a demand peak and (ii) at times when the thermal demand is very low.

6.2. Diesel engine emissions created deviations

During Experiment I, prior to short periods of Diesel operation, the EVPP provided less Carbon Credits than the Diesel engine had requested. The Carbon Credits provided were not sufficient for the Diesel engine to start up, therefore the Diesel agent decided to distribute them to the other sources and remain stopped. However, the Diesel engine produces more than 80% of the total EVPP emissions. Thus, the excess Carbon Credits were too many for the other sources to accommodate them. The Diesel engine still had excess Carbon Credits that it could not dissipate, thus a deviation from the EVPP desired output was recorded, as seen in Fig. 5(ii). One way of mitigating this would be for the EVPP aggregator to take into account the specific limitations of each micro-generator (in this case the Diesel engine) and distribute the Carbon Credits accordingly. However, this could complicate the EVPP aggregator algorithm unnecessarily and potentially reduce the flexibility and openness of the system.

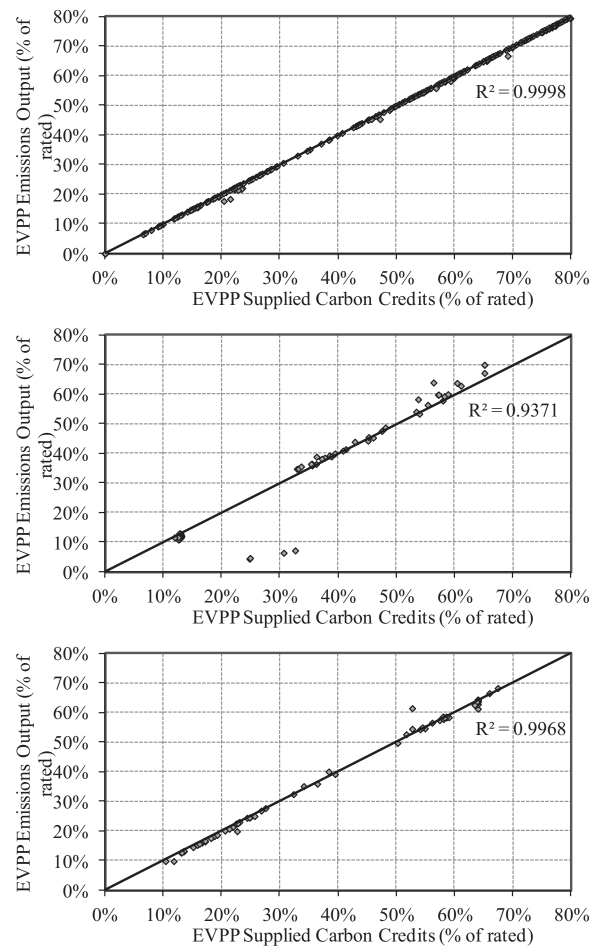

Fig. 5. Correlation between EVPP total Carbon Credits and actual emission output in (i) simulations, (ii) Experiment I and (iii) Experiment II.

6.3. Controllability

In Fig. 5, the EVPP actual emissions output is plotted as a correlation with the EVPP Carbon Credits for the Simulated case and Experiments I and II. This comparison is not directly influenced by initial conditions and indicates the ability of the EVPP aggregator to regulate the overall emissions of the micro-generators. The deviations described in the previous section can be identified as the few points which are most distant downwards of the trend line in Fig. 5(ii). The correlation is better in Experiment II, with only a few points deviating slightly. Thus, by increasing the number of participating micro-generators, the emissions controllability of the EVPP increased as well. Considerably fewer deviations were recorded, partly due to the lack of real system uncertainties of the simulated agents. However, the larger deviations were actually mitigated because more agents were available to compensate an agent's potential Carbon Credit excess or shortfall.

7. Conclusions

A methodology for controlling the emissions of a Virtual Power Plant was presented. The methodology has been tested by means of simulations and experimental demonstration. The methodology is based on the EU Emissions Trading Scheme. Trading of Carbon Credits was used to balance the micro-generator emissions within the VPP. This method was termed Environmental Virtual Power Plant (EVPP). An agent-based control system was designed and developed. A hierarchical control structure was defined. Three types of intelligent agents have been used: (i) the EVPP aggregator agent, (ii) the micro-grid and (iii) the micro-generator. Simulations were performed, indicating high precision in the regulation of the micro-generator emissions. The EVPP methodology was also tested using equipment from two laboratories, installed in NTUA and CRES.

Two experiments were performed. During both experiments, the EVPP was operated for approximately 8 h, using the mixed control policy (accounting for emissions and cost). In Experiment I, the EVPP included only the four sources installed in the two labs. In Experiment II, 55 additional sources were simulated. In the results from Experiment I, it was observed that the output of the EVPP was dominated by the Diesel engine, which was producing most (>80%) of the EVPP emissions. This disparity resulted in significant deviation of the EVPP output from the Carbon Credits that were supplied. In Experiment II, the EVPP included 59 sources. It was observed that the deviation from the Carbon Credits dropped significantly, compared to Experiment I. This was mostly due to two reasons: (a) The Diesel engine had access to much more micro-generation agents that could buy or sell Carbon Credits. Thus, incidents such as the deviation peaks in Experiment I were avoided. (b) Most of the sources (55 out of 59) were simulated, therefore lacking limitations of real systems, such as measurement errors, engine response delays, or generator start-up requirements. It was concluded that the controllability of the EVPP output primarily depends on the number of sources included in its portfolio. Individual micro-generation limitations are cancelled out as their number in the EVPP increases. Thus, the average EVPP output deviation can be expected to decrease, as the number of sources increases.

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