Emissions of Aggregated Micro-generators

Thesis submitted for the degree of
Doctor of Philosophy

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DECLARATION

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

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Summary of Thesis

The key question this thesis aims to address is to what extent can micro-generation sources contribute to the carbon emission reduction targets set by the UK government.

The operational emissions of micro-CHP capable micro-generators were examined against the UK grid electricity and gas boiler heat. Fossil and biomass fuels were considered. The life-cycle emissions associated with the manufacturing, transport and disposal of micro-generators were calculated. Case studies were constructed, based on the literature. It was found that emissions associated with domestic electrical and thermal demand would be reduced significantly.

A Virtual Power Plant (VPP) was defined for aggregating micro-generators, using micro-generation penetration projections for the year 2030 from the literature. An optimisation problem was described, where the goal was to minimise the VPP carbon emissions. The results show the amount of emissions that would potentially be reduced by managing an existing micro-generation portfolio in a VPP.

An Environmental Virtual Power Plant (EVPP) was defined, for controlling micro-generator carbon emissions. A multi-agent system was designed. The principle of operation resembles an Emissions Trading Scheme. Emission allowances are traded by the micro-generators, in order to meet their emissions needs. Three EVPP control policies were identified. Fuzzy logic was utilised for the decision making processes. Simulations were performed to test the EVPP operation. The main benefit for the micro-generators is the ability to participate in markets from which they would normally be excluded due to their small size.

The multi-agent system was verified experimentally using micro-generation sources installed in two laboratories, in Athens, Greece. Two days of experiments were performed. Results show that system emissions have been successfully controlled, since only small deviations between desired and actual emissions output were observed. It was found that Environmental Virtual Power Plant controllability increases significantly by increasing the number of participating micro-generators.

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List of publications

The following papers were published based on work done for this thesis, or work done within the framework of the doctorate degree:

Journal Papers

1. S. Skarvelis-Kazakos, E. Kolentini, I. Grau, P. Papadopoulos, L.M. Cipcigan, N. Jenkins and N. Hatziargyriou, **(2011)**, "Environmental Virtual Power Plant", [in preparation]
2. S. Skarvelis-Kazakos, E. Rikos, E. Kolentini, E. Chatzoplaki, G. Tzamalis, L.M. Cipcigan, N. Jenkins and N. Hatziargyriou, **(2011)**, "Control of Virtual Power Plant Emissions", [in preparation]
3. S. Skarvelis-Kazakos, L.M. Cipcigan and N. Jenkins, **(2009)**, "Micro-Generation For 2050: Emissions Performances Of Micro-Generation Sources During Operation", Pollack Periodica, Vol. 4, No. 2, pp. 89–99

Book Chapters

4. I. Grau Unda, P. Papadopoulos, S. Skarvelis-Kazakos, L.M. Cipcigan and N. Jenkins, **(2011)**, "Energy Storage for Balancing a Local Distribution Network Area", Chapter in Energy Storage in the Emerging Era of Smart Grids, InTech, 2011. ISBN 978-953-307-269-2

Conference Papers

5. S. Skarvelis-Kazakos, P. Papadopoulos, I. Grau, A. Gerber, L.M. Cipcigan, N. Jenkins and L. Carradore, **(2010)**, "Carbon Optimized Virtual Power Plant with Electric Vehicles", 45th Universities Power Engineering Conference (UPEC), Cardiff, 31 August – 3 September 2010
6. S. Skarvelis-Kazakos, L.M. Cipcigan and N. Jenkins, **(2009)**, "Micro-Generation For 2050: Life-Cycle Carbon Footprint of Micro-Generation Sources", 44th Universities Power Engineering Conference (UPEC), Glasgow, 1 – 4 Sept 2009
7. E. Karfopoulos, P. Papadopoulos, S. Skarvelis-Kazakos, I. Grau Unda, N. Hatziargyriou, L.M. Cipcigan and N. Jenkins, **(2011)**, "Extending the Microgrids

Concept to Integrate Electric Vehicles in Power Grids", 16th International Conference on Intelligent System Applications to Power Systems (ISAP), 25-28 Sept. 2011, Crete, Greece.

8. A. F. Raab, M. Ferdowsi, E. Karfopoulos, I. Grau Unda, S. Skarvelis-Kazakos, P. Papadopoulos, E. Abbasi, K. Strunz, L.M. Cipcigan, N. Hatziargyriou, and N. Jenkins, **(2011)**, "Virtual Power Plant Control Concepts with Electric Vehicles", 16th International Conference on Intelligent System Applications to Power Systems (ISAP), 25-28 Sept. 2011, Crete, Greece.
9. P. Papadopoulos, S. Skarvelis-Kazakos, I. Grau, L.M. Cipcigan and N. Jenkins, **(2010)**, "Predicting Electric Vehicle Impacts on Residential Distribution Networks with Distributed Generation", IEEE Vehicle Power and Propulsion Conference 2010 (VPPC), Lille, 1 – 3 September 2010
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11. I. Grau, P. Papadopoulos, S. Skarvelis-Kazakos, L.M. Cipcigan and N. Jenkins, **(2010)**, "Virtual Power Plants with Electric Vehicles", 2nd European Conference SmartGrids and E-Mobility, Brussels, 20 – 21 October 2010
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PROJECT DELIVERABLES

13. C.L. Moreira, D. Rua, E. Karfopoulos, E. Zountouridou, F.J. Soares, I. Bourithi, I. Grau, J.A. Peças Lopes, L.M. Cipcigan, L. Seca, M. Moschakis, P.M. Rocha Almeida, P. Moutis, P. Papadopoulos, R.J. Rei, R.J. Bessa, S. Skarvelis-Kazakos, **(2010)**, "Extend Concepts of MG by Identifying Several EV Smart Control Approaches to be embedded in the Smart Grid Concept to manage EV individually or in Clusters", MERGE - Mobile Energy Resources in Grids of Electricity, Deliverable 1.2, available at http://www.ev-merge.eu

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Standards Development and Project Participation

Within the framework of the doctorate degree, the author participated in the following projects and standards development:

1. **IEEE P2030.1 Guide for Electric-Sourced Transportation Infrastructure -** Task Force 2: Grid Impact - Generation Subgroup Leader
2. EU FP7 Project **DERri - Distributed Energy Resources Research Infrastructures** - *Contract No.: 228449.*
    - Lead User of DERri project: "**Carbon Agents for a Virtual Power Plant**" (ID: 20100531-02)
3. EU FP7 Project **MERGE - Mobile Energy Resources in Grids of Electricity** - *Contract No: 241399*, co-author in:
    - *Deliverable 1.2* Extend Concepts of MG by Identifying Several EV Smart Control Approaches to be embedded in the Smart Grid Concept to manage EV individually or in Clusters
    - *Deliverable 1.3* Controls and EV Aggregation for Virtual Power Plants

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NOMENCLATURE

LIST OF ABBREVIATIONS

AC	Alternating Current
ADMD	After Diversity Maximum Demand
AEFC	Alkaline Electrolyte Fuel Cells
AI	Artificial Intelligence

AID	Agent ID
AMS	Agent Management System
AP	Agent Platform
BEV	Battery Electric Vehicles
CC	Carbon Credits
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CERT	Carbon Emissions Reduction Target
CFP	Call For Proposal
CHP	Combined Heat and Power
CIF	Collective Insecurity Factor
CRES	Centre for Renewable Energy Sources
CVPP	Commercial Virtual Power Plant
DC	Direct Current
DEMS	Distributed Energy Management System
DER	Distributed Energy Resources
DF	Directory Facilitator
DG	Distributed Generation
DMFC	Direct Methanol Fuel Cells
DP	Dynamic Programming
ECN	Energy research Center of the Netherlands
EEA	Energy and Environmental Analysis Inc.
EG	Embedded Generation
EPA	Environmental Protection Agency
ETS	Emissions Trading Scheme
EV	Electric Vehicles
EVPP	Environmental Virtual Power Plant
FENIX	Flexible Electricity Network to Integrate the eXpected 'energy evolution'
FIPA	Foundation for Intelligent Physical Agents
FIPA-ACL	FIPA Agent Communication Language
GEMIS	Global Emission Model for Integrated Systems
GHG	Greenhouse Gases

HAWT	Horizontal Axis Wind Turbines
HHV	Higher Heating Value
HPR	Heat to Power Ratio
ICE	Internal Combustion Engine
ICE	Inventory of Carbon and Energy
IP	Interior Point
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JADE	Java Agent DEvelopment framework
LCA	Life Cycle Analysis / Assessment
LHV	Lower Heating Value
LP	Linear Programming
LV	Low Voltage
MAS	Multi-Agent System
MCB	Miniature Circuit Breaker
MCFC	Molten Carbonate Fuel Cells
MGCC	Micro-Grid Central Controller
MIP	Integer/Mixed Integer Programming
MTS	Message Transport System
NASA	National Aeronautics and Space Administration
NLP	Non-Linear Programming
NREL	National Renewable Energy Laboratory
NTUA	National Technical University of Athens
OP	Operational Period
PAFC	Phosphoric Acid Fuel Cells
PEMFC	Proton Exchange Membrane Fuel Cells
PEN	Positive-Electrolyte-Negative interconnect
PHEV	Plug-in Hybrid Electric Vehicles
PV	Photovoltaic
QP	Quadratic Programming
RPD	Reference Price Data
SCADA	Supervisory Control And Data Acquisition
SOFC	Solid Oxide Fuel Cells

T&D	Transmission and distribution
TP	Trading Period
TSO	Transmission System Operator
TVPP	Technical Virtual Power Plant
UKERC	United Kingdom Energy Research Centre
UML	Unified Modelling Language
V2G	Vehicle to Grid
VAWT	Vertical Axis Wind Turbines
VPP	Virtual Power Plant
VPS	Virtual Power Station

LIST OF SYMBOLS AND UNITS

a, b and c	Constants
B	Discrete set $\{z_1, z_2, \ldots, z_n\}$, resulting from defuzzification
C	Constraints
C_{eq}	Equality constraint function
CH_4	Methane
CO_2	Carbon Dioxide
CO_2-e	Carbon Dioxide equivalent
D	Daily randomisation (for the whole day). It is a random number.
$D(P_{t+1})$	Binary variable, equal to 0 if at time step (t+1) the generator will still be on, and 1 if it will shut down
d_{CG}	Defuzzified value
D_F	The factor by which fuel consumption increases at shut-down
dF	Frequency step
D_i	Demand at time-step *i*
D_P	Projected demand
E_C	Conventional (grid/boiler) emissions
E_{el}	Electrical energy generated (kWh_e)
EF	Emission factor of the conversion technology (gCO_2/kWh)
E_f	Energy content of fuel (kWh/L or m^3)
EF_{Fuel}	Fuel emission factor in gCO_2 per kWh of energy content
$EF_i(P_i)$	Resulting emission factor at power P for generator i

$EF_{i,FL}$	Emission factor at full load
$EF_{i,t}$	Emission factor of micro-generator i at time-step t
E_M	Micro-generation emissions
E_P	Stored energy projection for the next time step
E_S	Emission savings
E_T	Target storage level, defined by the micro-generator strategy
F	Fuel consumption measurement (L or m^3)
$F_C(P_{\%})$	Cost function
$F_{Ci}(P_{\%i})$	Cost function of generator i
$F_{GRID,t}(P_{GRID,t})$	Emissions from the grid, at time-step t
$F_i(P_i)$	Resulting emissions for generator i
$F_{i,t}(P_{i,t})$	Emissions of generator i, at time-step t
gCO_2/kWh	Grams of Carbon Dioxide per kilowatt-hour
G_{MAX}	Maximum generation limit coefficient
G_{MIN}	Minimum generation limit coefficient
G_R	Generator rated energy (rated power * time step duration)
H	H is the heat recovered (kWh_{th})
$H^{GEN}_{i,t}$	Heat generated by micro-generator i at time-step t
$H^{LOAD}_{i,t}$	Heat consumed by the owner of the micro-generator i at time-step t
HR	Heat rate (kJ/kWh)
I	Insecurity factor
I_G	Generation insecurity factor
I_S	Storage insecurity factor
K	Gain factor
$kgCO_2/MWh$	Kilograms of Carbon Dioxide per megawatt-hour
km	kilometre
kWh_e	Kilowatt-hour electrical
L_C	Overall cost of N generators to be minimised
L_E	Total emissions
MJ/kg	Megajoule per kilogram
$MtCO_2e$	Megatonnes of Carbon Dioxide equivalent
N	Total number of generators
N_2O	Nitrous Oxide

$P_{\%}$	Output power, relative to the generator full power capacity
$P_{\%i}$	Output power of generator i, relative to its full power capacity
$P_{desired}$	Total power output set-point
P_i	Power of generator i in kW
$P_{i,t}$	Power of generator i at time-step t, in kW
P_{iMAX}	Upper power limit of generator i
P_{iMIN}	Lower power limit of generator i
$P_{INVdesired}$	Desired power output of the inverter
$P_{inverter}$	Inverter power output set-point
$P_{INVmeasured}$	Inverter current power output
P_{LOAD}	Total power demand
P_{PV}	Photovoltaic current power output
$P_{PVforecasted}$	Photovoltaic forecasted power output
$P_{setpoint}$	Total power output set-point
Q	Time-step randomisation (different for each data point). It is a random number.
R	Resistance
RF	Randomisation factor
S	Storage capacity
T	Total number of time-steps
tCO_2-e/yr	Tonnes of Carbon Dioxide equivalent per year
U	Unserveable demand
$U(P_{t-1})$	Binary variable, equal to 1 if at time step (t) the generator is starting up (i.e. at the previous time-step (t-1) the generator was off) and 0 if at (t-1) it was on
U_F	The factor by which fuel consumption increases at start-up
X	Reactance
z_k	Discrete values of set B
z_{MAX}	The value in set B corresponding to the maximum B(z).
η	Conversion efficiency
η_{HR}	Heat recovery efficiency (%)
$\eta_i(P_i)$	Part-load efficiency curve
λ	Lagrange multiplier

CHAPTER 1
INTRODUCTION

1.1. KEY QUESTION

The key question this thesis aims to address is to what extent can micro-generation sources contribute to the carbon emission reduction targets set by the UK government.

To answer this question, the following objectives were set:

- Evaluate the potential of micro-generation sources in saving domestic carbon emissions.
- Assess the benefit of controlling aggregated micro-generators and optimising their emissions.
- Design and develop an agent-based control system for controlling aggregated micro-generator emissions.
- Experimentally test the developed control system.

1.2. POWER SYSTEM CARBON EMISSIONS

1.2.1. Definition of emissions

In this thesis, the term “emissions” is used to describe the Greenhouse Gases (GHG) released into the atmosphere by various processes, mostly related to the combustion of fuel. The expression “carbon emissions” is also used, since the principal greenhouse gas is carbon dioxide (CO_2).

Carbon dioxide is not the only gas that contributes to climate change. A range of gases are classified as Greenhouse Gases, and they are assessed according to their global warming potential [1]. This is measured against the global warming potential of carbon dioxide, and is referred to as CO_2 equivalence. The unit that is used in this thesis is the carbon dioxide equivalent (CO_2-e) and the potential of each gas is converted to this unit by using a CO_2 equivalence factor. The most important greenhouse gases are considered to be methane (CH_4) and nitrous oxide (N_2O). Their CO_2 equivalence factor is 21 and 310 respectively, according to the IPCC [1].

1.2.2. UK emissions targets

The UK Government with the Climate Change Act in 2008 has committed to a greenhouse gas emissions reduction of 34% by 2020 and 80% by 2050, with respect to the 1990 levels [2].

In order to split the targets in shorter periods, a carbon budgeting system was put in place, setting a cap on the emissions for near-future 5-year periods. The carbon budgets are shown in Table 1.I:

TABLE 1.I: CARBON BUDGETS [2]

	Budget 1 (2008-12)	Budget 2 (2013–17)	Budget 3 (2018–22)
Carbon budgets ($MtCO_2e$)	3018	2782	2544
Percentage reduction below 1990 levels (%)	22	28	34

The power sector is a large contributor of the carbon emissions. Therefore, a series of measures are being implemented, such as the Carbon Emissions Reduction Target (CERT). This requires energy suppliers to reduce the amount of carbon emissions associated with households, by promoting low carbon solutions [2].

1.2.3. The future UK energy mix

Stricter targets were set regarding the power sector, as shown in the Extended Ambition scenario in [3]. The power sector emissions are expected to be reduced by 53% by 2020 and the target for the grid carbon intensity is to reach roughly 300 gCO_2/kWh from approximately 544 gCO_2/kWh in 2008 [3].

This will be done by changing the energy mix. Retirement of coal plants is planned, as well as investment in renewable, nuclear and Carbon Capture and Storage (CCS) technologies.

Table 1.II shows the power sector targets for meeting the carbon budgets, as presented in [3]. According to projections in [4], depending on the scenario that will be followed, the future energy mix will be dominated by nuclear plants, coal plants with CCS and wind generation. In most cases, it is projected that in the near future the coal-fired power plants will be replaced by CCS-enabled plants. Gradually, nuclear plants will take over and dominate the energy system. Only in the most ambitious

scenario the power system is projected to include wind power to more than one third of the overall capacity by 2050 [4].

TABLE 1.II: POWER SECTOR EMISSIONS REDUCTION TARGETS [3]

	Budget 1 (2008-12)	Budget 2 (2013–17)	Budget 3 (2018–22)
Emissions intensity (g/kWh)	509	390	236
Total emissions (% change from 2007)	-15%	-39%	-64%
Wind Generation (TWh)	21	50	98
Nuclear Generation (TWh)	58	30	48
CCS Generation (TWh)	0	5	11

1.2.4. EU Emissions Trading Scheme

The EU Emissions Trading Scheme (ETS) is designed with the prospect of reducing the overall carbon emissions from a set of organizations. For energy generators this translates to facilities with installed thermal input capacity over 20MW, regardless of their conversion efficiency [5]. It is expected to deliver savings of approximately 40 $MtCO_2$ by 2020 [4].

The operational principle of this scheme is based on the “cap and trade” concept. A cap is placed on the total emissions of an organization, e.g. 90%. The organization is then responsible for reducing its emissions by the remaining 10%. However, not all organizations can reduce their emissions by that amount, or at least not with a reasonable cost.

The amount of allowed emissions is split into allowance units, called Carbon Credits. In the EU trading system, one Carbon Credit represents 1 tonne of CO_2 emissions [5]. The allowances can be traded freely, either through a specially established market, or bilaterally. With this provision, some organizations may find it more cost-effective to buy allowances for the additional emissions, than to pay a significantly higher cost of emission reduction.

In any case, these allowances have to be sourced from another organization, which will need to reduce its emissions further, to meet its remaining allowances. The benefit comes from the fact that it may cost the second organization less to reduce its emissions, than the first one. More significantly, one organization may not be able to reduce its emissions at all. The ETS would allow these organizations to delegate their emissions reduction to other scheme participants, but pay for it by buying their allowances.

Overall, this system allows the regulator to directly control the total emissions from the set of organizations that participate in the scheme. This is done by means of varying the total allowances (Carbon Credits) that are fed into the system.

1.3. THESIS STRUCTURE

Chapter 2: This chapter is a review of the literature. It presents the background and state of the art for the studies presented in the following chapters. An overview is given regarding (i) the micro-generation technologies, (ii) their emissions, (iii) methods for optimising generator schedules, (iv) aggregation concepts, (v) intelligent agents and (vi) electric vehicles.

Chapter 3: In this chapter, the greenhouse gas emissions of micro-generators were investigated. A distinction is made between (i) operational emissions and (ii) life-cycle emissions. Study cases were defined for each of them. The operational emissions of selected micro-generation sources were calculated with two tools and one manual calculation method. The life-cycle emissions of selected micro-generation sources were also calculated, using two sets of tools. Operational and life-cycle emission factors were derived for the micro-generators. Electric Vehicle life-cycle emissions were also calculated.

Chapter 4: In this chapter, a method is described for optimising the emissions of aggregated micro-generation sources. A study case was drawn, comprising micro-generators aggregated in a Virtual Power Plant. The emissions from the VPP under study were calculated and optimised. The emissions savings attained by the VPP operation were calculated. Further emissions benefits by optimising micro-generator schedules were evaluated. Emission factors were calculated for (i) the electricity and heat supplied to the customers in the studied VPP, and (ii) the Electric Vehicles that charge their batteries with this electricity mix.

Chapter 5: In this chapter, the concept of the Environmental Virtual Power Plant (EVPP) is described. A multi-agent system was designed, for the control of

EVPP emissions. The operation of the EVPP simulates an emission trading scheme. A study case was built and simulations were performed. The benefits of the EVPP were described. An evaluation was performed on whether the micro-generator emissions can be consistently controlled.

Chapter 6: The multi-agent system built in Chapter 5 has been tested experimentally. This chapter presents the experimental procedure and results. Four micro-generators installed in two laboratories in Greece were used. The agents were modified and adapted to these sources. Two experiments were conducted. The first one included only the four aforementioned sources, while the second one also included additional simulated sources. The controllability of the multi-agent system was evaluated. Composite EVPP characteristics were measured. Finally, the change in EVPP controllability was evaluated, when increasing the number of micro-generators.

Chapter 7: This chapter presents the main conclusions of this thesis, regarding: (i) carbon emissions (ii) optimisation of Virtual Power Plant emissions and (iii) control of Environmental Virtual Power Plant emissions. Suggestions for further work on the subject of this thesis are given.

CHAPTER 2

BACKGROUND AND STATE OF THE ART

2.1. MICRO-GENERATION TECHNOLOGIES

Micro-generation technologies, including micro-CHP (Combined Heat and Power), are a range of technologies that present benefits for emission reduction from households [6]. It is projected that 18% of UK electricity could be provided by micro-generation without significant power system modifications [7]. As micro-generation is the prime focus of this thesis, the most prominent micro-generation technologies are described in detail in the next sections.

The micro-generation technologies that will be studied in this thesis are the following:

- Wind turbines,
- Photovoltaics,
- Fuel cells,
- Microturbines,
- Stirling engines and
- Diesel engines.

Apart from the wind turbines and the photovoltaics, the micro-generators were considered to be capable of Combined Heat and Power (CHP) operation, as described below.

2.1.1. Distributed Generation (DG) classification

According to [8], distributed generation sources are normally connected to the distribution network, usually having a power rating of less than 50 MW. Distributed generation sources are otherwise referred to as Dispersed Generation (DG), Embedded Generation (EG), or Distributed Energy Resources (DER). The term DER is more general and may also be used to characterise other resources such as energy storage systems.

There is no consistent approach in the literature regarding the power rating of Distributed Generation. In [9], micro-generation is defined as distributed generation with rated electrical output up to 5 kW. The classification of distributed energy resources as suggested in [9] is presented in Table 2.I:

TABLE 2.I: DISTRIBUTED GENERATION CLASSIFICATION [9]

Characterisation	Power from	Power up to
Micro	1 Watt	5 kW
Small	5 kW	5 MW
Medium	5 MW	50 MW
Large	50 MW	300 MW

2.1.2. Micro-CHP

A range of micro-generation technologies are also capable of operating as Combined Heat and Power units, or otherwise referred to as micro-CHP. A micro-CHP unit recovers the waste heat from its power generation system, e.g. an internal combustion engine. It utilises this heat locally, reducing or avoiding other heat generation needs such as from a domestic boiler. Micro-CHP technologies, according to [10] and [11] include:

- Reciprocating Internal Combustion Engines (ICE),
- Microturbines,
- Fuel cells and
- Stirling engines.

The operation of micro-CHPs is usually heat-led, since the heat is normally utilised locally. Wide employment of these technologies is still a challenge. Field trials of micro-CHP operation are being performed throughout the EU [11].

Since micro-CHP recovers heat that would otherwise be wasted, the overall system efficiency is increased, as can be seen in Fig. 2.1. In this figure, a combustion engine micro-generator is assumed (e.g. Diesel engine). This leads to reduced fuel consumption, thus reduced emissions. The Carbon Trust reports that 5% - 10% reduction in emissions is possible [6], while other studies suggest a reduction of approximately 10% - 40% [12].

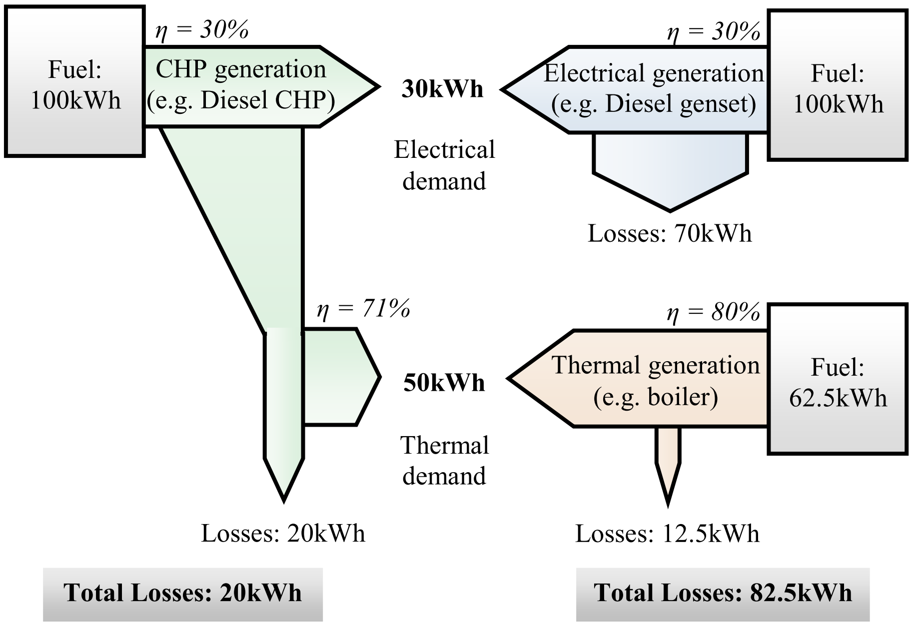

Fig. 2.1 Comparison of fuel efficiency (η) of CHP and conventional generation

In a micro-CHP system, one of the most important parameters to take into account is the Heat to Power Ratio (HPR) [13]:

$$HPR = \frac{\text{Heat Generation (kWh)}}{\text{Electricity Generation (kWh)}} \quad (1)$$

It is important to identify the HPR of the micro-generator, as well as the thermal demand, so that both the electrical and thermal demand can be met. The HPR is not constant, as it depends on the micro-generator heat recovery efficiency. It varies with generator loading [13]. Typical HPRs and average electrical efficiencies for micro-generators are presented in Table 2.II:

TABLE 2.II: HPR AND ELECTRICAL EFFICIENCY OF DIFFERENT MICRO-CHP TECHNOLOGIES [6][13][14][15][16]

Technology	Heat to Power Ratio (HPR)	Electrical efficiency (%)
Fuel Cell	1.4	40.4
Diesel Engine	1.6	37.5
Microturbine	2.6	25.9
Stirling Engine	5-10	13.2

2.1.3. Wind turbines

Wind turbines can be characterised as horizontal axis wind turbines (HAWT), or vertical axis wind turbines (VAWT), depending on the rotor orientation [17]. The most common type of wind turbines is the horizontal axis, mostly due to their higher conversion efficiency [17][18].

Domestic wind turbines have also emerged as a micro-generation technology, in the kW scale [18][19]. They can be mounted on the roof of the residence or on their own mast [18]. The output is normally DC power, which may be converted to AC by an inverter to be fed to the grid. They usually generate electricity at wind speeds in the range of 3-15m/s [7]. The hub height of domestic wind turbines is relatively low, aggravating the effect of significant obstacles, such as surrounding houses. This reduces the wind speed and makes the flow more turbulent [17]. Therefore, their actual output compared to the rated power is less than in large, industrial scale wind turbines.

The realistic scenario in [20] projects a potential generation of 1.34 TWh/yr from domestic wind turbines in 2050.

2.1.4. Photovoltaics

Solar photovoltaic technology is one of the most expensive established types of renewable generators. In the last few years the prices began to drop, mostly due to economies of scale and improved manufacturing methods [21]. Thus, they are becoming more attractive for homeowners. They are better suited for small applications, because of the small size of the solar elements and the large area to power ratio. Photovoltaic panels generate electricity in DC, which is converted to AC by an inverter.

It is projected in the most reasonably ambitious scenario in [20] that generation from domestic photovoltaic installations could reach 60 TWh/yr in 2050. This would require roughly 70 GWp installed power, or about $4m^2$ per person in the UK [20].

2.1.5. Fuel Cells

Fuel cells are in the early stages of commercialisation, despite not being a new technology. They are not widely used yet, mostly due to the exotic materials used in their construction, which increases their production cost. Their operating principle is similar to electrical batteries, since they are both based on electrochemical principles. Several types of fuel cells can be found in the literature, such as [22]:

- Proton Exchange Membrane Fuel Cells (PEMFC),
- Alkaline Electrolyte Fuel Cells (AEFC),
- Direct Methanol Fuel Cells (DMFC),
- Phosphoric Acid Fuel Cells (PAFC),
- Molten Carbonate Fuel Cells (MCFC) and
- Solid Oxide Fuel Cells (SOFC).

The PAFC, MCFC and SOFC fall in the category of medium or high temperature fuel cells, because their operational temperature is in the scale of 1000°C [22]. Their conversion efficiency is quite high, sometimes reaching up to 50% [22]. The most common type for small scale applications is the PEMFC, mostly due to its low temperature. Some SOFC products are also in the market both for small and medium scale applications [23]. Most of the fuel cell technologies operate much more efficiently when fuelled by pure hydrogen (H_2). If pure H_2 is not available, a reformer is necessary, extracting the hydrogen from other fuels, such as natural gas [22].

Their high efficiency has the consequence of low waste heat output, thus a low heat to power ratio, as can be seen in Table 2.II. For this reason, high temperature fuel cells are better suited for micro-CHP applications. The electrical output of fuel cells is DC power, which is converted to AC by an inverter.

It is suggested in [20] that anywhere from 16 to 90% of the total UK built environment heat demand in 2050 could be supplied by fuel cells.

2.1.6. Microturbines

Microturbines are small gas turbines. They range normally from 25kW to 250kW, but some smaller applications exist (1-10kW) in the domestic sector [10][11]. They are characterised by lower electrical efficiency than internal combustion engines or fuel cells, especially in part-loading conditions [11]. Their lower efficiency and high temperature of the exhaust gases makes them suitable for micro-CHP operation, since they have high heat output [10].

Low vibration levels are observed during their operation. The range of fuels that can be used with microturbines is wide, ranging from the most common natural gas to diesel, biofuels and other gases [10][11].

2.1.7. Stirling engines

Stirling engines are external combustion engines. They differ from internal combustion engines (ICE) because the combustion of the fuel is done outside the cylinder [6]. Similar to a boiler, heat is transferred from the combustion to the water of the heating system. However, during this transfer, a piston linked with a generator is displaced, thus producing electricity.

Their electrical efficiency is usually low (5-25%), which translates to high levels of heat output for limited electrical production [6][16]. This makes them suitable mostly for micro-CHP operation. The most common fuel is natural gas, but they can utilise many types of fuels [6].

Stirling engines can be seen as a replacement for a domestic boiler [6]. It is suggested in [20] that 10-24% of the total UK built environment heat demand in 2050 could be supplied by Stirling engines.

2.1.8. Diesel engines

Diesel Internal Combustion Engines (ICE) are an established technology. They are characterised by high reliability and long life. ICE micro-CHP units are commercially available and the most mature among the micro-CHP technologies [6]. High levels of noise and vibrations make them inappropriate for domestic installations inside the residence. They need to be installed in a separate space. They may be better suited for supplying more than one residence [6].

Their electrical efficiency is higher than the Stirling engines, but not as much as the fuel cells. Large domestic applications are expected to comprise only 2.6% of the 2050 micro-generation capacity [7].

2.2. SIGNIFICANT LOADS IN THE FUTURE POWER SYSTEM

2.2.1. Electric Vehicles

Electric Vehicles (EV) are not considered as sources (Vehicle to Grid – V2G) in this thesis, but only as additional load. The future EV emissions performance is studied in Chapters 3 and 4. This section describes the future trends of EVs.

Electric Vehicles (EV) have been identified as a potential solution towards the decarbonisation of the transport sector. Field trials are already taking place and studies are being performed, to estimate uptake levels and possible impacts [24][25]. An estimate of three possible EV household penetration levels in 2030 is presented in Table 2.III [26]. Two types of EV were considered, Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV).

TABLE 2.III: ELECTRIC VEHICLES PENETRATION PROJECTIONS FOR 2030 [26]

Level	Penetration per household
Low	12.5%
Medium	33%
High	70%

Studies examine the integration of electric vehicles to the power system and exploitation of their capabilities for improving power system operation [27]. It has been found that the introduction of EVs in low voltage distribution systems may have adverse effects on transformers and may cause cable thermal limits violation [26]. Depending on the uptake levels and charging regimes, it is predicted that significant increase in peak demand will take place [28]. However, part of the impacts would be offset if EVs are combined with micro-generation [29].

2.2.2. Heat Pumps

Heat pumps can be described as reverse fridges, in the sense that they transfer heat from the outside of the home to the inside, through heat exchangers. Thus, they can supply thermal energy 3 or 4 times greater than the electrical energy they consume, which makes them more efficient than resistive heaters [20]. Heat pumps can be described as Ground Source Heat Pumps (GSHP) and Air Source Heat Pumps (ASHP), depending on the source of the heat that is transferred into the home [20]. GSHPs are expected to supply roughly 20-30% of the total UK built environment heat demand in 2050 [20]. The respective range for ASHP is 14-60% [20].

Heat pumps are not taken into account in the studies in this thesis. They would not affect the results significantly, because they are not micro-generators. However, considering a penetration of heat pumps may slightly reduce the emissions savings recorded in Chapter 4. This would be due to the increase of the total load considered, reducing the share of the load that is covered by micro-generators.

2.3. CARBON EMISSIONS

In order to evaluate the micro-generation potential to contribute to the emissions reduction targets, the emissions of micro-generators need to be determined. Two types of emissions are defined in the following sections: (i) the operational and (ii) the life-cycle emissions.

2.3.1. Operational emissions

The operational emissions of a micro-generation system are the carbon dioxide (CO_2) emissions incurred by this system during its operation. The emissions source is normally the combustion of fuels, whether they are fossil fuels or biofuels. The measure of CO_2 emissions is generally expressed as an emission factor, in terms of mass of CO_2 per unit of energy generated, such as the kilowatt-hour (kWh). Usually, the units are in the scale of gCO_2/kWh, or $kgCO_2$/MWh.

Operational emission factors for the different micro-generation technologies considered in this thesis are presented in Table 2.IV. The operational emission factors of wind turbines and photovoltaics are not considered, since they do not produce any direct carbon emissions during their operation. The emission factors are presented in gCO_2 per electrical kWh, except for the last column. This expresses the overall CHP emission factor, in gCO_2 per kWh produced, either electrical or thermal.

TABLE 2.IV: OPERATIONAL EMISSION FACTORS OF DIFFERENT MICRO-CHP TECHNOLOGIES

Micro-generation type	CO_2 emissions (gCO_2/kWh_e) - [Reference]					Average (gCO_2/kWh)	
	[6]	[13]	[14]	[15]	[16]	Electrical	CHP
Fuel Cell	-	477	460	499	460	474.0	197.5 [1]
Microturbine	-	725	724	703	720	718.0	199.4 [1]
Diesel ICE	-	695	650	680	650	668.8	257.2 [1]
Stirling Engine	2448 [2]	-	-	-	915 [2]	1681.6 [2]	199.3 [2]

[1] calculated using HPR values in Table 2.II
[2] calculated from data in the literature

The emission factors can be calculated in a straightforward way as follows, given the emission factor of the fuel and the efficiency of the conversion technology [30]:

$$EF = \frac{EF_{Fuel}}{\eta} \quad (2)$$

where: EF is the emission factor of the conversion technology (gCO_2/kWh),
EF_{Fuel} is the fuel emission factor in gCO_2 per kWh of energy content,
η is the conversion efficiency.

The fact that the emission factor is linked with conversion efficiency can be observed in the last column of Table 2.IV. Although the electrical efficiency of different micro-generators varies from 5% to 50%, their CHP efficiency is relatively similar, approaching 90%. Thus, the fuel cell, microturbine and Stirling engine, which are all assumed to consume natural gas, have very similar CHP emission factors.

The emission factors in Table 2.IV are for fossil fuels. That is, natural gas for the fuel cells, microturbines and Stirling engines, and diesel fuel for the Diesel engines. Biomass fuels can also be used. However, the Carbon Cycle theory [31] states that the biomass fuel CO_2 emissions would be absorbed by the next generation of biomass producing plants. Consequently, even though biofuels emit CO_2 when they are combusted, this is considered as neutralized or offset. Greenhouse gases other than CO_2 are not considered to be offset by the Carbon Cycle, since they are not absorbed by plants [31].

2.3.2. Life-cycle emissions

The total environmental impact of a product or process can be evaluated using a Life Cycle Analysis methodology, otherwise referred to as Life Cycle Assessment. Externalities that are not directly related to the source of the impact are included in a LCA. Life-cycle emissions are calculated as part of a full LCA process.

According to ISO 14040 [32], the Life Cycle Analysis methodology contains four components, as can be seen in Fig. 2.2 [32]. The ISO 14040 standard also introduces the concept of the functional unit. This is described as the measure by which to assess the impact of the studied subject. The most relevant contemporary choice of a functional unit for the environmental impact of micro-generators would be the carbon dioxide equivalent (CO_2-e) emissions. It serves as a measure of the greenhouse gas emissions contribution of the micro-generator. The expression "carbon footprint" is widely used to describe the overall life-cycle CO_2-e emissions of a product or process.

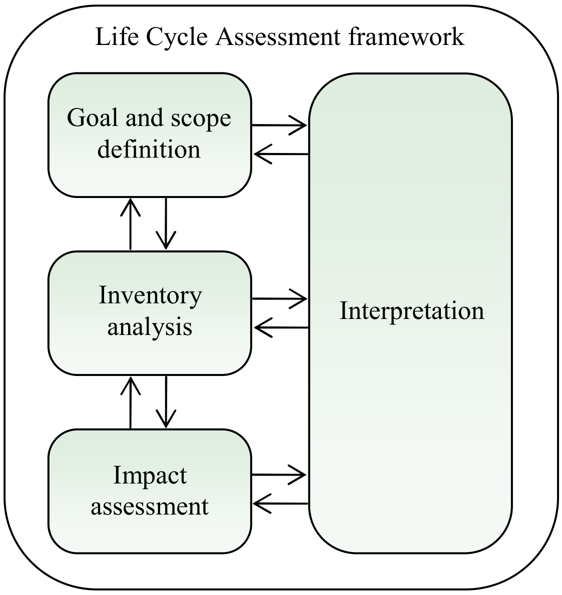

Fig. 2.2 The stages of Life Cycle Analysis according to ISO 14040.

It has been shown by previous studies that renewable technologies are not completely free of carbon emissions, when evaluating the whole life-cycle of the equipment [33]. The manufacturing of equipment such as a photovoltaic module or the electrodes of the fuel cells [23] is energy intensive, and part of this energy is normally drawn from the electricity network. Thus, the carbon efficiency of the manufacturing process depends partly on the energy mix of the network that supplies the manufacturing plant.

During a life-cycle analysis, the micro-generator is analysed into components, up to the level of primary energy and raw materials. The amount of energy consumed and the amount of carbon emitted for manufacturing a unit (e.g. kg) of each material is determined by going through the process chain. The sum of this energy and carbon is called embodied energy and embodied carbon respectively [34]. In micro-generators that use processed fuels as their source of energy, the production process of the fuel (e.g. refinery) is accounted for as well [35].

The life-cycle carbon footprint can be expressed either in terms of total CO_2-e emissions, or per unit of energy produced (kWh). For the latter, it is necessary to evaluate the overall energy production of the micro-generator during its operational lifetime, and divide the total emissions with this value [36].

2.3.3. Electric Vehicle emissions

Electric Vehicles produce no direct emissions during their operation. The level of emissions they emit is linked to the source of their electrical charge. Table 2.V presents estimated EV emissions rates (gCO_2/km) for different electricity sources [25]. The life-cycle emissions associated with the vehicle manufacturing may also be taken into account. Table 2.VI presents the calculated life-cycle emissions and emission factor, taken from [24].

TABLE 2.V: ELECTRIC VEHICLES EMISSION FACTORS [25]

Electricity source	Average electricity carbon intensity (gCO_2/kWh)	BEV emissions (gCO_2/km)	PHEV emissions (gCO_2/km)
Current EU-15 mix	389	60	85
Current UK grid mix	450	77	109
Future UK low-carbon mix	176	30	85

TABLE 2.VI: PROJECTED LIFE-CYCLE EMISSIONS FOR VEHICLES IN 2030 [24]

Vehicle type	Emission factor well to wheel (gCO_2-e/km)	Life-cycle vehicle carbon use ($kgCO_2$-e)
Electric Vehicle	47	8,514
Conventional (Petrol)	120	21,639
Conventional (Diesel)	109	19,606

2.4. OPTIMISATION OF GENERATOR SCHEDULES

In Chapter 4, the emissions of a cluster of micro-generators are evaluated. An optimisation technique is applied, to optimise their emissions output. Optimisation techniques have traditionally been used for optimising the schedules of large generators. The following sections present established optimisation techniques, and how they are applied in power system operation.

2.4.1. Optimising a function

Optimisation can be defined as a method of minimising or maximising the output of a given objective function within predefined constraints [37]. The true optimal point of a function is called a global optimum. In many cases, though, local optimal points exist, in the form of local peaks or troughs in the search space of the variables. An optimisation algorithm can be trapped in such a local optimum and present it as an optimisation result.

The constraints in an optimisation problem can be either equality or inequality constraints [38]. Equality constraints dictate that a given function, containing at least one variable from the objective function, must be equal to a given value. Respectively, inequality constraints state that the result of a given function must always be lower (<), or higher (>), than a given value.

2.4.2. Optimisation techniques

Two broad categories of optimisation techniques stand out [37]:

(i) The numerical/mathematical methods and
(ii) The Artificial Intelligence (AI) methods.

Most of the numerical methods are based on the gradient (rate of change) of the function, to find the direction of optimality. Numerical algorithms can estimate the gradient by probing the function variables. Numerical methods are generally prone to be trapped in local optima [37]. Careful problem formulation is necessary to avoid such a drawback. Numerical methods include [37]:

- Linear Programming (LP),
- Interior Point (IP),
- Quadratic Programming (QP),
- Non-Linear Programming (NLP),
- Integer/Mixed Integer Programming (MIP) and
- Dynamic Programming (DP).

Artificial Intelligence techniques are powerful techniques suitable for large-scale problems, due to their ability to find the global optimum. Power system problems are generally large-scale problems [37]. AI techniques include [37]:

- Evolutionary Computation,
- Genetic Algorithms and
- Ant Colony Search.

2.4.3. Unit commitment and economic dispatch

A unit commitment / economic dispatch problem can be defined as an optimisation problem. The aim is to find the generation mix that can cover a given energy demand over a period of time with the minimal cost [38].

- **Generator cost curves**

When solving such a problem, the part-load cost curve of the generators is required. This is used to calculate the cost of running a generator at a fraction of its rated capacity. Thus, an optimisation algorithm can choose which generator is economically preferable to be part-loaded when its full capacity is not required. Typically, this cost curve is a quadratic equation of the relative output power, but this depends on the type of generator and requested accuracy [38]:

$$F_C(P_{\%}) = a \cdot P_{\%}^{\ 2} + b \cdot P_{\%} + c \qquad (3)$$

where $F_C(P_{\%})$ is the cost function.
$P_{\%}$ is the output power, relative to the generator full power capacity.
a, b and *c* are constants.

- **Objective function**

Economic optimisation is usually solved using numerical methods, such as Linear or Non-Linear Programming. The objective function is normally described as a sum of the cost curves of all the generators. The output power of the generators is the variable that is probed by the optimisation algorithm.

$$L_C = \sum_{i=1}^{N} F_{Ci}(P_{\%i}) \quad (4)$$

where L_C is the overall cost of N generators to be minimised.

$F_{Ci}(P_{\%i})$ is the cost function of generator i.

$P_{\%i}$ is the output power of generator i, relative to its full power capacity.

- **Generator operational limits constraint**

The generator operational constraints, such as minimum and maximum power output, can be expressed as inequality constraints:

$$C_{ineq} \Rightarrow P_{i\,MIN} \leq P_{\%i} \leq P_{i\,MAX} \quad (5)$$

where $P_{\%i}$ is the output power of generator i, relative to its full power capacity.

P_{iMIN} is the lower power limit of generator i.

P_{iMAX} is the upper power limit of generator i.

- **Constraint of covering the demand**

Additionally, the total output of the generators has to meet the demand. This would be expressed as an equality constraint. The equality constraint is that the sum of the generators must equal the total load. Therefore:

$$C_{eq} \Rightarrow \sum_{i=1}^{N} \left(P_{\%i} \cdot P_{Ri}\right) = P_{LOAD} \quad (6)$$

where C_{eq} is the constraint function.

$P_{\%i}$ is the output power of generator i, relative to its full power capacity.

P_{Ri} is the rated power (full power capacity) of generator i.

P_{LOAD} is the total power demand.

- **Lagrange objective function**

The constraints (C) are inserted in the objective function by means of a Lagrange multiplier (λ), giving the final function to be optimised for N generators, where L_C is the final cost [38]. It is referred to as the Lagrange function [38]:

$$L_C = \sum_{i=1}^{N} F_{Ci}(P_{\%i}) + \lambda \cdot C \qquad (7)$$

The above procedure is being performed at every time step (T) of the power system operation, since the load is variable throughout the day. Large generation plants, though, need to know in advance the load that is expected to be met over the next few hours. The optimal daily generation profiles should be provided. This leads to a multi time period optimisation and is expressed as unit commitment and economic dispatch [38]. The objective function then becomes:

$$L_C = \sum_{t=1}^{T} \left(\sum_{i=1}^{N} F_{C(i,t)}(P_{\%(i,t)}) \right) + \lambda \cdot C \qquad (8)$$

2.4.4. Environmental dispatch

Environmental dispatch can be defined as a method to reduce environmental impacts of committed generators by arranging their schedule [39]. Instead of reducing the operational cost, like economic dispatch, environmental dispatch aims to reduce environmental indicators, most commonly greenhouse gas emissions.

The techniques normally utilised take into account both environmental and economic dispatch, since reducing the cost is usually prioritised over reducing emissions. Multi-objective algorithms are found in the literature, which perform such tasks [39][40]. The simplest way of performing environmental/economic dispatch would be to assign a cost factor to the emissions and then optimise only the cost.

2.5. MICRO-GENERATION AGGREGATION

The rating of micro-generation sources is too small for them to actively participate in power system related markets on their own. Consequently, they are excluded from electricity markets and the emissions trading scheme.

Technical issues are expected to arise in the distribution network as micro-generation penetration increases [7]. It has been suggested that aggregation of distributed resources would reduce their technical impacts and enhance their commercial potential [41]. Research projects investigating resource aggregation include the FENIX project [42], the Microgrids and More Microgrids projects [43],[44] and the EU-DEEP project [45].

An aggregation system is encapsulating its resources, controlling them in such a way as to meet targets defined by a given control strategy. This strategy may be driven by market price, carbon emissions, or other factors.

Two concepts are most prominent in the literature [46]:

(i) Micro-grids and

(ii) Virtual Power Plants (VPP).

Both concepts are studied in this thesis, for aggregating micro-generation sources. The VPP concept is extended in Chapter 5. A control system for a VPP is designed in Chapter 5 and tested experimentally in Chapter 6. The two concepts are described in the following sections.

2.5.1. Micro-grids

Micro-grids can be regarded as individual controllable regions in a low voltage distribution network [47]. A micro-grid is normally composed of local energy resources, including micro-generation, energy storage systems and controllable loads. A control system is normally set up, so that the resources aggregated under a micro-grid contribute to achieving the benefits of such a configuration [48].

The operation of micro-grids has been evaluated and demonstrated in a number of installations around the world [49]. A benchmark micro-grid has been described in [50], which can be used for modelling and simulation of micro-grids. Example micro-grids are illustrated in Fig. 2.3.

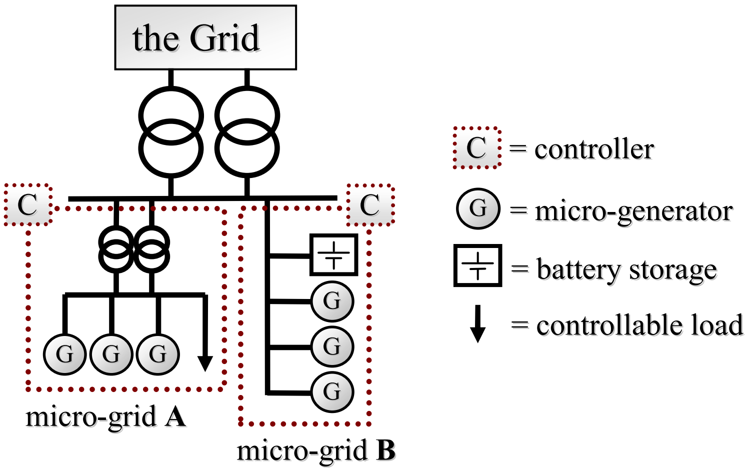

Fig. 2.3 Example micro-grids

Micro-grids provide benefits both to the customer and the utility. Part of the customer electricity and heat demand is covered, while the reliability of the local network is increased, along with an improvement of power quality [48]. By generating all or part of the customer electricity locally, the power flows and line losses in the distribution and transmission systems are reduced. Another benefit is the potential utilisation of waste heat from micro-generators to supply customer thermal demand, increasing overall fuel efficiency and reducing carbon emissions [48].

The micro-grids can be operated either interconnected to the grid or as an autonomous island system [48][49]. It is proposed that in cases of severe grid disturbance, the micro-grid can be disconnected and operate autonomously, sustaining customer energy supply [49].

There are significant technical issues associated with micro-grid operation [51] [52]. Compared with the transmission system, the ratio of resistance (R) to reactance (X) in the low voltage cables is higher. Thus, the effect of active power on voltage is comparable to that of reactive power, which means that voltage control cannot be decoupled from frequency control [48]. Additionally, micro-grid components with power electronic interfaces lack the inertia of rotating machines that is utilised for the stability of power systems [48].

The distributed nature of the resources in a micro-grid makes the use of distributed control a suitable option. Distributed intelligence techniques offer considerable potential for the control of micro-grid resources. Intelligent agents have been proposed in [53][54] for such control. Field trials using intelligent agents for distributed micro-grid control have proven their feasibility [44].

2.5.2. Virtual Power Plants

The concept of Virtual Power Plants (VPP) proposes a wider resource aggregation that extends beyond the limits of a local system, enabling the balancing of many Distributed Energy Resources (DER) [41][42]. A similar concept is the Virtual Power Station (VPS), presented in [55] and [56].

This significantly enhances the controllability of a DER cluster. It enables small resources to participate in power system operation and electricity markets that would otherwise be unreachable to them, due to their size. An ideal VPP would offer controllability equivalent to that of a conventional power plant [41]. A VPP incorporates several parameters of its resources, such as generator limits, generation profiles and ramp rates, to come up with a composite operational profile. This profile represents the aggregated capabilities of the VPP resources.

The Virtual Power Plant concept is shown schematically in Fig. 2.4.

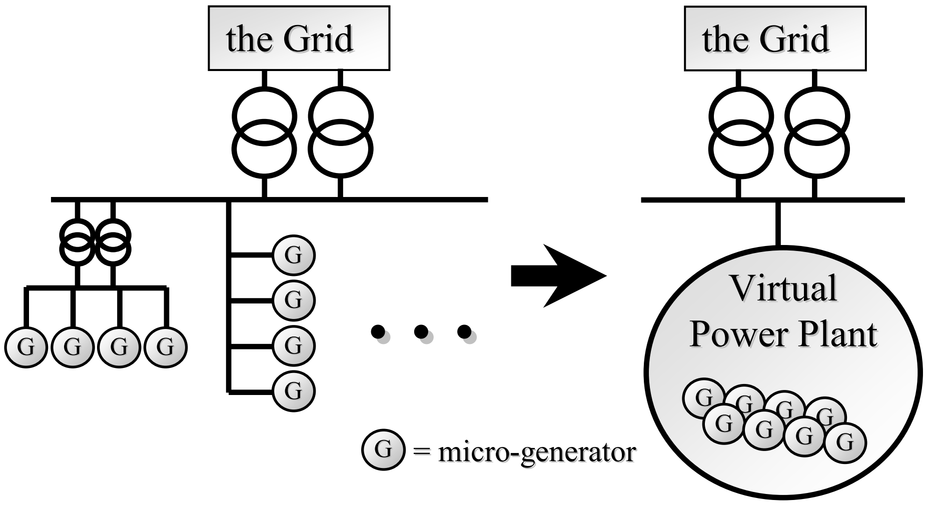

Fig. 2.4 The Virtual Power Plant

According to [41], two types of Virtual Power Plant are defined:

- the Commercial Virtual Power Plant (CVPP) and
- the Technical Virtual Power Plant (TVPP).

2.5.2.1. Commercial Virtual Power Plant (CVPP)

- Purpose: To optimise the revenue of the VPP, by managing DER portfolio in order to participate in the electricity markets.
- Target: Forward contracts and power exchange markets.

- Aggregates: DER operational characteristics to create a combined profile of the aggregated DER capacity.
- Locality: Normally not constrained to a specific geographical area, unless the nature of the markets create the need to do so (e.g. locational marginal pricing-based markets).

2.5.2.2. Technical Virtual Power Plant (TVPP)

- Purpose: To participate in distribution system operation by aggregating individual DER characteristics to come up with an aggregated operational profile.
- Target: To assist with network management and power system operation and/or provide ancillary services.
- Aggregates: Individual DER response characteristics, local network characteristics.
- Locality: It is restricted to the local network that forms the TVPP. The point of aggregation is the connection of the local network to the rest of the system.

2.5.3. Hierarchical Structure of a VPP

A hierarchical structure for the aggregation of DER has been discussed in the literature [41][44][57]. Such a structure is illustrated in Fig. 2.5.

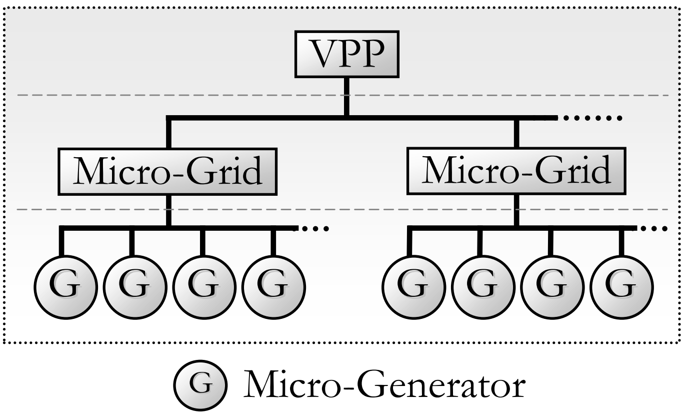

Fig. 2.5 Hierarchical structure of a Virtual Power Plant

This structure is composed of several micro-grids, forming a single controllable entity that can be characterised as a Virtual Power Plant. Different levels of aggregation are defined. The micro-generators are aggregated under micro-grids and the micro-grids are aggregated to form a Virtual Power Plant. Such a structure can be characterised as a distributed design, with all the associated benefits. Typical distributed system benefits include flexibility and adaptability [58][59].

2.6. INTELLIGENT AGENTS AND MULTI-AGENT SYSTEMS

Intelligent agents have been used traditionally in computer science as an extension of the object oriented programming concept [58]. According to [59], a Multi-Agent System (MAS) is defined "simply as a system comprising two or more agents or intelligent agents". The use of MAS as distributed control systems for micro-grids has been proposed [53][54]. The VPP control system that is designed in Chapter 5 is a Multi-Agent System, based on emissions trading. The following sections describe the concepts of intelligent agents and MAS, and their applications in power engineering.

2.6.1. Multi-agent systems in power engineering

According to [59] multi-agent systems should be considered for applications exhibiting one or more of the following characteristics:

1. Requirement for interaction between distinct conceptual entities.
2. Need for interaction of a very large number of entities.
3. Enough data and information available locally for analysis/decisions.
4. Need for new functionality to be implemented in existing systems.
5. Requirement for continuous functionality extension or addition.

Points 1-3 are based on the distributed nature of MAS, which enables interaction of numerous agents to reach a common goal without the need for centralised decision-making. Points 4 and 5 refer to the openness of MAS. In a distributed control system, generators can be connected or disconnected with minimal changes to the system (plug-and-play functionality) [53].

Four main fields of MAS application in power engineering have been identified in [59]:

1. Monitoring and diagnostics:
    - Condition monitoring and
    - Post-fault diagnosis of power system faults.

2. Distributed control,
3. Modelling and simulation and
4. Protection.

The fields that are being researched more actively were found to be the fields of Distributed Control and Modelling and Simulation [59]. In the latter, agents are utilised to create models of complex systems that cannot be analysed traditionally, or in cases where the dynamic behaviour of a system is studied.

The field of distributed control concerns the application of distributed systems to control multiple entities, such as generators. A centralised control system is replaced by local controllers, which have access to local data and information that cannot be processed by a centralised structure [53]. This provides solutions more balanced between individual controller and overall system goals. Prominent applications include active distribution networks operation, micro-grid control, energy management and Virtual Power Plants [53][57][59][60][61]. An illustration of such a VPP is shown in Fig. 2.6:

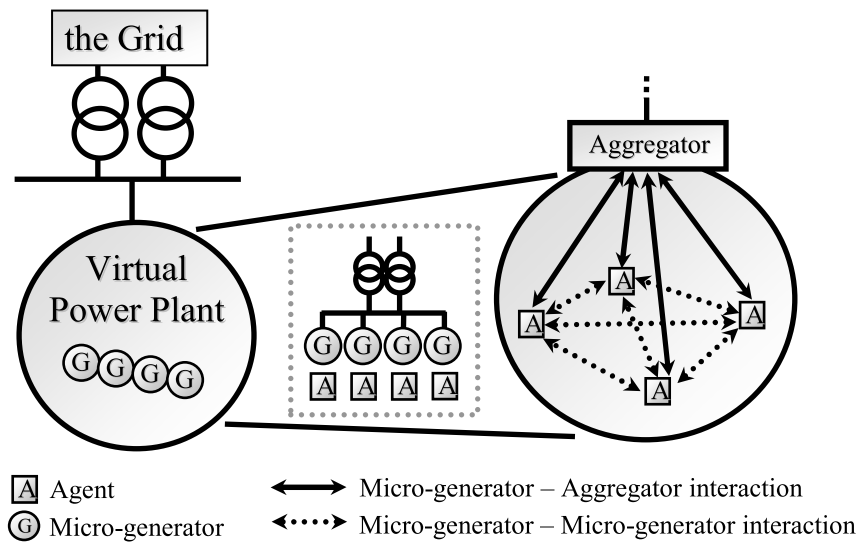

Fig. 2.6 Agent-based Virtual Power Plant

In a hierarchical approach such as the one presented in Fig. 2.5, a micro-grid agent would act as an aggregator for the micro-generators and a VPP agent would act as an aggregator for the micro-grids. Aggregation levels would be defined [57].

Such systems have been developed and field trials have been performed. Distinct examples are:

- The laboratory microgrid in the National Technical University of Athens (NTUA) [53], which is linked with the Microgrids and More Microgrids projects [43][44].
- The PowerMatcher, an agent-based system developed by the Energy research Center of the Netherlands (ECN) [60], linked with the FENIX project [42]. Field trials have also been performed [61].
- The laboratory micro-grid in Durham University [54][62].

2.6.2. Emissions trading with agents

In [63], the authors use the LV network from [50] and the micro-grid control structure presented in [53] to investigate the benefits of DER participation in emissions markets. A Micro-Grid Central Controller (MGCC) is considered as an entity which links DER with the market. The MGCC follows predefined policies, aiming at (i) cost minimisation, (ii) DER emissions minimisation and (iii) profit maximisation by participation of DER in emissions markets. Significant benefits from DER participation in emissions markets were found. However, a centralised decision-making methodology was used as the control mechanism, where the MGCC was controlling the DER directly.

In [64], a Distributed Energy Management System (DEMS) is proposed. Agents are assigned to generators and consumers, which aim at optimising their own economical profit. A market is set up and auction protocols are implemented. The CO_2 emissions are taken into account in the auction process, creating a multi-objective trading environment. A multi-agent system is created that resembles the operation of energy markets. Results show that the profits of each entity in the system are optimised, by trading energy based not only on the kWh price, but also the price of CO_2 emissions credits. Despite the fact that this system uses a market-based control methodology, the agents are not trading emissions credits. The main purpose of this system is the management of energy within a group of generators and consumers.

In Chapter 5, a market-based multi-agent system that simulates an emissions trading scheme was designed. The main difference from the system in [63] is that it is not based on a centralised architecture. The difference from the system in [64] is that it controls and manages the emissions, not the energy, and the agents are trading emissions credits between them.

2.6.3. Formal definition of intelligent agents

The concept of agency implies the property of autonomy. An agent would be able to act autonomously in its environment [58]. In order to implement autonomy, the agent developers often use Artificial Intelligence (AI) techniques. However, agent systems themselves can be considered as an AI technique [59]. According to [65], an intelligent agent is defined as a physical of virtual entity which possesses a set of qualities. These qualities are summed up in [58] as follows:

(i) **Reactivity:** "Intelligent agents are able to perceive their environment, and respond in a timely fashion to changes that occur in it in order to satisfy their design objectives."
(ii) **Proactiveness:** "Intelligent agents are able to exhibit goal-directed behaviour by taking the initiative in order to satisfy their design objectives."
(iii) **Social ability:** "Intelligent agents are capable of interacting with other agents (and possibly humans) in order to satisfy their design objectives."

In [65], the agents are characterised based on their representation of the environment as:

(i) **Cognitive:** "The agent has a symbolic and explicit representation of the world, on which it can reason."
(ii) **Reactive:** "Its representation is situated at a sub-symbolic level, that is, integrated into its sensory-motor capacities."

In [65], it is stated that a MAS needs to encompass an environment in which the agents can act, a set of objects on which the agents can act upon and an assembly of operations, which enable the agent's actions.

2.6.4. Standards for agent development

The Foundation for Intelligent Physical Agents (FIPA) has developed a series of standards and guidelines related to agent development [66][67][68].

The agents are communicating using messages. An agent communication language (FIPA-ACL) is described in [66], which is used by the agents to formulate the content of a message. Standard fields are defined in the message, such as the type of communicative act, or the message recipients [66].

An agent management structure is also defined, which is illustrated in Fig. 2.7 [67]. This structure is described as an Agent Platform (AP) and includes, apart from the agents:

- a Message Transport System (MTS),
- an Agent Management System (AMS) and
- (optionally) a Directory Facilitator (DF).

The AMS is responsible for keeping record of the agents, by means of special identifiers, the Agent IDs (AID). The DF can offer yellow pages services, by locating agents based on a given service that they can offer. The MTS is a communication method between two or more platforms.

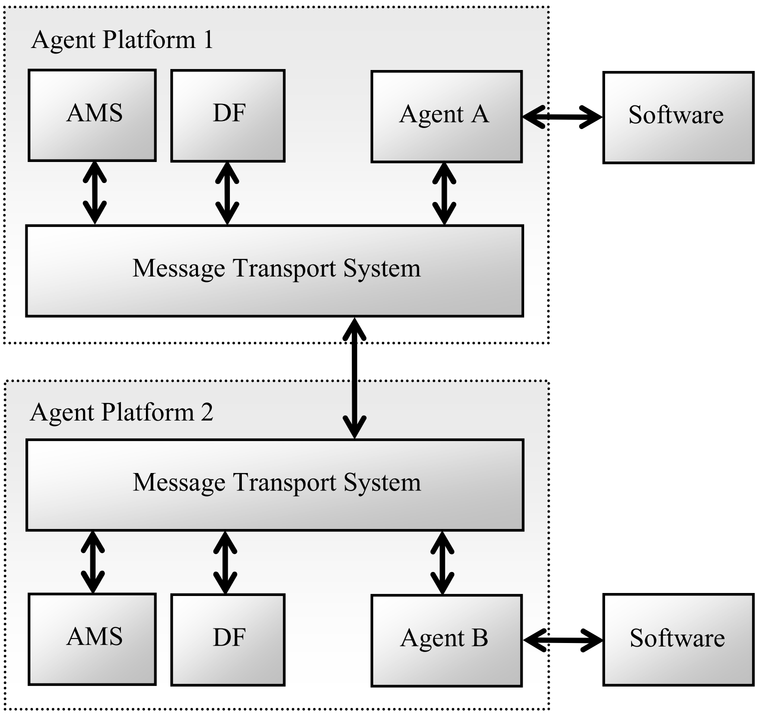

Fig. 2.7 FIPA Agent Management Reference Model [67]

FIPA standards also define the modes of communication between agents, termed as communication protocols [68]. The interaction protocols describe a standardised series of messages that the agents have to exchange in order to perform a specific function. The interaction protocols that were used in this thesis are the following:

- FIPA Request Interaction Protocol,
- FIPA Query Interaction Protocol,
- FIPA Contract Net Interaction Protocol and
- FIPA Subscribe Interaction Protocol.

2.6.5. Java Agent DEvelopment framework (JADE)

The most widely used tool for the development of agents for power engineering is the Java Agent DEvelopment framework (JADE) [69][70]. JADE is an open-source Java-based development framework, originally developed by Telecom Italia.

It implements a number of the FIPA standards. It provides a platform set-up facility, with a fully developed Message Transfer System. Agent Management System and Directory Facilitator agents have already been developed and are created automatically when a developed system runs. Agent interaction protocols and the FIPA Agent Communication Language have also been implemented.

A set of graphical management tools is available. JADE acts as a middle-ware, in the sense that it provides a set of Java classes that the developer can handle and/or modify, in order to deploy a functional multi-agent system. Extensive documentation is available [70].

2.6.6. Agents with fuzzy logic

The MAS control system that is developed in Chapter 5 uses fuzzy logic techniques for realising the intelligence and decision-making capabilities of the agents. Fuzzy logic techniques provide the agents with an approximate representation of their environment, while facilitating inference on diverse and incomparable factors. The next sections describe the relevant fuzzy logic concepts.

2.6.6.1. Fuzzy sets

Fuzzy sets are considered a shift from the traditional crisp set of numbers to a more “fuzzy” equivalent. Whether a number belongs to a given fuzzy set is not definitely true or false. A fuzzy number has degrees of membership in a fuzzy set (e.g. 20% high and 80% low) [71]. Examples of fuzzy sets are given in Appendix A.

However, the fuzzy sets are not always known, or they may be dynamic. Fuzzy sets can be constructed from a set of data, e.g. historical market price data. This can be done by means of fuzzy clustering [71].

2.6.6.2. Fuzzy clustering

Fuzzy clustering is a pattern recognition method used for clustering data into fuzzy sets [71]. A set of data can be partitioned into clusters without clearly defined limits. These partitions are called fuzzy pseudopartitions. They do not represent clear limits, but rather a pivot around which the data exhibit degrees of membership, as shown in Fig. 2.8. An example of fuzzy clustering is given in Appendix A.

The fuzzy pseudopartitions from a set of data can be determined using several algorithms, with most prominent the Fuzzy c-Means algorithm [71]. It is an iterative process, briefly described below:

- **Step 1.** Select an initial fuzzy pseudopartition P(t) for t=0.
- **Step 2.** Calculate the cluster centres.
- **Step 3.** Update the pseudopartition P(t+1).
- **Step 4.** Compare P(t+1) with P(t) and if the difference satisfies a stopping criterion (tolerance) finish the algorithm, otherwise increment t by one and go back to Step 2.

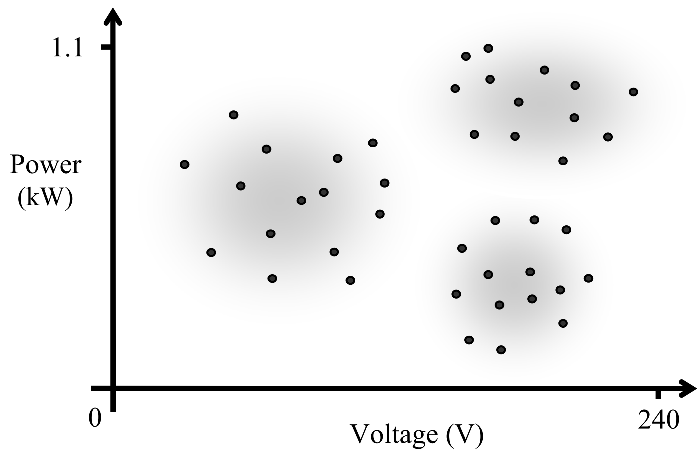

Fig. 2.8 Fuzzy clusters for a set of data

2.6.6.3. Fuzzy inference

Fuzzy inference is the process of reaching a conclusion based on a collection of *if-then* rules [71]. These are of the form: *IF* **X is A**, *THEN* **Y is B**. They can be grouped in a table, called the implication matrix.

One method to find the result from a collection of fuzzy rules is the method of interpolation. The outcome of this method is a fuzzy number. An example of fuzzy inference is given in Appendix A.

2.6.6.4. Defuzzification methods

A fuzzy number is an array of real numbers, which are degrees of membership for each of the fuzzy sets considered. A defuzzification method is necessary, in order to convert it to a real number.

Defuzzification converts the result of a fuzzy inference engine into a real number. The two defuzzification methods that were used in this thesis are the Centre of Gravity and the Mean of Maxima [71]:

- **Centre of Gravity**: this method determines the centre of gravity of the area under the resulting fuzzy number, using the equation below [71]:

$$d_{CG} = \frac{\sum_{k=1}^{n} B(z_k) \cdot z_k}{\sum_{k=1}^{n} B(z_k)} \qquad (9)$$

where: d_{CG} is the defuzzified value.
B is the discrete resulting set $\{z_1, z_2, \dots, z_n\}$.
z_k is the discrete values of the set.

- **Mean of Maxima**: this method finds the average of all values in the resulting fuzzy number that are equal to the maximum value [71]:

$$M = \{z \in B \mid B(z) = z_{MAX}\} \qquad (10)$$

$$d_{MM} = \frac{\sum_{z_k \in M} Z_k}{|M|} \tag{11}$$

where: d_{MM} is the defuzzified value.

B is the discrete resulting set $\{z_1, z_2, \ldots, z_n\}$.

z_k is the discrete values of the set.

z_{MAX} is the value in the set corresponding to the maximum $B(z)$.

2.7. CONCLUSIONS

In this chapter, the literature relevant to this thesis was analysed. A description of the studied micro-generators was given. Their emissions and calculation techniques were analysed, since they are used along with the optimization techniques to assess the benefits of optimising aggregated micro-generation emissions. Micro-generation aggregation was described, to give the background for the aggregation system for emissions control that is developed in Chapter 5. Since the aforementioned system is agent-based, the concept of intelligent agents and multi-agent systems was described.

Micro-generation technologies have been identified as distributed generation resources with capacity up to 5kW. The micro-generation technologies that were described were (i) wind turbines, (ii) photovoltaics, (iii) fuel cells, (iv) microturbines, (v) Stirling engines and (vi) Diesel engines. The principle and benefits of heat recovery by micro-CHP systems were explained. The future trends of electric vehicles were given, since they are studied in Chapters 3 and 4.

Micro-generation emissions and calculation methodologies were described, with regards to two aspects: (i) the operation and (ii) the full life-cycle of micro-generators. Electric vehicle emissions were presented. These methodologies are used in Chapter 3 to calculate micro-generator and electric vehicle emissions. The calculated emissions are compared to the literature for validation.

Techniques for the **optimisation of generator schedules** and their application in power system operation were described. It was shown that these techniques can be focused on minimising the cost or the environmental impact of generator operation. These methodologies are traditionally used for large power stations. They are used in

Chapter 4, together with the concept of aggregation, to optimise the emissions of a cluster of micro-generators and electric vehicles.

Micro-generation aggregation was identified as a means of clustering distributed resources to bring benefits to their owners and the power system. Technical and economic benefits were found. Two concepts were described: (i) the micro-grids and (ii) the Virtual Power Plants (VPP). The VPP was distinguished as being either a Technical or a Commercial VPP, based on the purpose and the nature of aggregation. A hierarchical structure for VPP realisation was described. These concepts are applied on a distributed control system developed in Chapter 5 for regulating the emissions of a VPP. The system developed in Chapter 5 is defined as an Environmental Virtual Power Plant (EVPP), extending the concept of VPP.

Intelligent agents and multi-agent systems were explained, as well as their potential applications in power engineering. Examples of agent-based application with regards to emissions and emissions trading were presented. Agent formal definitions, standards and tools were described. A multi-agent system is designed in Chapter 5, for regulating the emissions of a VPP. Finally, since fuzzy logic is used in the agents developed in Chapter 5, fuzzy logic principles were also described.

In the next chapters:

- The micro-generator emissions presented in this chapter are validated.
- The power system optimisation methods presented in this chapter are employed in a micro-generation emissions optimisation case study.
- The resource aggregation concepts that were presented in this chapter are extended and tested experimentally.

Chapter 3
Carbon emissions

3.1. Introduction

In order to study the potential of micro-generation to reduce power system emissions, the emissions incurred by micro-generators should be evaluated.

The objective of this chapter is to calculate the Greenhouse Gas (GHG) emissions performance of selected micro-generation sources. This emissions performance will be used in later chapters to optimise VPP emissions and to design a VPP control system. Simulated case studies were also conducted. A comparison was made with respect to conventional generation. The emissions savings potential of a number of micro-generation mixes was evaluated.

Two aspects of micro-generation emissions were investigated: (i) the emissions during operation and (ii) the emissions during the whole life-cycle of the equipment.

3.1.1. Operational emissions

The most carbon efficient micro-generation technologies are the wind turbines and the photovoltaic generators, since they produce no operational emissions. Wind turbines utilise the wind as primary energy resource and the photovoltaics utilise the solar energy, both of which are carbon-free.

Regarding micro-CHP, the CO_2 emissions per unit of generated electrical energy vary depending on the technology. The operational emission factors (gCO_2/kWh_e) for three micro-CHP technologies, as well as a typical gas boiler, are presented in Table 3.I. Data have been gathered from the literature.

Table 3.I: Carbon Dioxide emissions per electrical kWh produced from each technology

Micro-generation type	CO_2 emissions (gCO_2/kWh_e) - [Reference]				Average emission factor (gCO_2/kWh_e)
	[13]	[14]	[15]	[16]	
Fuel Cell	477	460	499	460	474.0
Microturbine	725	724	703	720	718.0
Diesel ICE	695	650	680	650	668.8
Boiler (Gas)	201	-	-	-	201.0

3.1.2. Life-cycle emissions

Table 3.II shows a collection of life-cycle CO_2 emission factors from the literature, in terms of gCO_2 per kWh produced from wind turbines and photovoltaics. The emission factors vary significantly, which is mostly due to the different climatic conditions considered in the studies, as well as the different assumptions made. Some of the values are expressed in CO_2 equivalent, which includes the Greenhouse Gas equivalence of methane (CH_4) and nitrous oxide (N_2O).

TABLE 3.II: CO_2 EMISSION FACTORS FOR WIND TURBINES AND PHOTOVOLTAICS

Source	WT	PV
[18]	24 ^{e}	-
[33]	-	104 ^{e}
[36]	-	60
[72]	28 ^{e}	190 ^{e}
[73]	34	-
[74]	17 ^{e}	95 ^{e}
[75]	47 ^{e}	-
Average (gCO_2/kWh)	30	112.25

^{e} expressed as CO_2 equivalent

3.2. MICRO-GENERATOR LIFE-CYCLE EMISSIONS

The life-cycle carbon footprint of different micro-generators was assessed. Manufacturing and decommissioning of the equipment was considered. The effects of part-loading conventional generation were also examined. The principles set out in ISO 14040:2006 were followed, wherever possible [32].

3.2.1. Methodology

Fig. 3.1 shows the study process that was followed. The analysis was split in four stages, covering the life-cycle of the system. These are the manufacturing, transport, operation and decommissioning stage. The operation stage was not considered for renewable energy generators, i.e. wind turbines and photovoltaics, as they produce no direct emissions during their operation. Finally, the results were compared and validated against the literature, they were interpreted and conclusions were drawn.

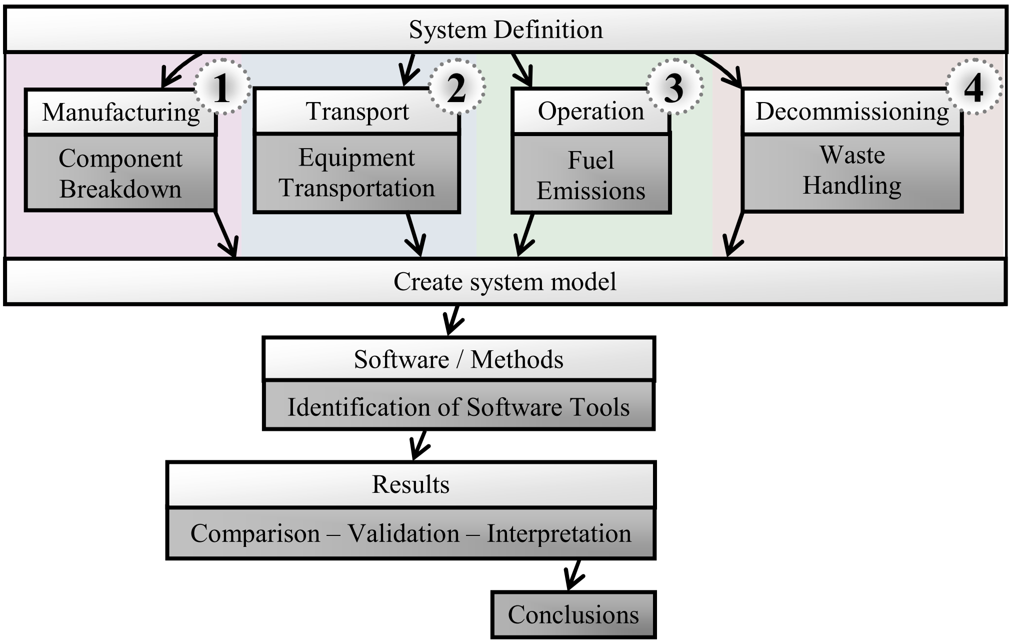

Fig. 3.1 Study process diagram.

A list of the materials used in the manufacturing of the equipment was necessary for determining the life-cycle emissions from the manufacturing stage. This was done by breaking down the equipment into their components. The micro-generator components and materials were collected from the literature. The life-cycle emissions associated with the fuels utilised by the micro-CHP were taken into account. The full calculation method is described in Fig. 3.2.

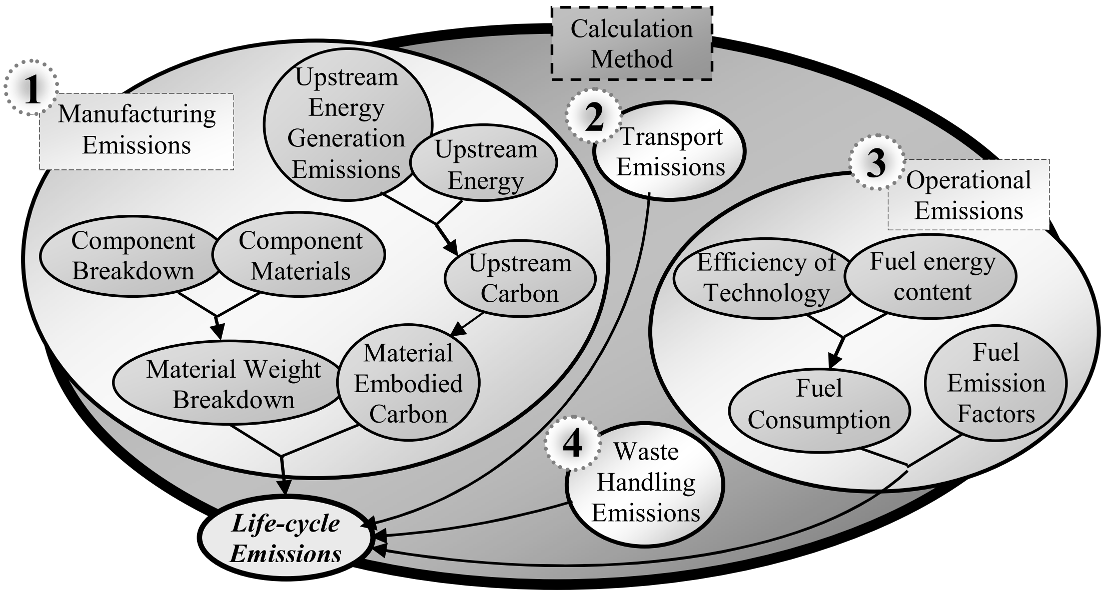

Fig. 3.2 Calculation method.

The operational emissions performance of micro-generators was calculated as follows:

- The fuel consumption was calculated by multiplying the efficiency of the generation technology with the energy content of the fuel.
- This was used along with the fuel emission factors to calculate the emissions.

For calculating the emissions saving potential, the amount of displaced emissions had to be calculated. The displaced generation emissions were calculated by multiplying the total electrical or thermal energy generated during the micro-generator operation with the grid electricity or boiler heat emission factor respectively. The total emission savings (E_S) were calculated as follows:

$$E_S = \frac{E_C - E_M}{E_C} \tag{12}$$

where: E_S is the emission savings.
E_C is the conventional (grid/boiler) emissions.
E_M is the micro-generation emissions.

CO_2 equivalent emissions: The CH_4 and N_2O emissions were also considered as Greenhouse Gases, according to the IPCC [1]. Where possible, the emission factors were expressed as CO_2 equivalent (CO_2-e).

3.2.2. Calculation tools

3.2.2.1. Global Emission Model for Integrated Systems (GEMIS)

The Global Emission Model for Integrated Systems (GEMIS) was used to calculate the carbon footprint of the micro-generators. GEMIS is a life-cycle analysis program and database for energy, material, and transport systems. The parameters that were input in GEMIS were:

- The weight of each of the materials for each micro-generator.
- Micro-generator parameters such as lifetime, fuel efficiency, fuel type and operational availability.

- The assumed transport (tonnes*km) for the equipment from the point of manufacture to the point of installation.
- The weight of the waste, which is equal to the equipment weight.

3.2.2.2. Inventory of Carbon and Energy, RETScreen and Homer

Analytical calculation of the outputs was also done manually, to validate the GEMIS output, as described below:

Manufacturing emissions: A database called the Inventory of Carbon and Energy was used to find the emissions which are embodied in the materials [34]. The term embodied carbon is used to describe the carbon emitted for the production of a given quantity of a material. Likewise, the embodied energy is the energy required to produce a given quantity of a material [34].

Operational emissions: Two software tools and a manual method were used for the operational emissions calculations. The software tools were: (i) RETScreen International and (ii) NREL Homer. Both of them follow a similar methodology, with small variations. The average of the two software tools was considered. The manual method was used to verify the results obtained from the software tools. Detailed input data for the tools and the manual methodology are provided in Appendices B to D.

Waste and transport emissions: The waste handling and transport emissions were not taken into account. The calculation methodology involved very rough assumptions due to lack of important data. The difference was negligible, so it was considered out of scope.

3.2.3. Components breakdown

The expected lifetime and calculated weight of each micro-generator are shown in Table 3.III. The photovoltaic inverter was considered as a separate component, according to [36].

TABLE 3.III: LIFETIME AND WEIGHT OF THE EQUIPMENT [19][23][35][76][77].

Component	Lifetime (years)	Total Weight (kg)
Wind Turbines (x4)	15.0	3400
Photovoltaics (x9)	25.0	3490
PV Inverter (x9)	-	1000
Fuel Cell (Natural Gas)	9.4	1110
Microturbine (Biogas)	5.4	534

The micro-generators were split into their structural components. Table 3.IV presents the relative weight of each component in a wind turbine, as a percentage. Similar tables are presented for photovoltaics (Table 3.V) and Solid Oxide Fuel Cells (SOFC) (Table 3.VI).

TABLE 3.IV: COMPONENT BREAKDOWN OF A WIND TURBINE BY WEIGHT [77][78].

Component	% weight
Rotor	4.8%
Gearbox	4.6%
Generator	3.3%
Nacelle & Machinery	7.0%
Tower	20.1%
Foundations	60.3%
Total	100%

TABLE 3.V: COMPONENT BREAKDOWN OF A PHOTOVOLTAIC BY WEIGHT [72][79].

Component	% weight
Photovoltaic Cells	2.3%
Frame	4.4%
Steel Support Structure	41.3%
Electricals	6.1%
Glass cover	17.4%
Concrete Support	24.2%
Insulation	4.3%
Total	100%

TABLE 3.VI: COMPONENT BREAKDOWN OF A FUEL CELL (SOFC) BY WEIGHT [23].

Component	% weight
Casing	9.0%
Air/Fuel Supply system	18.0%
Desulphuriser	0.5%
Pre-reformer/gas burner	5.0%
Heat exchangers	3.6%
Power conditioning system	0.3%
Conventional gas heating unit	45.0%
Positive-Electrolyte-Negative-Interconnect (PEN)	18.5%
Total	100%

The component and material breakdown of the microturbine was simplified to the steel required for manufacturing (100% steel), as in [35].

3.2.4. Materials breakdown

The materials in each component were identified. The embodied energy and carbon were calculated. Estimates of the relative weight of the materials were collected from the literature. They are presented, along with the material embodied energy and carbon, in Table 3.VII for wind turbines, Table 3.VIII for photovoltaics and Table 3.IX for fuel cells.

It can be seen from Table 3.VII, Table 3.VIII and Table 3.IX that the weight percentage is not proportional to the percentage of embodied energy or carbon. In a photovoltaic module, although silicon takes up slightly more than 2% of the weight, it carries more than two thirds of the total embodied energy and more than half of the total embodied carbon. A similar observation to a smaller extent can be made for the PEN materials of the fuel cell.

TABLE 3.VII: MATERIAL BREAKDOWN OF A WIND TURBINE, EMBODIED ENERGY AND EMBODIED CARBON OF THE MATERIALS [18][34][73][74][77][78].

Material	% weight	Embodied Energy		Embodied Carbon	
		(MJ/kg)	(%)	($kgCO_2/kg$)	(%)
Aluminium	13.8%	147.50	60.7%	8.24	55.5%
Steel	20.3%	33.92	20.6%	2.82	28.0%
Copper	2.0%	73.23	4.4%	3.01	3.0%
Polymers/Glass Fibre/Epoxy	3.0%	95.08	8.6%	5.32	7.8%
Concrete	60.3%	2.08	3.7%	0.13	3.8%
Magnetic Material [a]	0.6%	103.50	2.0%	5.87	1.8%
Total	100%	-	100%	-	100%

[a] assuming a Mn-Al-C permanent magnet [80], and approximated according to the embodied energy and carbon values in [34] for Manganese and Aluminium.

TABLE 3.VIII: MATERIAL BREAKDOWN OF A PHOTOVOLTAIC MODULE, EMBODIED ENERGY AND EMBODIED CARBON OF THE MATERIALS [34][72][79].

Material	% weight	Embodied Energy		Embodied Carbon	
		(MJ/kg)	(%)	(kg CO_2/kg)	(%)
Silicon/Wafer	2.3%	2,355.00	67.1%	98.08	56.3%
Aluminium	4.4%	190.15	10.3%	5.14	6.0%
Steel	41.3%	21.38	10.9%	2.55	28.0%
Copper	6.1%	73.75	5.6%	2.16	3.5%
Glass	17.4%	15.00	3.2%	1.39	6.4%
Concrete	24.2%	2.08	0.6%	0.13	0.8%
Insulator	4.3%	45.00	2.4%	1.86	2.1%
Total	100%	-	100%	-	100%

TABLE 3.IX: MATERIAL BREAKDOWN OF AN SOFC FUEL CELL, EMBODIED ENERGY AND EMBODIED CARBON OF THE MATERIALS [23][34].

Material	% weight	Embodied Energy		Embodied Carbon	
		(MJ/kg)	(%)	(kg CO_2/kg)	(%)
Steel	78.82%	24.4	34.11%	1.77	41.70%
Zinc	0.09%	61.9	0.10%	3.31	0.09%
Nickel	0.45%	164.0	1.33%	12.40	1.67%
Incaloy 825	1.80%	49.4	1.61%	8.89	4.79%
Aluminium	0.27%	155.0	1.12%	8.24	0.67%
Purified Silica	<0.01%	-	-	-	-
Plastics	0.02%	80.5	0.03%	2.53	0.01%
Copper	0.01%	47.5	<0.01%	3.01	<0.01%
PEN Materials	18.54%	184.2	61.70%	9.22	51.07%
Total	100%	-	100%	-	100%

3.2.5. Electrical efficiency

Electrical efficiency values for all the micro-CHP technologies were drawn from the literature [13][14][15][16]. Average values were used in the calculations. The values for the electrical efficiencies are presented in Table 3.X.

TABLE 3.X: ELECTRICAL GENERATION EFFICIENCIES OF THE DIFFERENT TECHNOLOGIES*

Micro-CHP source	Efficiency (%) – [Reference]				Average (%)
	[13]	[14]	[15]	[16]	
Fuel Cell	38.0	39.5	39.5	44.5	40.4
Microturbine	25.0	25.0	26.0	27.5	25.9
Diesel ICE	35.0	38.0	37.5	39.5	37.5

* The gas boiler thermal efficiency was considered to be 90%, from [13].

3.2.6. Results - Calculated emission factors

Table 3.XI presents the operational emission factors for each of the micro-CHP technologies, as well as for the gas boiler. Values from the literature were averaged and compared to the calculated values. They were found to be similar, which provides a first validation of the calculations.

TABLE 3.XI: OPERATIONAL EMISSION FACTORS

Emission source	Average literature emission factors (gCO_2-e/kWh) [13],[14],[15],[16]	Calculated emission factors (gCO_2-e/kWh)
Fuel Cell	474.0	446.8
Microturbine	718.0	695.8
Diesel ICE	668.8	661.8
Boiler (Gas)	201.0	204.2

Table 3.XVI presents the average life-cycle emission factors calculated with the two sets of tools. The emission factor is calculated by dividing the life-cycle emissions with the life-cycle energy produced. It is observed that the wind turbine and photovoltaic emission factors calculated with GEMIS are in agreement with the values from the literature, presented in Table 3.II. The overall CHP emission factor is also shown, expressed in gCO_2 per kWh produced, either electrical or thermal.

TABLE 3.XII: LIFE-CYCLE EMISSION FACTORS.

Component	Emission factor (gCO_2-e/kWh)					
	GEMIS			**ICE** and **RETScreen/Homer**		
	Electricity	*Heat*	*CHP*	*Electricity*	*Heat*	*CHP*
Wind Turbines	29.67	-	-	21.04	-	-
Photovoltaics	117.62	-	-	56.17	-	-
Fuel Cell (Natural Gas)	421.40	0.00	175.59	460.50	0.00	191.87
Microturbine (Biogas)	285.87	0.00	79.41	265.98	0.00	73.88
Grid [30]	544.00	-	-	544.00	-	-
Boiler (calculated)	-	204.20	-	-	204.20	-

3.3. CASE STUDIES

3.3.1. Operational emissions case study

A case study was performed to evaluate micro-generation emissions only in the operational phase. The calculations were performed with (i) RETScreen, (ii) Homer and (iii) manually.

3.3.1.1. System description

The system under study was based on the UK generic distribution network in [81]. It includes one micro-grid comprised of 96 domestic customers, connected to the Low Voltage (LV) distribution network. Micro-generation was considered as aggregated. The studied system is illustrated in Fig. 3.3.

In this system, 100% micro-generation penetration corresponds to 1.1 kW installed capacity per customer [81], or 105.6 kW aggregated. Respectively, 50% penetration corresponds to 0.55 kW installed capacity per customer.

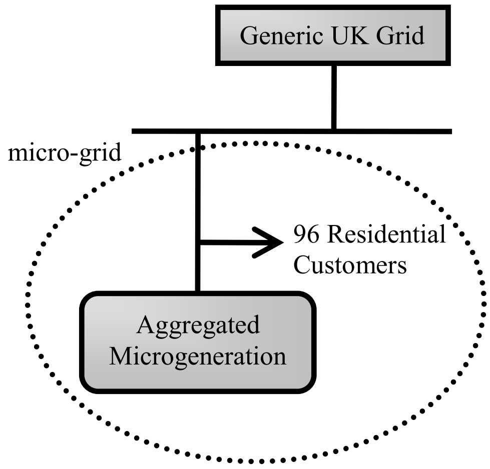

Fig. 3.3 Schematic of the system under study.

Three micro-CHP technologies were chosen in accordance to the following criteria [10],[11]:

- Microturbines have high Heat to Power Ratio, due to their lower electrical efficiency compared to other technologies.
- Diesel engines are an established and flexible technology, which requires little modifications for transition to bio-fuels.
- Fuel cells are a promising high-efficiency low-emissions technology, in the first stages of commercialization.

3.3.1.2. Study cases

Three main study cases were defined, with regards to the micro-generation penetration (also see Fig. 3.4):

- Case 1 consists of 100% micro-CHP penetration. Fossil fuels are used.
- Case 2 consists of 50% micro-CHP penetration. Fossil fuels are used.
- Case 3 consists of 25% micro-CHP penetration. Biomass fuels are used.

Three distinct sub-cases were defined for each main case by considering the micro-CHP technology as being (a) Fuel Cell, (b) Microturbine or (c) Diesel Engine. The study cases were also characterized by the fuel used by the micro-CHP. Natural gas is used in Cases 1.a, 1.b, 2.a and 2.b and biogas in Cases 3.a and 3.b. The Diesel engine uses diesel fuel in Cases 1.c and 2.c and biodiesel in Case 3.c.

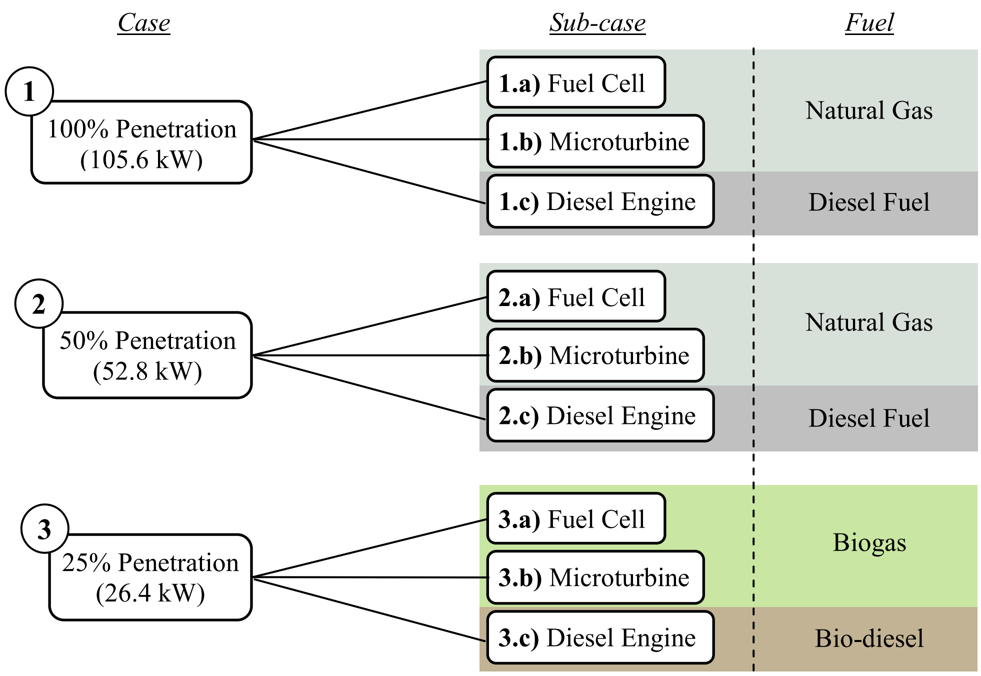

Fig. 3.4 Study cases

3.3.1.3. Input data

All the inputs to the tools and the fuel data were drawn from the literature. The fuel emission factors and the energy content of the fuels were taken from the Carbon Trust [30], as well as the average emission factor for the UK grid (544 gCO_2/kWh), and the unit conversion factors. The energy content of biodiesel, according to the UK Department of Transport, is 92% of the regular diesel fuel [82]. The density of biodiesel was taken as 0.88 kg/L [83]. Biogas data were taken from [84].

- **Carbon cycle**

It is noted that the CO_2 emission factor for biogas and biodiesel was assumed to be zero, for simplicity, based on the Carbon Cycle theory [31]. Even though biofuels may emit CO_2 when they burn, this is considered as neutralized or offset. However, the CO_2 equivalent of CH_4 and N_2O emissions is not offset.

- **Transmission and distribution losses**

The transmission and distribution (T&D) losses were considered for the calculations. Micro-generation sources are located near the load and generation is normally consumed locally, which reduces the energy that needs to be transferred, as well as the associated losses [85]. The calculations were performed considering (i) no losses and (ii) 7.04% losses, according to [86].

- **Energy demand**

For calculating the annual electrical demand of the customers, data from [87] was used. For the calculation of the annual heat demand, a value of 18,000 kWh was considered per customer [88]. The total annual energy demand for all the 96 customers was calculated:

✓ **520.8 MWh** electrical demand and

✓ **1,728 MWh** heat demand.

Electricity generated by the micro-generators, but not consumed on-site, was considered to be fed to the grid. Excess heat was considered to be dissipated.

- **Demand and generation profiles**

Generic annual half-hour generation profiles from [87] were used for the study. Annual average power values were derived and used for calculating the annual energy generation of a typical unit from each technology. All the calculations were based on annual energy values.

According to [81] a load range of 0.16 kVA - 1.3 kVA is typical per customer. An electrical demand profile from [87] was scaled to these values and multiplied with 96 to get the aggregated customer electrical demand profile (see Fig. 3.5).

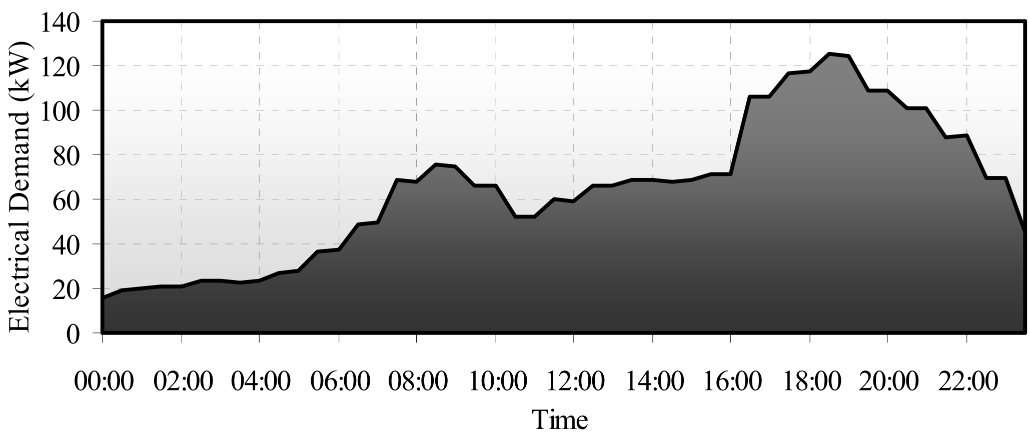

Fig. 3.5 Aggregated customer electrical demand.

3.3.1.4. Emission savings

Fig. 3.6 shows the micro-generation emissions for Cases 1.a, 1.b and 1.c (Fig. 3.4), calculated with the three methods. It can be seen that the results obtained from all three methods are consistent.

Fig. 3.7 presents the emissions savings, when compared to the base case, where the demand is met with grid electricity and boiler heat. The results from the three methods were averaged. The error bars show the standard deviation.

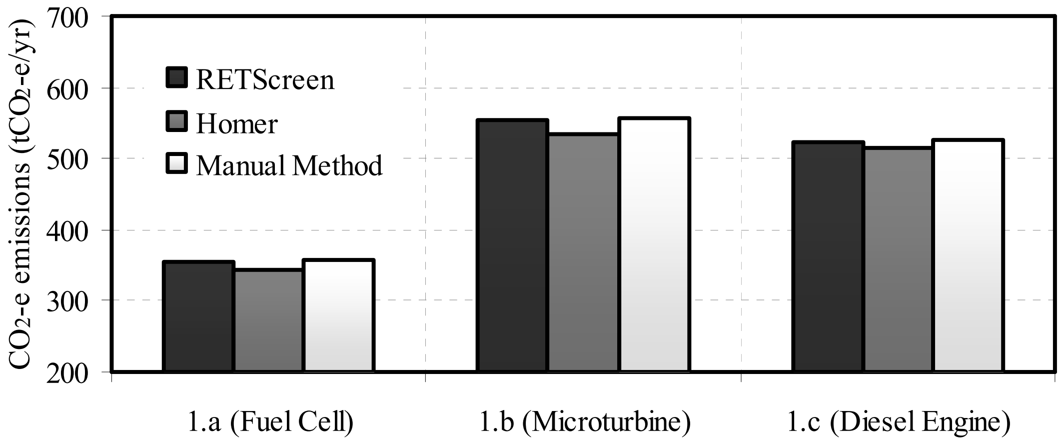

Fig. 3.6 Emissions in Cases 1.a, 1.b and 1.c. All emissions are shown in tonnes CO_2 equivalent per year

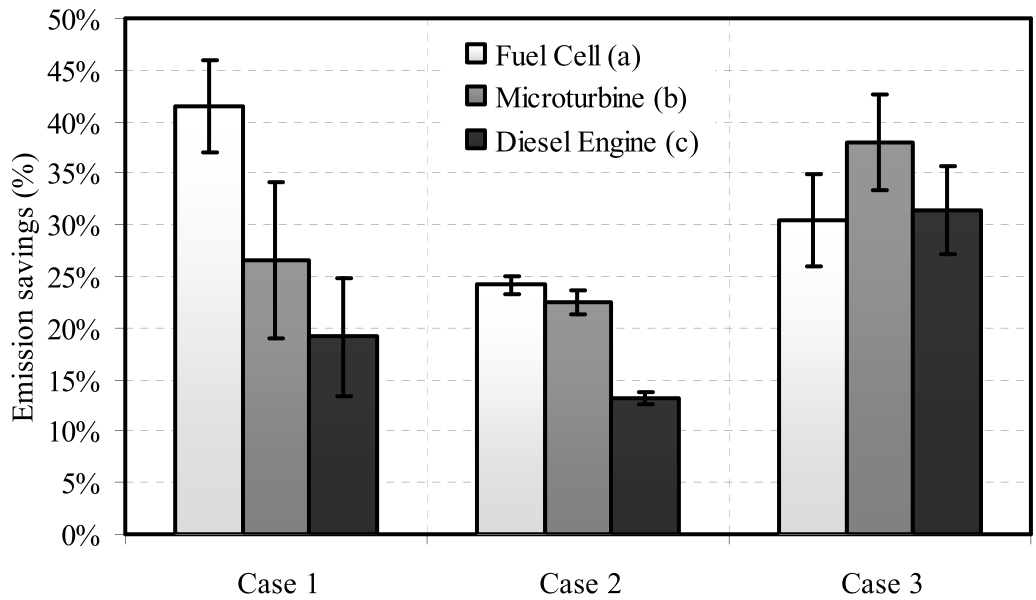

Fig. 3.7 Annual emission savings due to micro-generation, when compared to the UK conventional grid generation emissions, plus the boiler emissions.

Annual emission savings in the range of 13-41% can be attained. These figures are in accordance with similar studies in the literature [12]. The Carbon Trust [6] gives a respective range of 5% to 10%.

It is noted that in Case 1, the microturbine produces too much heat, which cannot be utilised by the customers, and is therefore wasted. Thus, a microturbine penetration of over 50% (Case 2) would have little value in terms of emissions savings.

Diesel was found to give the least savings when fossil fuels are used, due to its high emission factor. Combined with the relatively low heat recovery, the Diesel engine emissions are not much lower than the grid and boiler. However, Diesel engines have the advantage of being an established and cheap technology, compared to the other two. The greatest value of this technology is the capability of a relatively simple transition to biodiesel.

In Case 3, the higher fuel efficiency of the fuel cell no longer gives it an emissions advantage, since the emissions are already low, due to biomass. In contrast, the lower heat to power ratio [13] results in saving less boiler emissions.

3.3.1.5. Transmission and distribution losses

If the transmission and distribution losses would be taken into account, additional emission savings would be achieved. That is because the base case emissions would be higher, due to generation of electricity to cover the losses. These additional savings are shown in Table 3.XIII:

TABLE 3.XIII: ADDITIONAL SAVINGS DUE TO LOSSES

Case	Additional savings	
	tCO_2-e/yr	%
1	17.51	2.75%
2	13.70	2.15%
3	7.30	1.15%

3.3.2. Life-cycle emissions case study

3.3.2.1. System description

A study case has been constructed to evaluate the life-cycle emissions of typical micro-generation installations. The studied system is a micro-grid comprising micro-generation and 96 domestic customers, assumed to be located in Cardiff, Wales. The micro-generation installed power and resource type were based on the benchmark low voltage micro-grid presented in [50].

Micro-generation comprises 4 wind turbines, 9 photovoltaics, a microturbine operating with biogas and a fuel cell operating with natural gas. A diagram of the system is presented in Fig. 3.8. All micro-generation was regarded as aggregated and the residential loads as lumped.

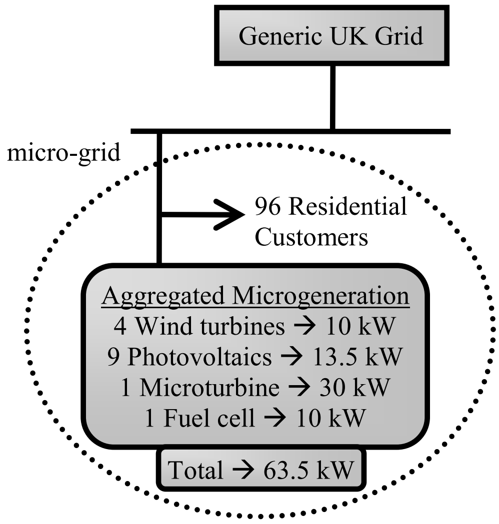

Fig. 3.8 Schematic of the studied system.

The typical installed power per customer was considered 2.5kW for wind turbines, 1.5kW for photovoltaics and 1.1kW for micro-CHP [19][81][89][90]. The microturbine and fuel cell units were taken as single micro-CHP units of 30kW and 10kW, supplying 27 and 9 customers respectively.

The electrical demand that was not met from the micro-generation was supplied by the grid and the heat demand by typical domestic gas boilers. The minimum and maximum electrical load per customer was taken as 0.16kW and 1.3kW respectively, according to [81]. Annual half-hour profiles for load and generation were taken from [87]. Aggregated profiles were calculated. The micro-CHP units were considered to operate 7,455 hours per year [87].

Micro-generation operation causes the part-loading of conventional generators, as a result of displacing electricity generation. The additional emissions incurred by part-loading a Combined Cycle Gas Turbine (CCGT) were calculated. The CCGT part-load fuel efficiency was used to calculate the additional emissions [91]. A value of 500MW was considered a typical CCGT power rating [92].

3.3.2.2. Life-cycle energy and emissions

Table 3.XIV presents the life-cycle energy and emissions of each micro-generator, calculated with GEMIS. Table 3.XV shows the same values calculated with the ICE database [34] and RETScreen / Homer. The emissions from transport and waste handling were not calculated with this method. There is no large discrepancy, though, since these emissions do not exceed 0.1% of the total emissions. The emissions at each life-cycle stage are expressed as a percentage of the total micro-grid life-cycle emissions.

TABLE 3.XIV: LIFE-CYCLE ENERGY AND EMISSIONS, CALCULATED WITH **GEMIS**.

Component	Life-cycle energy (MWh)		Life-cycle CO_2 equivalent emissions (% of total)				
	Electricity	Heat	Manuf.	Operation	Transp.	Waste	Overall
Wind Turbines (x4)	330.00	-	1.41%	-	0.01%	<0.01%	1.43%
Photovoltaics (x9)	281.16	-	4.80%	-	0.02%	<0.01%	4.82%
Inverter (x9)	-	-	0.34%	-	0.01%	<0.01%	0.35%
Fuel Cell (Natural Gas)	701.00	981.40	0.52%	42.51%	0.01%	<0.01%	43.04%
Microturbine (Biogas)	1209.00	3143.40	0.12%	50.23%	0.01%	<0.01%	50.36%
micro-grid	**2521.16**	**4124.80**	**7.19%**	**92.74%**	**0.06%**	**<0.01%**	**100.00%**
with CCGT part-loading	-	-	-	21.37%	-	-	121.37%

TABLE 3.XV: LIFE-CYCLE ENERGY AND EMISSIONS, CALCULATED WITH **ICE** AND **RETSCREEN/HOMER**.

Component	Life-cycle energy (MWh)		Life-cycle CO_2 equivalent emissions (% of total)		
	Electricity	Heat	Manufact.	Operation	Overall
Wind Turbines (x4)	330.00	-	1.04%	-	1.04%
Photovoltaics (x9)	281.16	-	2.36%	-	2.36%
Inverter (x9)	-	-	0.32%	-	0.32%
Fuel Cell (Natural Gas)	701.00	981.40	0.55%	47.68%	48.23%
Microturbine (Biogas)	1209.00	3143.40	0.14%	47.91%	48.05%
micro-grid	**2521.16**	**4124.80**	**4.42%**	**95.58%**	**100.00%**
with CCGT part-loading	-	-	-	21.91%	121.91%

3.3.2.3. Emission savings

Table 3.XVI presents the life-cycle CO_2 savings calculated with the two sets of tools, as an annual percentage of total customer emissions. The baseline for calculating the emission savings was the average emissions incurred by the UK grid and a typical natural gas boiler. Grid exports count towards the operational emissions savings, as grid electricity is being displaced. This contributes significantly towards increasing Microturbine and Fuel Cell emission savings.

TABLE 3.XVI: LIFE-CYCLE ANNUAL SAVINGS.

Component	Annual CO_2-e Savings (%)	
	GEMIS	**ICE** and **RETScreen/Homer**
Wind Turbines	42.07%	42.79%
Photovoltaics	7.88%	9.05%
Fuel Cell (Natural Gas)	50.50%	45.61%
Microturbine (Biogas)	87.73%	90.22%
micro-grid	**32.14%**	**30.25%**
with CCGT part-loading	27.75%	25.87%

3.3.2.4. Observations

It can be observed that the photovoltaics produce fewer savings per customer, due to their low average energy output, compared to other micro-generators. The microturbine produces significant savings due to the high heat output and because electricity is being exported to the grid. The same applies for the fuel cell, but to a lesser extent, since it has a higher emission factor and lower heat output.

The largest part of the emissions savings is achieved by the recovery of waste heat from the micro-CHP. This is essentially saving boiler emissions that would otherwise be required to cover the heat load.

This micro-generation configuration can save approximately one third (30%) of the CO_2 emissions from the energy delivered to the studied micro-grid customers.

When a CCGT is being part-loaded, its conversion efficiency is reduced, thus consuming more fuel and emitting more CO_2 per unit of generated electricity. In the studied case, this increases the total emissions associated with micro-generation by approximately 20%, thus reducing the savings by approximately 5 percentage points.

Biomass CO_2 emissions are normally assumed to be offset by the next generation of plants [31]. However, the microturbine life-cycle emission factor was found to be significantly higher than the near-zero estimation of this assumption.

A point that should be addressed is the locality of the emissions. The manufacturing emissions are not necessarily emitted in the same country that the equipment is installed. Therefore, the emissions prior to transport are located in the country of manufacture. On the other hand, the emissions after transport, as well as the emission savings, are credited to the country of installation. This is in fact outsourcing emissions from one place to the other and may distort relevant statistics.

3.4. ELECTRIC VEHICLES LIFE-CYCLE EMISSIONS IN 2030

The life-cycle emissions of electric vehicles were also calculated with GEMIS, since it was required for the case study in Chapter 4. In Table 3.XVII, a comparison between the predicted emissions from Battery Electric Vehicles (BEV), Plug-in Hybrid Electric Vehicles (PHEV) and conventional vehicles is given, for 2030.

- **Input data**

Plug-in hybrids are assumed to be powered by 50% electricity and 50% petrol [24]. The source of electricity considered is the 2030 UK grid, with a carbon intensity of 248 gCO_2/kWh, as predicted in the low-carbon resilient scenario in [4]. Data for the materials of the electric vehicle were drawn from [93] and [94] and for the usage from [24]. Data for conventional vehicles were also taken from [24].

- **Baseline**

A vehicle complying with the 2020 vehicle emissions target of 95 gCO_2/km set by the European Parliament in 2009 [95] would produce 17.1 tCO_2 during its life-cycle, considering a life of 180,000 km [24]. Such a vehicle was taken as the baseline. The results were compared with that value and potential emission savings were calculated, shown in Table 3.XVII.

TABLE 3.XVII: COMPARISON OF LIFE-CYCLE EMISSIONS AND EMISSION FACTOR OF ELECTRIC VEHICLES AND CONVENTIONAL VEHICLES [24] FOR 2030.

Vehicle Type	Electric Vehicles		Conventional Vehicles	
	BEV	PHEV	Petrol	Diesel
Emission factor (gCO_2-e/km)	**54.9**	**85.7**	**120.2**	**108.9**
Life-cycle emissions (tCO_2-e)	9.88	15.42	21.64	19.61
Life-cycle emission savings (tCO_2-e)	7.22	1.68	-4.54	-2.51
Life-cycle emission savings (%)	42.21%	9.82%	-26.54%	-14.65%

3.5. Uncertainties related to calculations in case studies

3.5.1. Operational emissions case study

The efficiency of the micro-CHP is not constant, but it depends on generation loading level. The same applies with heat to power ratio. Throughout the year, it is expected that the micro-CHP will be occasionally part-loaded. A deviation of 10% from the average efficiency is considered as a reasonable estimate.

The efficiency values from the literature also have a small variation between different literature sources. The standard deviation was calculated as 5%.

Regarding the calculation method, standard deviations in the scale of 10% were observed in the results from the different methods.

Consequently, the total uncertainty of the operational emissions case study results is estimated at 15%.

3.5.2. Life-cycle emissions case study

A considerable variation of values was found in the literature regarding both the components and the materials of the system. Most of the values used in this study are averaged values. An uncertainty of 10% is estimated for these values.

There are different options for the material composition, in terms of recycled or virgin resources. This can vastly increase the uncertainty of the material initial values.

The lifetime of the equipment depends on many parameters, mostly related to the installation environment, such as adverse weather conditions. In [74], a 25% uncertainty margin is used for the actual lifetime.

Although the usage is considered as 7,455 h/yr for the micro-CHP, this depends largely on the operator/owner. This can give an uncertainty of approximately 10% as can be estimated from RETScreen outputs.

Finally, environmental parameters such as the wind or solar resource vary not only by location, but also on an annual basis. A further 15% uncertainty can be assumed for this parameter.

In total, by adding the above uncertainties, a 30-35% deviation would be a reasonable estimation of the overall uncertainty in the life-cycle emissions case study. An analysis of the uncertainties of a similar study can be found in [74].

3.6. SUMMARY

This chapter investigates the CO_2 emissions of micro-generators during their whole life-cycle, including the stages of manufacturing, transport, operation and decommissioning. Component and material breakdown of different micro-generators was performed. The embodied carbon from the manufacturing process was assessed.

Two methodologies were used: (i) GEMIS and (ii) ICE with RETScreen and Homer. The results were compared between the methodologies and with the literature, for validation. Emission factors in gCO_2-e/kWh were calculated for the micro-generators.

Three case studies were defined for the operational emissions, with different micro-CHP penetration levels. The penetration levels were 100%, 50% and 25% for Cases 1, 2 and 3 respectively. Three sub-cases were also defined for each case, considering different micro-CHP technologies. The micro-generation technologies considered were three types of micro-CHP: fuel cells, microturbines and Diesel engines.

The emissions savings of the end-users in the studied micro-grid were calculated for each case. They were found to vary approximately from 13% to 41%. When the transmission and distribution losses were included in the calculations the savings increased by an additional 1-3%.

A case study based on the literature [50] was also defined to examine the life-cycle emissions of micro-generators. Results suggest that approximately one third (30%) of the life-cycle CO_2 emissions would be avoided with the studied configuration. Part-loading of a Combined Cycle Gas Turbine would increase the total amount of emissions incurred by micro-generation operation by more than 20%, reducing the savings to approximately 25%.

Overall, the largest part of the savings from micro-generation was obtained by the recovery of waste heat from the micro-CHP. This is essentially saving boiler emissions that would otherwise be required to cover the heat load.

The expected life-cycle emissions from electric vehicles were also calculated for the year 2030. It was found that they would be less carbon-intensive, compared to the conventional vehicles.

Chapter 4

Virtual Power Plant emissions optimisation

4.1. Introduction

The use of demand-side micro-generation is growing, being considered a key element of future networks [90]. As explained in Section 2.5.2, the VPP is a virtual entity which aggregates system assets, including micro-generation, into a single resource. An aggregator entity acts as a controller, managing the VPP resources [41]. Aggregation facilitates micro-generation active participation in electricity markets and power system operation, by providing visibility to the system operator [41].

Unit commitment and economic dispatch are methods used in power systems to optimise generator output [38]. An evolution of economic dispatch is the environmental dispatch, which deals with environmental aspects of power system operation [40]. Both economic and environmental dispatch mainly relate to large power systems consisting of MW-scale generators.

This chapter presents an optimisation method that can be described as environmental dispatch. It would be used by a VPP aggregator/controller to determine the optimal micro-generation set-points, in terms of carbon emissions.

4.2. Emissions optimisation method

4.2.1. Environmental dispatch in a VPP

Environmental dispatch is a method for dispatching the available generators so that environmental impacts are minimised (see Section 2.4.4). In this study, the environmental indicator to be minimised was considered to be the micro-generator emissions. An optimisation problem was formulated (see Section 2.4). The schedules of micro-generators included in the studied Virtual Power Plant were optimised in terms of the overall emissions. An implementation of such a system would imply micro-generation control, which will be addressed in Chapter 5.

4.2.2. Factors affecting VPP emissions

4.2.2.1. Micro-CHP part-load emissions

Part-load CO_2 emission curves of the micro-generators were used for calculating micro-CHP emissions at part-load. The full-load emission factor represents full-load efficiency, since the emission factor is proportional to the fuel consumption. Thus, the part-load emission factor would be inversely proportional to the part-load efficiency, normalised relative to the full-load efficiency:

$$EF_i(P_i) = \frac{EF_{i,FL}}{\eta_i(P_i)} \tag{13}$$

where: $EF_i(P_i)$ is the resulting emission factor at power P for generator i.
$EF_{i,FL}$ is the emission factor at full load.
$\eta_i(P_i)$ is the part-load efficiency at power P for generator i.

4.2.2.2. Micro-CHP start-up and shut-down emissions

When a micro-CHP is switched on, additional fuel is consumed to heat up the device, thus operating at a lower efficiency for a while. Furthermore, when it is switched off, an amount of electricity is used to cool the equipment [6]. A factor for the increase in fuel consumption is defined (see U_F and D_F). Then, this effect can be expressed mathematically as follows:

$$EF_{i,t} = \left[U(P_{t-1})\cdot U_F + D(P_{t+1})\cdot D_F + 1\right]\cdot EF_{i,t} \tag{14}$$

where: $EF_{i,t}$ is the emission factor of micro-generator i at time-step t.
$U(P_{t-1})$ is a binary variable, equal to 1 if at time step (t) the generator is starting up (i.e. at the previous time-step $(t-1)$ the generator was off) and 0 if at $(t-1)$ it was on.
$D(P_{t+1})$ is a binary variable, equal to 0 if at time step $(t+1)$ the generator will still be on, and 1 if it will shut down.
U_F is the factor by which fuel consumption increases at start-up.
D_F is the factor by which fuel consumption increases at shut-down.

4.2.2.3. Grid emission factor variation

The emission factor of the grid is assumed to reflect the grid energy mix at each instant. A daily emissions profile was taken from [96] for the average UK grid electricity, from which the grid carbon intensity at each instant can be drawn. This enables the optimisation algorithm to schedule available micro-generator production to the times when the grid emits at its highest rate. This way, the overall emissions are reduced, by displacing more carbon-intensive generation.

4.2.3. Optimisation method

4.2.3.1. Micro-generator emissions for the objective function

Part-load efficiency curves (η) were derived from the literature and from manufacturer data [6][97][98]. The MATLAB Curve Fitting toolbox was used to get part-load emissions curves [99]. Then, the function used to calculate the generator emissions is the following:

$$F_i(P_i) = P_i \cdot EF_i(P_i) \tag{15}$$

where: $F_i(P_i)$ is the resulting emissions for generator i.

P_i is the power of generator i in kW.

$EF_i(P_i)$ is the emission factor at power P for generator i.

4.2.3.2. Objective function

The objective function was formulated as follows:

$$L_E = \sum_{t=1}^{T}\left(\sum_{i=1}^{N}\left[F_{i,t}(P_{i,t})\right] + F_{GRID,t}(P_{GRID,t})\right) \tag{16}$$

where: L_E is the total emissions.

$F_{i,t}(P_{i,t})$ is the emissions of generator i, at time-step t.

$P_{i,t}$ is the power of generator i at time-step t, in kW.

$F_{GRID,t}(P_{GRID,t})$ is the emissions from the grid, at time-step t.

T is the total number of time-steps.

N is the total number of generators.

4.2.3.3. Constraints

There are three types of constraints in this study:

(i) Generator operational limits,

(ii) Electricity generation/supply has to be equal to the demand at all times and

(iii) When micro-CHPs are employed, the heat co-produced during the whole day has to be less or equal to the total daily thermal demand of their customer.

Constraints (i) and (ii) are addressed in every economic/environmental dispatch problem (see Section 2.4.3). Constraint (iii) can be described as follows: Micro-CHPs are predominantly heat-led. Since heat can only be utilised on-site, heat produced in excess of the demand would be dissipated. Thus, total micro-CHP recovered heat should be less or equal to the total heat demand throughout the day:

$$C \Rightarrow \sum_{t=1}^{T} H_{i,t}^{GEN} \leq \sum_{t=1}^{T} H_{i,t}^{LOAD} \tag{17}$$

where: $H^{GEN}{}_{i,t}$ is the heat generated by micro-generator i at time-step t.

$H^{LOAD}{}_{i,t}$ is the heat consumed by the owner of the micro-generator i at time-step t.

Assuming that there is enough heat storage capacity on-site, this constraint still allows the optimisation algorithm to decide at what time of the day it is best to operate the micro-CHPs. Otherwise, if no heat storage is available, the micro-CHP operational profile needs to match the heat demand profile throughout the day at all times.

4.2.3.4. Optimisation algorithm

The optimisation algorithm that was used in this study is the Interior Point algorithm in the "fmincon" tool of the MATLAB Optimization Toolbox [100]. The inequality constraints which represent the operating limits of the generators were introduced into the algorithm as upper and lower variable bounds.

The gradient of the objective function was supplied manually, which was used by the algorithm to determine the search direction that will lead to a minimum.

Customised acceleration factors were implemented on the gradient, thus helping the algorithm to reach an optimal solution faster. The gradient was also modified in such a way as to impose a lower operational limit on the micro-generators. With this limit, the optimiser cannot allocate a generator to produce below a given power level, or the generator would shut down.

4.3. VIRTUAL POWER PLANT CARBON OPTIMISATION STUDY

4.3.1. Virtual Power Plant description

The studied system is a Virtual Power Plant consisting of aggregated micro-generation sources and domestic customer loads which include electric vehicles. It is based on the UK generic distribution network described in [81]. The year 2030 was considered for the study, to ensure significant micro-generator and EV penetration. The VPP is illustrated in Fig. 4.1, and is described as follows:

- In total 18,432 domestic customers were included, split in 48 micro-grids, each comprising 384 customers.
- The micro-grid loads were lumped at the point of connection with the rest of the network.
- All micro-grids are assumed to be identical. The optimisation routine was run for one micro-grid and the output is scaled up to the whole VPP.
- Electrical network aspects were not considered.

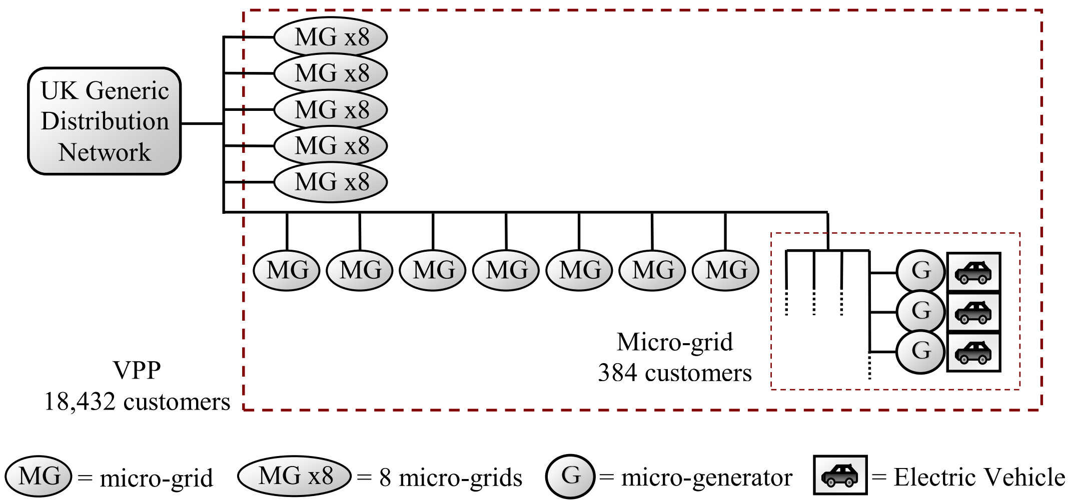

Fig. 4.1 The VPP and a micro-grid are depicted with dashed lines.

4.3.2. Inputs

4.3.2.1. Micro-generation data

Micro-generation types considered were:

(i) Wind turbines,

(ii) Photovoltaics,

(iii) Fuel cells (micro-CHP),

(iv) Microturbines (micro-CHP),

(v) Stirling engines (micro-CHP).

Renewables: Half-hourly wind and photovoltaic generation profiles were drawn from [87], for average winter and summer days. These profiles were taken as constant and were not optimised.

Micro-CHPs: The micro-CHP units were considered to be heat-oriented, without predefined daily profiles. The carbon optimal micro-CHP profiles are determined by the optimisation algorithm. When no heat storage is available, the micro-CHPs were considered to be forced to follow the heat demand profile. If the micro-CHP output cannot cover the customer heat load on a specific time step, a backup boiler was considered to provide the supplement.

4.3.2.2. Electric Vehicle charging regimes

The charging of EV batteries was treated as an additional electrical load [101]. Two charging regimes were used to examine different EV charging behaviours:

- **Uncontrolled charging regime:** All EVs are plugged in and start charging when commuters return home after work.
- **Economy charging regime:** Commuters charge their EVs during off peak times (i.e. between 23.00 and 6.00) [28]. Customers engaged with Economy 7 were considered to be engaged with the Economy EV charging regime as well.

A 13A charger was considered to be used by the EVs, which draws approximately 3kW, connected at a single phase in low voltage [101]. The EVs were considered to be of two types: Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV). The BEVs can reach full charge in 16 hours, while PHEVs in 4 hours [26].

4.3.2.3. Customer data

Electrical Profiles: Data from UKERC [102], provided by the Electricity Association were used to model the domestic electrical demand. Winter and summer typical weekdays were simulated to show the marginal cases of minimum and maximum load. The electrical load profiles were scaled according to values from [81], i.e. summer minimum load of 0.16kW and winter maximum load of 1.3kW per household. These values take into account the After Diversity Maximum Demand (ADMD) factor. It was considered that 16% of the domestic consumers are committed to dual tariff programs, Economy 7 in particular, as this was the case in 2006 [103][104].

According to [105], domestic electricity demand is increasing by 1% each year. This increase was taken into account in the reproduction of the domestic load profiles for 2030, considering the year 2003 as a base (starting) scenario.

Thermal Profiles: Regarding the heat demand, daily profiles from [106] were used, for both winter and summer (see Fig. 4.2). From these profiles, the daily heat demand per household was calculated to be approximately 61kWh in winter and 8kWh in the summer.

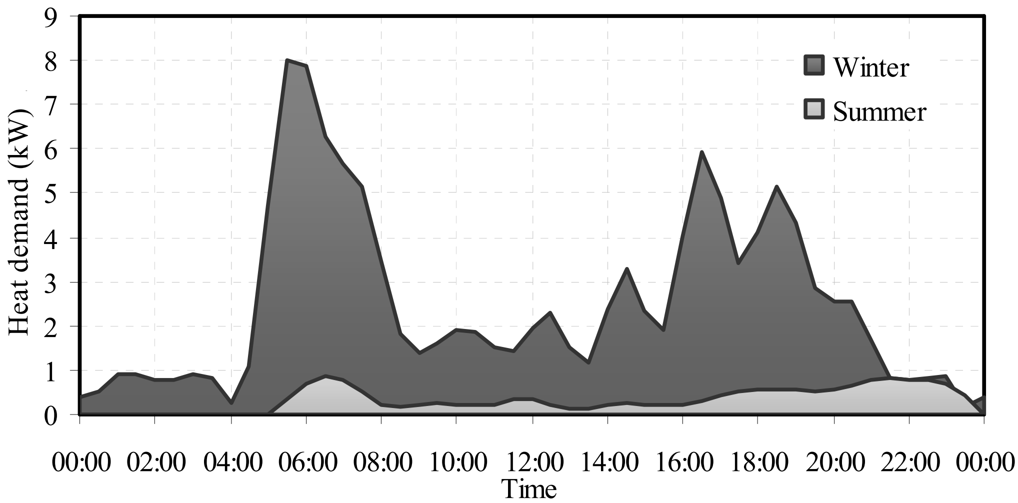

Fig. 4.2 Daily domestic heat demand for winter and summer [106]

4.3.3. Study cases

4.3.3.1. Micro-generation penetration scenarios

The total micro-generation penetration is calculated based on a typical installation of 1.1kW per customer, as in [81]. A penetration of 100% is considered as the equivalent of every customer owning a 1.1kW micro-generator. Three penetration scenarios were defined:

(i) Low (10%),
(ii) High (30%),
(iii) Full (100%).

Table 4.I shows the micro-generation penetration levels considered for 2030. The Microturbines, Fuel Cells and Stirling Engines are considered to be micro-CHP units, capable of producing heat at a Heat to Power Ratio (HPR) of 2.6, 1.4 and 5 respectively [6][13]. The percentages of installed micro-generator per type were based on an estimate of the 2030 micro-generation mix, found in [7]. Nationwide low and high micro-generation penetration predictions were taken from [90] and scaled down to the VPP level. The typical installed power per customer was considered 2.5kW for wind turbines, 1.5kW for photovoltaics, 3kW for microturbines and fuel cells and 1.2kW for Stirling engines [7][19][89][90]. The typical installed values were assumed to be the same in 2030.

TABLE 4.I: MICRO-GENERATION PENETRATION LEVELS PER 18432 CUSTOMERS

Micro-generator type	Unit Power (kW)	Penetration (Units)			Micro-generator ratio of installed power per type
		Low	**High**	**Full**	
Wind Turbines	2.5	192	528	1824	22.64%
Photovoltaics	1.5	96	288	960	7.24%
Fuel Cell (Natural Gas)	3	144	432	1536	22.73%
Microturbine (Biogas)	3	96	192	720	10.88%
Stirling Engine (Wood Pellets)	1.2	624	1824	6144	36.50%
Total (No. of Installations)		1152	3264	11184	100.00%
VPP Installed Power (MW)		2.1	5.9	20.3	-
Penetration Level (%)		10%	30%	100%	-

4.3.3.2. Electric Vehicles penetration scenarios

The 2030 EV penetration projections from [107] were considered. The corresponding number of EVs predicted to be owned by the total number of VPP customers (18,432 customers) in 2030 is presented in Table 4.II. Two penetration levels were forecasted.

TABLE 4.II: EV PENETRATION LEVELS PER 18432 CUSTOMERS [107]

Low Penetration (12%)		High Penetration (70%)	
BEV	PHEV	BEV	PHEV
768	1536	3840	9216

4.3.3.3. Thermal storage scenarios

In order to study the effect of thermal storage on VPP emissions, three cases were considered: (i) no storage, (ii) a 500L water tank and (iii) unlimited storage. The minimum and maximum water temperature was assumed to be 50°C and 85°C respectively [108]. Given that 1.16 Wh is required to heat 1 litre of water by 1°C [109], the 500L water tank would store approximately 20 kWh of heat.

4.3.4. Carbon Emissions

4.3.4.1. Micro-generation emission factors

The emission factors used to calculate the emissions of the VPP were presented in Chapter 3. They have been re-calculated to reflect the year 2030. Life-cycle emissions were also considered. The methodology is fully described in Chapter 3. All the emission factors used in this study are presented in Table 4.III, including the average grid emission factor, as it is calculated from data found in [96] (see next section).

TABLE 4.III: EMISSION FACTORS FOR THE DIFFERENT COMPONENTS OF THE VPP

Component	Emission Factor (gCO_2-e/kWh)
Wind Turbines	28.94
Photovoltaics	86.78
Fuel Cell (Natural Gas)	421.23
Microturbine (Biogas)	285.81
Stirling Engine (Wood Pellets)	76.46
Grid electricity (average) [4][96]	495.24 → 248.00

4.3.4.2. Grid carbon intensity profile

In order to study the effect of grid carbon intensity variations throughout the day, UK grid emissions data were collected from [96] for five consecutive weekdays and averaged to create a half-hour daily carbon intensity profile. This profile was scaled down to the average UK grid carbon intensity in 2030, as predicted in the Low-Carbon Resilient scenario in [4], which is 248 gCO_2/kWh. Original data are shown in Fig. 4.3 and the constructed profile in Fig. 4.4.

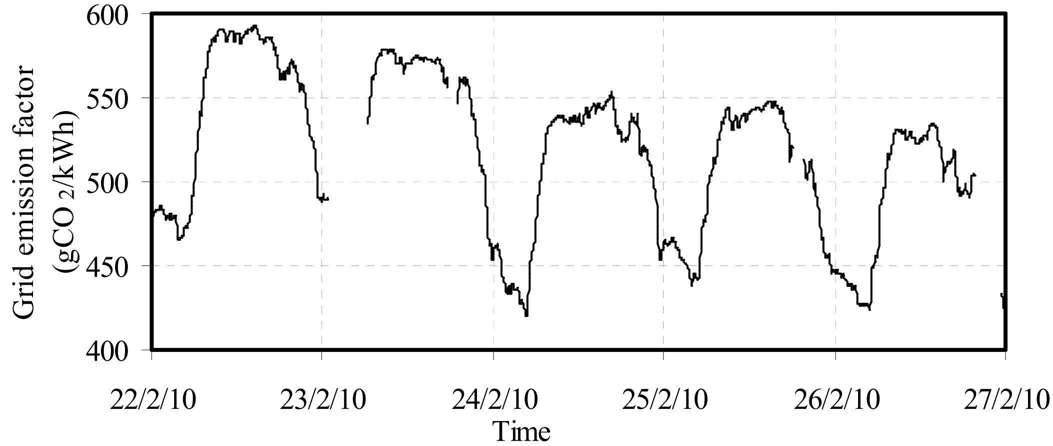

Fig. 4.3 Instantaneous UK grid carbon intensity in five weekdays [96]

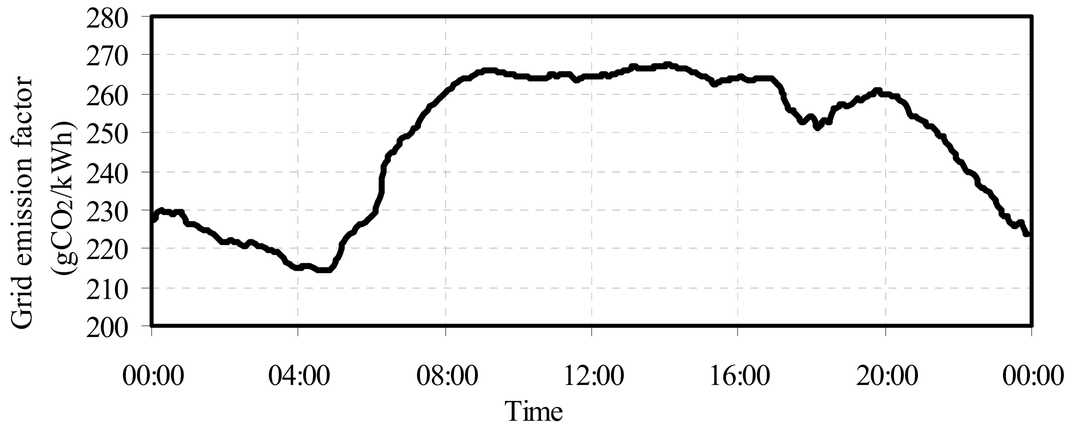

Fig. 4.4 Daily UK grid carbon intensity profile in 2030

4.3.4.3. Micro-CHP part-load emissions

Part-load efficiency curves were drawn from the literature and the industry for fuel cells, microturbines and Stirling engines [6][97][98]. The part-load efficiency curves from Fig. 4.5 and the emission factors in Table 4.III were used with Equation (13) to derive the part-load emission factor curves shown in Fig. 4.6.

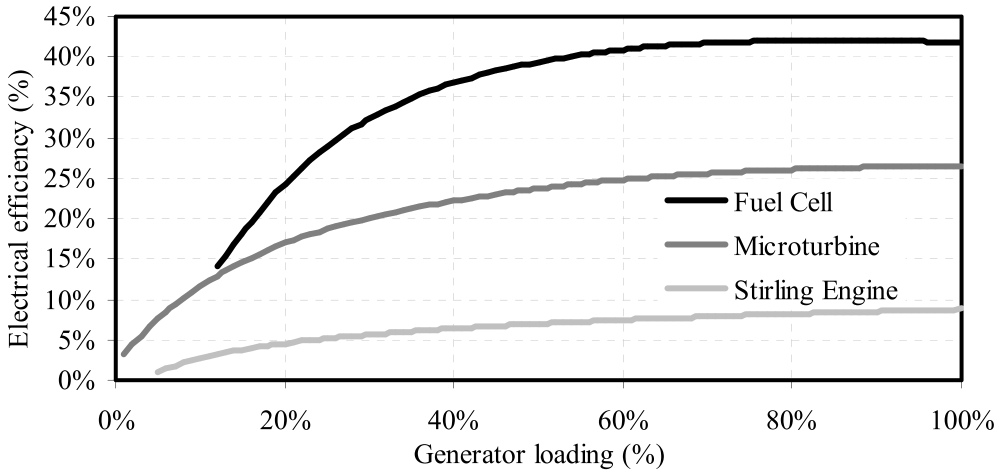

Fig. 4.5 Part-load micro-generator electrical efficiency, from [6], [97] and [98]

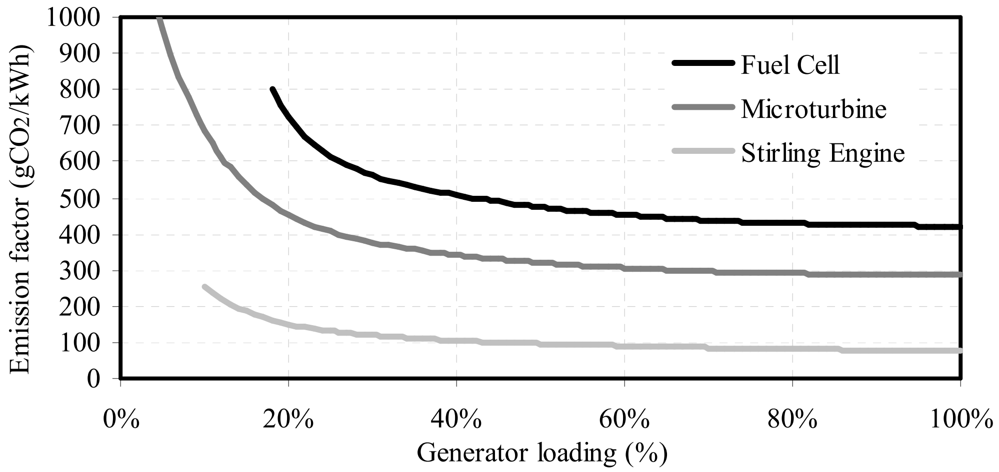

Fig. 4.6 Part-load micro-generator emissions factors, calculated using data from [6], [97] and [98]

4.4. Optimisation Results and Discussion

4.4.1. Optimal profiles

4.4.1.1. Optimal profiles by micro-generation type

In Fig. 4.7, the micro-CHP winter day optimal profiles are presented for the full micro-generation penetration (100%) and low EV penetration (12%) scenario, with 500L thermal storage per customer. The total power of all micro-generators of each type is shown. The photovoltaic and wind turbine profiles were not optimised. They are shown in Fig. 4.8. The sum of all the micro-generator power plus the grid power always equals the total electricity demand within the VPP area.

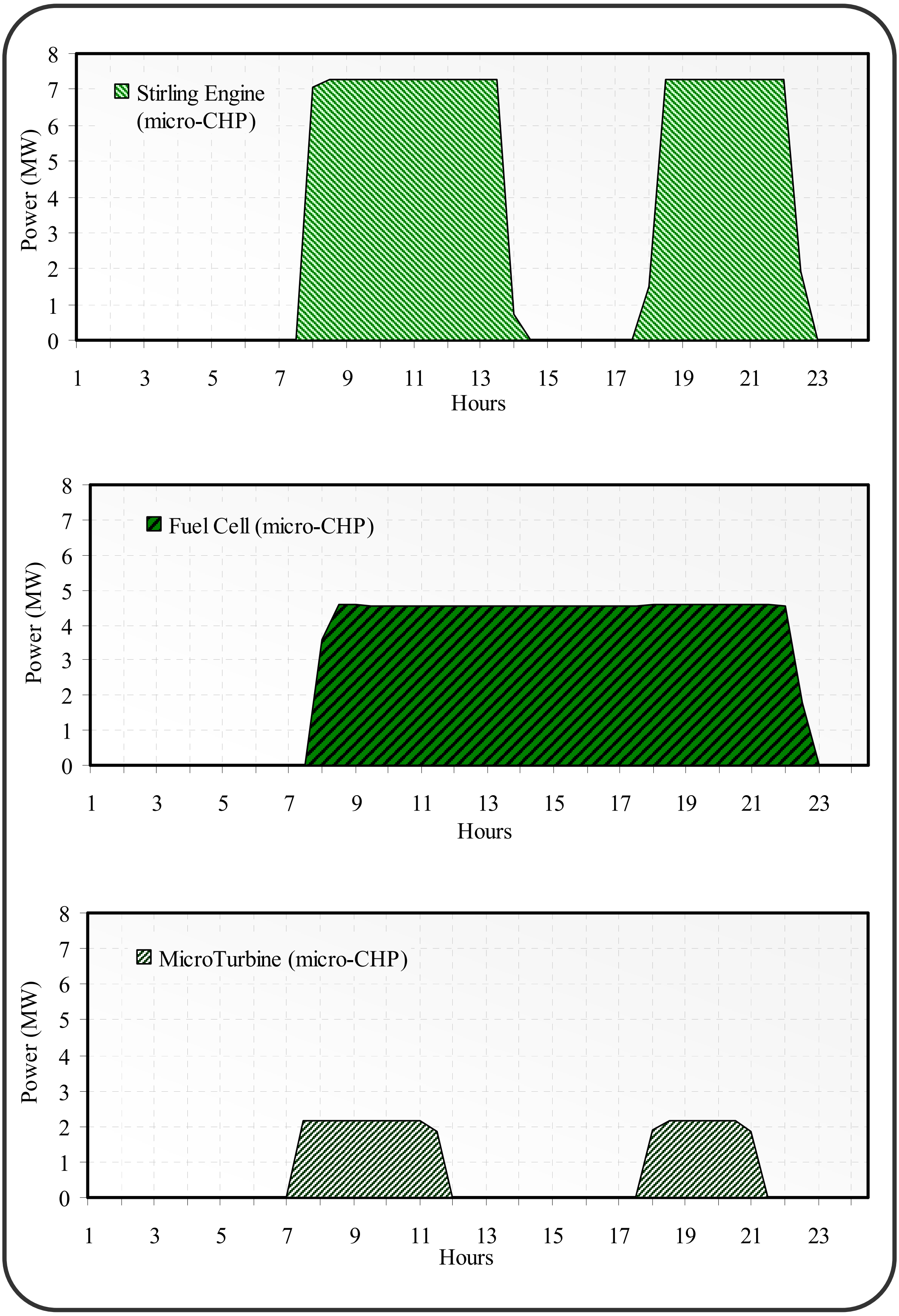

Fig. 4.7 Total micro-CHPs electricity generation profiles in **winter** at Full penetration **(100%)**.

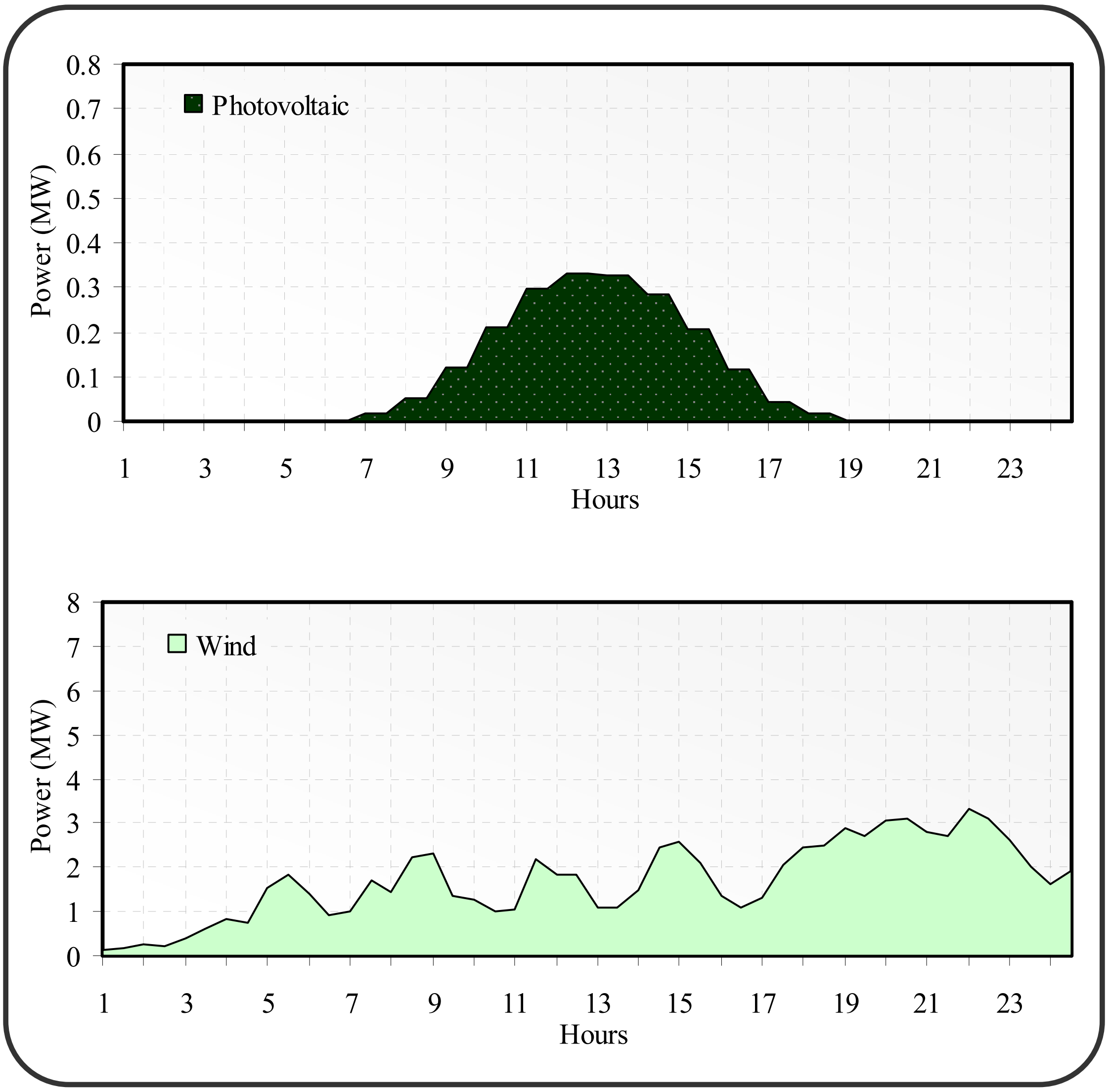

Fig. 4.8 Total renewables electricity generation profiles in **winter** at Full penetration **(100%)**.

The micro-CHPs were found to produce almost constantly, near the middle of the day, when the grid emission factor is high. The interruption observed in Stirling engines and microturbines in Fig. 4.7 is due to the thermal storage being full. The micro-CHPs then shut down, and do not start up until the storage levels drop again.

4.4.1.2. Cumulative optimal profiles by season

In Fig. 4.9, the above profiles are added, to come up with the cumulative profile for all the penetration scenarios. The dashed line shows the load without any Electric Vehicles. In Fig. 4.10, the results for the respective micro-generation penetrations during the summer are shown. The low EV penetration scenario (12%) was considered in all the figures.

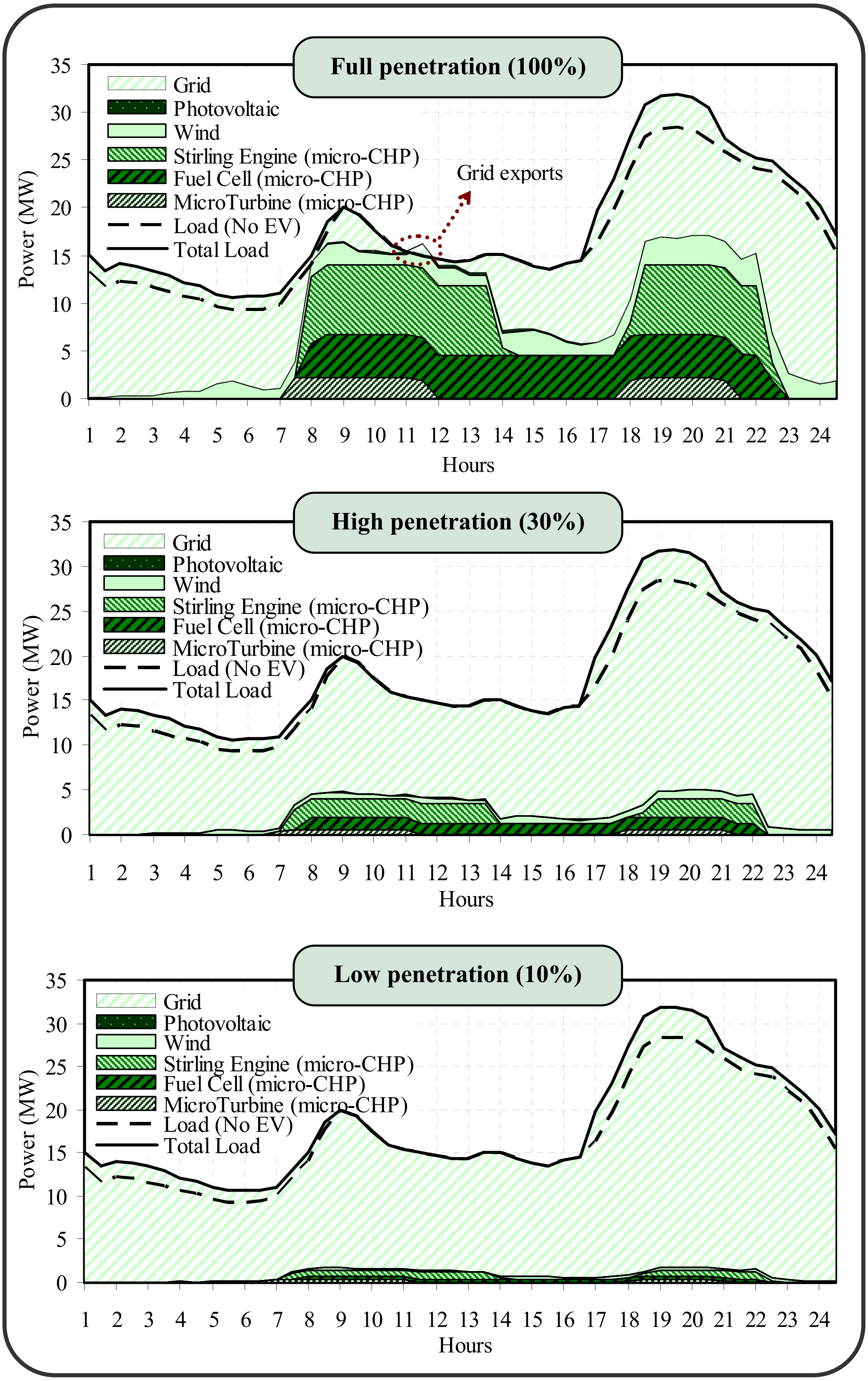

Fig. 4.9 Electrical profiles in **winter** at various micro-generation penetration levels.

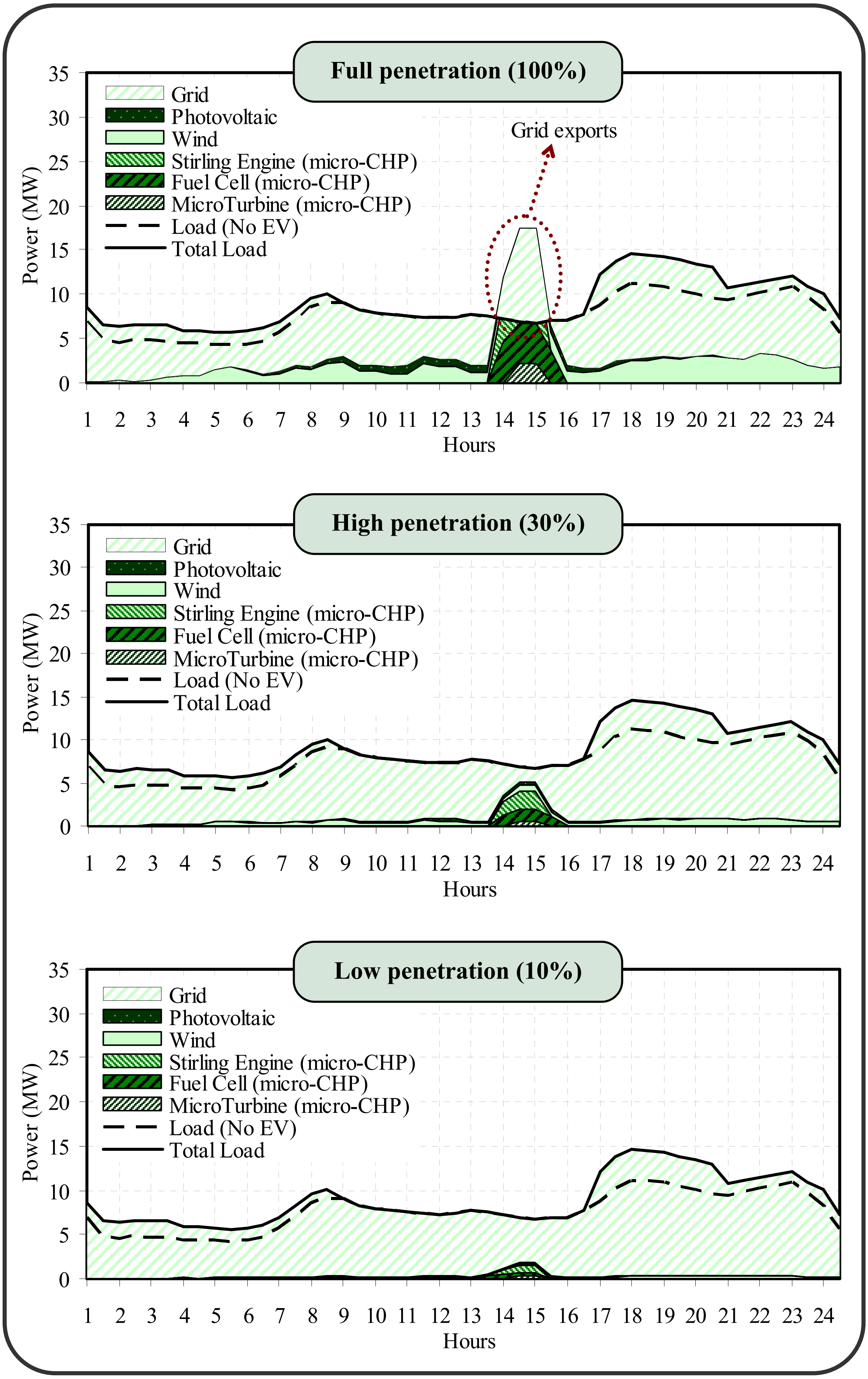

Fig. 4.10 Electrical profiles in **summer** at various micro-generation penetration levels.

In the summer cases, the micro-CHPs were found to produce only for a short period in the middle of the day, when the grid emission factor is high. That is because the summer thermal demand was low. The electrical demand was also low. Thus, at the Full micro-generation penetration scenario, a significant portion of the produced electricity was being exported to the grid (see Fig. 4.10). Small electricity exports are also observed in winter (see Fig. 4.9).

4.4.2. Daily carbon emissions

In Table 4.IV, the total emissions incurred to cover the demand of the 18,432 customers in the VPP area are presented for each of the scenarios. This includes emissions from the grid. They are shown schematically in Fig. 4.11.

TABLE 4.IV: TOTAL VPP DAILY CARBON EMISSIONS BY SCENARIO (tCO_2)

Micro-generation Penetration	Carbon Emissions (tCO_2)			
	Low EV penetration		High EV penetration	
	Winter	Summer	Winter	Summer
Base Case (0%)	**337.29**	**83.19**	**369.94**	**115.84**
Low (10%)	325.48	80.79	358.12	113.44
High (30%)	304.18	76.41	336.83	109.07
Full (100%)	188.81	55.55	221.77	88.20

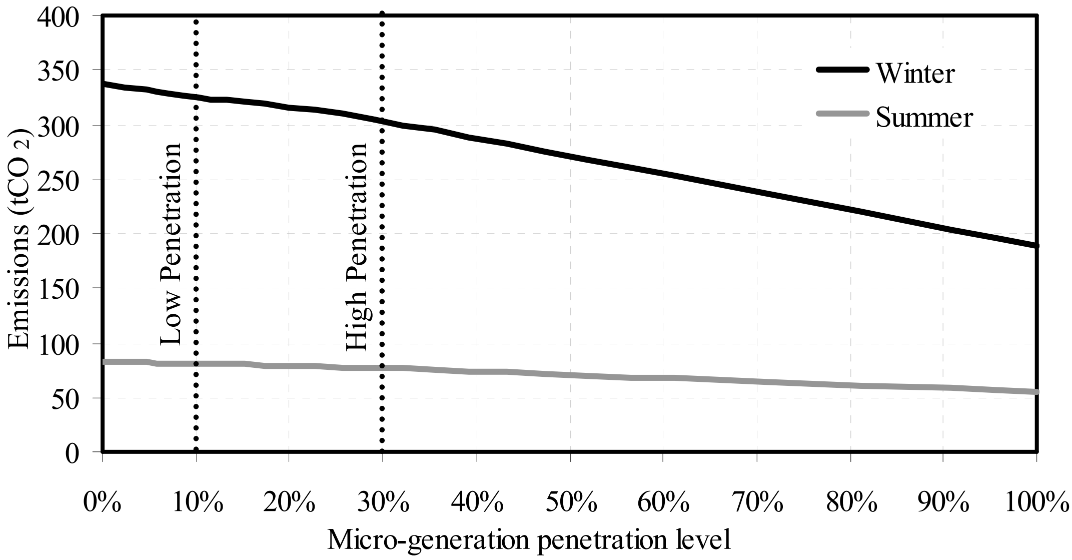

Fig. 4.11 Total daily carbon emissions incurred to serve the electrical and heat demand of the 18,432 customers included in the VPP area.

4.4.3. Emissions savings

Overall, the emission savings were assessed in three ways, compared with the reference case (without micro-generation installed). At Full (100%) micro-generation and Low (12%) EV penetration, it was found that:

(i) Total savings of a VPP with optimised profiles, utilising thermal storage were **44%** (modelled in MATLAB).

(ii) Total savings of a VPP without optimised profiles, utilising thermal storage were **42%** (modelled in Microsoft Excel).

(iii) Total savings of a VPP without optimised profiles, not utilising thermal storage were **41%** (modelled in MATLAB).

4.4.3.1. Total savings with optimised profiles

Table 4.V presents the carbon emission savings that would be achieved in the three studied micro-generation penetration scenarios, compared to the reference case (no micro-generation). A 500L thermal storage tank was considered.

TABLE 4.V: SAVINGS COMPARED TO NO MICRO-GENERATION (LOW EV PENETRATION – 500L THERMAL STORAGE)

Micro-generation Penetration	Emission Savings (%)	
	Winter	Summer
Base Case (0%)	**0.00%**	**0.00%**
Low (10%)	3.50%	2.89%
High (30%)	9.82%	8.15%
Full (100%)	44.02%	33.23%

4.4.3.2. Benefit of optimisation

When the micro-CHP output is not optimised, it simply follows the heat load. The difference between optimised and unregulated generation can be seen in Table 4.VI. Sub-optimal (unregulated) savings were calculated using Microsoft Excel. A 500L thermal storage tank was considered.

TABLE 4.VI: SAVINGS INCREASE BY OPTIMISING THE VPP (WINTER – LOW EV PENETRATION – 500L THERMAL STORAGE)

Micro-generation Penetration	Emission Savings (%)		Savings Increase	
	Unregulated	Optimised	absolute	relative
Low (10%)	**3.30%**	3.50%	+ 0.20%	+ 5.78%
High (30%)	**9.37%**	9.82%	+ 0.45%	+ 4.59%
Full (100%)	**42.12%**	44.02%	+ 1.90%	+ 4.33%

4.4.3.3. Effect of thermal storage

When thermal storage is installed at the premises of a customer, the micro-CHP unit can supply the heat load with more flexibility. The optimisation algorithm exploited that flexibility and the emissions savings were increased. The effect of thermal storage on emission savings can be seen in Table 4.VII.

TABLE 4.VII: SAVINGS INCREASE WITH HEAT STORAGE (WINTER – LOW EV AND MICRO-GENERATION PENETRATION)

Heat storage size	Emission Savings (%)	Savings Increase	
		absolute	relative
No Heat Storage	**3.15%**	**+ 0.00%**	**-**
500L Tank	3.50%	+ 0.35%	+ 11.13%
Unlimited Storage	3.54%	+ 0.39%	+ 12.40%

4.4.4. Carbon intensity – emission factor

The average emission factor (gCO_2/kWh) of the electricity and heat delivered to the customers is presented in Fig. 4.12, with respect to the micro-generation penetration level. Similarly, the average emission factor per km travelled by the EVs when charged with energy supplied by the resulting generation mix (VPP and the grid) can be seen in Fig. 4.13.

The values used to draw Fig. 4.12 and Fig. 4.13 are shown in Table 4.VIII and Table 4.IX. The base case involves exclusively grid electricity and heat from a standard gas boiler. For calculating heat emission factors, the heat supplied by the micro-CHPs was considered to be emission-free. The micro-CHP emissions were incorporated only in the co-generated electricity.

TABLE 4.VIII: CARBON INTENSITIES BY SCENARIO – LOW EV PENETRATION

Micro-generation Penetration	Carbon Intensity (gCO_2/kWh)			Carbon Intensity (gCO_2/km)	
	Electricity (Winter)	Electricity (Summer)	Heat	BEV (Winter)	BEV (Summer)
Base Case (0%)	**248.00**	**248.00**	**204.00**	**54.90**	**54.90**
Low (10%)	245.52	243.40	194.44	54.54	54.23
High (30%)	241.02	235.10	176.91	53.88	53.01
Full (100%)	225.87	204.52	80.22	51.66	48.54

TABLE 4.IX: CARBON INTENSITIES BY SCENARIO – HIGH EV PENETRATION

Micro-generation Penetration	Carbon Intensity (gCO_2/kWh)			Carbon Intensity (gCO_2/km)	
	Electricity (Winter)	Electricity (Summer)	Heat	BEV (Winter)	BEV (Summer)
Base Case (0%)	**248.00**	**248.00**	**204.00**	**54.90**	**54.90**
Low (10%)	245.85	244.57	194.44	54.59	54.40
High (30%)	241.87	238.29	176.91	54.00	53.48
Full (100%)	228.74	215.70	80.22	52.08	50.17

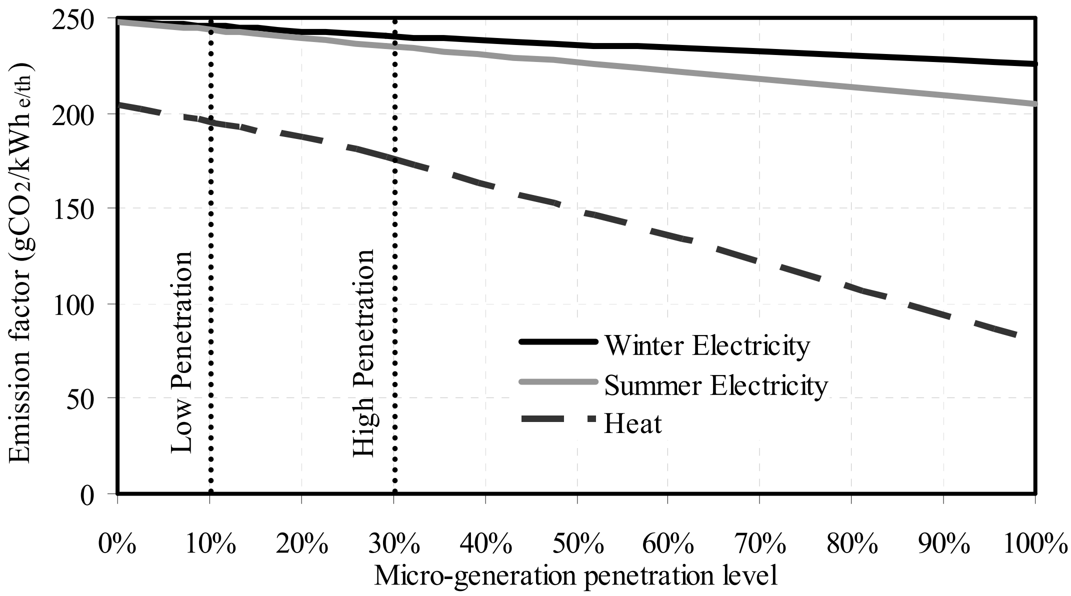

Fig. 4.12 Overall emission factor of electricity and heat delivered to the load, according to penetration level of micro-generation (low EV penetration).

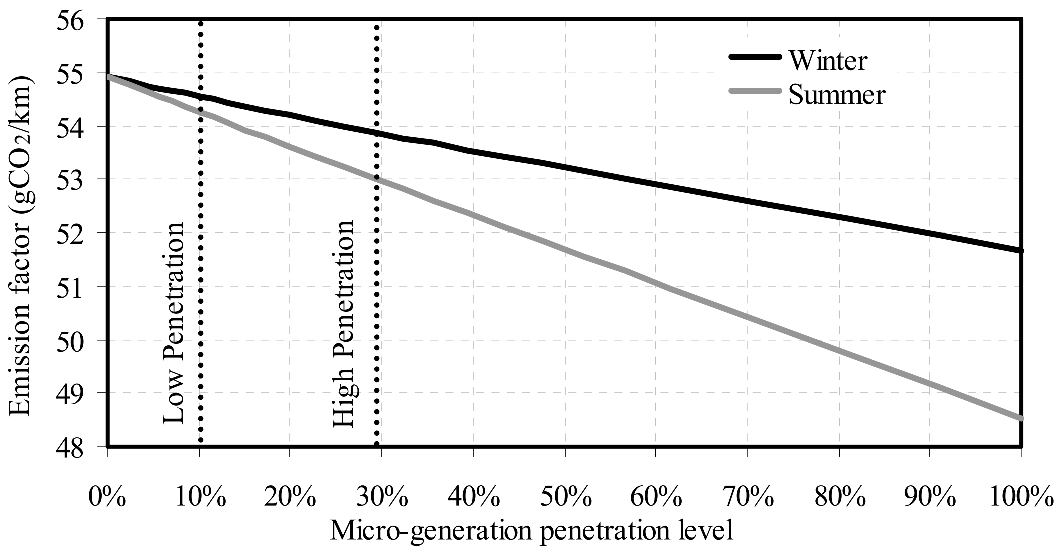

Fig. 4.13 Final emission factor of distance travelled by Battery Electric Vehicles (BEV) charged by the studied generation mix (low EV penetration).

4.4.4.1. Emission factor daily variation

Fig. 4.14 presents the overall emission factor daily variation of the electricity supplied to the customers during the winter, and how this changes at each micro-generation penetration level. It incorporates micro-generation and grid electricity emission factors. The same graph is presented in Fig. 4.15 for the summer.

It is observed from Fig. 4.14 and Fig. 4.15 that when the micro-generators are starting up and shutting down, the overall emission factor increases sharply for a short period. This is due to the effect described in Section 4.2.2.2. When they produce constantly, the overall emission factor is reduced because they are less carbon intensive than the grid.

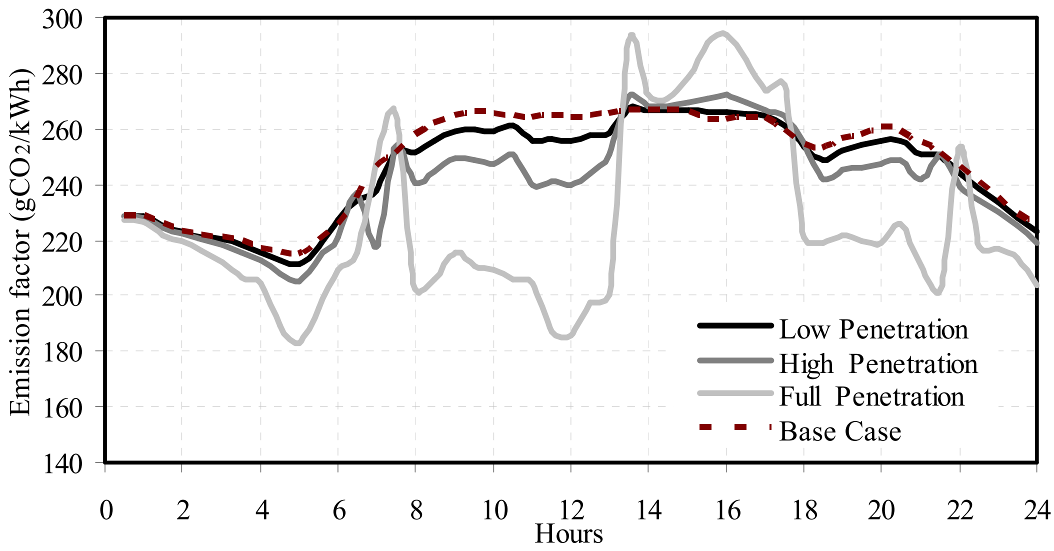

Fig. 4.14 Emission factor variation of electricity delivered to the load during the **winter**.

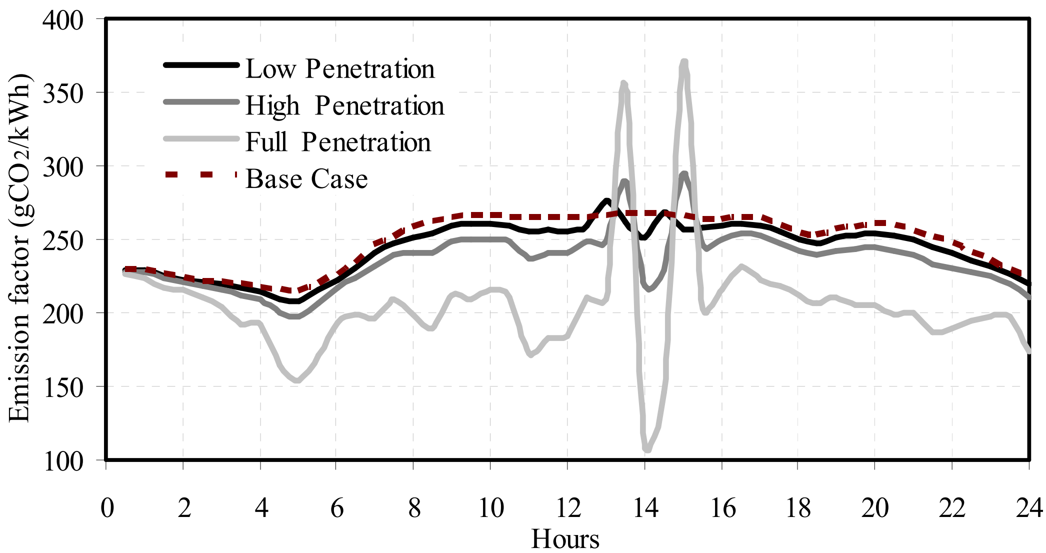

Fig. 4.15 Emission factor variation of electricity delivered to the load during the **summer**.

4.5. SUMMARY

In this chapter, an optimisation method was used to optimise the emissions of aggregated micro-generation. A Virtual Power Plant case study was constructed for the year 2030. The VPP was considered to include five types of micro-generators and electric vehicles as additional electrical load. Three of the micro-generation types were considered to be CHP-capable. The emissions from the energy supplied to the customers in the VPP area were minimised. Only the profiles of micro-CHPs were optimised.

Three micro-generation penetration scenarios and two EV penetration scenarios were considered. The micro-generation penetration was characterised as: (i) low (10%), (ii) high (30%) and (iii) full (100%). In the base case, no micro-generation was considered to be installed.

The main findings are stated below:

Emission savings: With the studied micro-generation mixes, the carbon emissions required to supply the electrical and thermal load of 18,432 domestic customers can be reduced up to 44%, compared to the base case scenario. This reduction is mainly due to the waste heat being recovered by the micro-CHPs. The low emission factors of the micro-generators that utilise renewable sources also affected the savings significantly.

Optimal profiles: The optimal generation profiles for each type of micro-generation were drawn. It was found that if the micro-CHP generation profiles were not optimised, the emission savings would be limited from 44% to 42%.

Thermal storage gives flexibility to the micro-CHP with respect to when the heat is produced. For instance, the micro-CHP can produce at times when the grid emission intensity is higher, avoiding more grid emissions. When no storage was considered, the micro-CHP would have to follow the thermal demand. The emission savings would then be limited from 44% to 41%.

Start-up/shut-down emissions: As a result of the optimisation, many micro-CHPs are started or stopped simultaneously at specific time periods. This causes some spikes in the emissions profile (see Fig. 4.14 and Fig. 4.15), which are due to the micro-CHP additional start-up/shut-down emissions.

Electricity and heat carbon intensity: The aggregated carbon intensity of the electricity supplied to the load has been found to reduce from 248 gCO_2/kWh forecasted in [4] to 205 gCO_2/kWh, during the summer. Likewise, the average carbon intensity of the produced heat is found to be reduced from the 204 gCO_2/kWh of a typical boiler, to approximately 80 gCO_2/kWh.

Electric Vehicle carbon intensity: The reduction of electricity carbon intensity is reflected in the Electric Vehicle carbon intensity. This would drop from approximately 55 gCO_2/km, as projected for 2030, to 48.5 gCO_2/km during the summer.

Chapter 5
Environmental Virtual Power Plant

5.1. Introduction

Micro-generation has the potential to reduce emissions by displacing generation from conventional power plants [6]. However, their size does not allow them to participate individually in the EU Emission Trading Scheme, since the minimum rating for participation is 20MW [5].

Aggregation of distributed resources has been studied extensively and benefits to power system operation have been demonstrated [42][43][44][45]. By aggregating resources, the controllability and predictability of distributed generation is improved. Distributed control using intelligent software agents has been proposed as a promising method of aggregation, otherwise referred to as Multi-Agent Systems (MAS) [53][57]. This method offers the benefit of increased flexibility and extensibility. Distributed energy resources can be integrated or removed, with little or no changes to the control system. On the contrary, a centralised system would need fundamental changes to add a new resource, which involves an associated cost [59][69].

Most of the research performed on aggregation has been focused either (i) on technical aspects such as power system stability and voltage control or (ii) on economic aspects such as electricity market participation [41]. In [63], centralised control of aggregated micro-generation for participation in emissions trading schemes has also been demonstrated. Participation of distributed energy resources in emissions markets has been shown to have a positive effect in the overall power system emissions and an economic benefit for the owners of the resources. However, no decentralised approach has been considered. In [64], a market-based multi-agent system has been designed for the control of distributed resources with emissions considerations. So far, the emissions element was either factored in the cost, or set as a constraint, not as the main goal.

In this chapter, a multi-agent system for the distributed control of micro-generation emissions is presented. An Environmental Virtual Power Plant (EVPP) is defined, incorporating an internal emissions market. An aggregation entity is created, which is regulating the EVPP emissions. The micro-generators can collaborate to satisfy their operational needs while adhering to the aggregator emissions requirements. Control policies are established for the aggregator. The control policies are: (i) emissions reduction, (ii) profit maximisation by participation in the electricity market or (iii) a multi-objective balance of both. Therefore, the aggregator acts as a proxy for the micro-generation participation in the electricity or emissions markets. The developed MAS control system is evaluated using a simulated case study. The results are reported together with the benefits and limitations of the approach and implementation.

This technique can be used by business entities acting as distributed resource aggregators. Its purpose is to use the market concept of the emissions trading schemes for the distributed control of micro-generators. It inherits the benefits of distributed control systems, while adding direct compatibility with existing emissions markets. The benefit is bilateral:

- For the aggregator, a potential customer base is created and
- For the micro-generators, the participation in emissions markets is facilitated.

5.2. ENVIRONMENTAL VIRTUAL POWER PLANT (EVPP) DEFINITION

5.2.1. A Virtual Power Plant with emissions trading

In [41], the Commercial Virtual Power Plant (CVPP) and the Technical Virtual Power Plant (TVPP) are defined, according to the orientation of the aggregation towards markets and power system operation respectively.

A control system is proposed for the Virtual Power Plant that was described in Chapter 4. Following on the designation in [41], this control system is referred to as an Environmental Virtual Power Plant (EVPP), since the target is the control of greenhouse gas emissions from the micro-generators. An EVPP would be a sub-type of the CVPP if its operation is oriented towards emissions markets.

The EVPP simulates the operation of the EU Emissions Trading Scheme [5]. The main aspects of the proposed control system are the following:

- The EVPP Aggregator is acting as the regulator, who issues Carbon Credits.
- The micro-generators are EVPP participants and receive the Carbon Credits.
- An emissions market is created by allowing the micro-generators to trade Carbon Credits between them to cover their needs.
- Intermediate aggregators may be necessary for reducing communications.

An emissions-oriented aggregator policy can be guided either by regulatory frameworks requiring emissions reductions, or by providing economic incentives such as the emissions markets. The emissions of a single micro-generator depend on many factors such as temperature, type of fuel, generator loading, etc. It may be impractical or sometimes impossible to centrally predict and individually control the emissions of a large number of micro-generators.

Thus, a hierarchical control approach is proposed. Intelligence is distributed to the micro-generator controllers, to handle their individual goals and limitations locally. The aggregated emissions policy is placed at the EVPP Aggregator, while the rest of the intelligence is placed at the level of individual micro-generator controllers.

The main **purpose** of the EVPP is to control the overall emissions without managing individual micro-generators.

5.2.1.1. Benefits

This approach inherits the benefits of a distributed aggregation system, which include flexibility, extensibility and robustness [59],[69]. The main benefits are:

- **Emissions reduction** of the overall power system, due to better emissions performances of micro-generators compared to conventional generation.
- **Micro-generators access** and participation in the electricity and/or emissions markets.
- **Security and robustness:** In the case of a control system failure, only part of the EVPP is affected.
- **Flexibility and extensibility:** A micro-generator may be added or removed without complex and costly modifications to the control system.

5.2.1.2. Limitations

The main limitation of this hierarchical control approach is that the EVPP is not as predictable or controllable as a large conventional power plant. Despite other drawbacks, direct control of micro-generators would offer more controllability than the proposed system. In the EVPP, direct control signals are replaced by incentives and penalties, which actually allow the micro-generators not to follow EVPP directions.

5.2.2. EVPP Aggregator Carbon Credits

The Carbon Credit is defined as an emission certificate, allowing the release of a given quantity of carbon dioxide equivalent (CO_2-e) emissions by the holding party [5]. The Carbon Credits are transferrable; therefore they can be traded between the participants of the same scheme. One Carbon Credit in the EU emissions market represents 1 tonne of CO_2-e [5].

In the EVPP, the EVPP Aggregator issues Carbon Credits to the micro-generators through the intermediate aggregators (micro-grid). These internal EVPP Carbon Credits can be traded between micro-generators and are decoupled from the Carbon Credits traded in the emissions markets. In the EVPP, the internal Carbon Credits may represent 1 kg CO_2-e or 1 gram CO_2-e, depending on the size and emission rates of the generators.

The EVPP Aggregator manages the micro-generator Carbon Credits and participates in the emissions market as one entity. It trades Carbon Credits in the emissions market to justify the emissions of the micro-generators as if they were its own emissions. However, the trading periods are different in the EU emissions market, where closure occurs once a day, and within the EVPP, where trading periods may vary from minutes to hours. Thus, the aggregator acts as an interface between the external market Carbon Credits and the internal aggregator Carbon Credits. This concept is illustrated in Fig. 5.1.

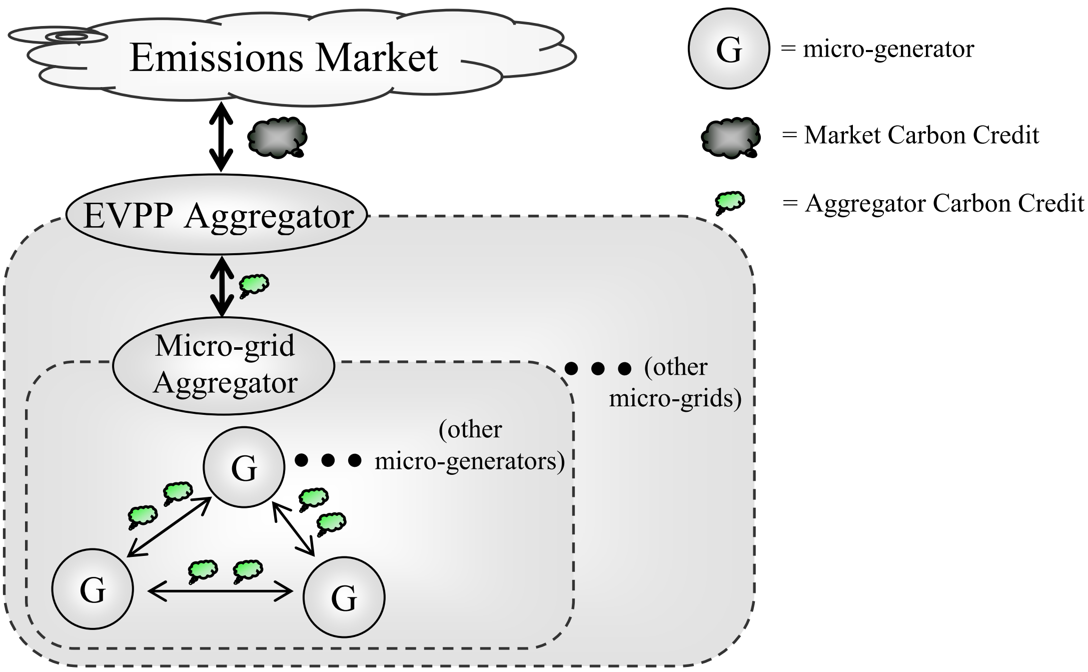

Fig. 5.1 Aggregator and market Carbon Credits trading

5.2.3. EVPP Control Policies

The control policy that is followed by the EVPP Aggregator defines the amount of Carbon Credits that are created at each trading period and consequently fed into the internal market. The control policies may cover many aspects, but the policies considered in this research are the following:

(i) **Emissions policy:** The grid emission factor is not constant, but it varies according to the instantaneous electricity mix [96]. In this policy, the amount of Carbon Credits that are created is proportional to the grid emission factor. The goal of this policy is to increase the EVPP output during high grid emissions factor periods, hence displacing more carbon-intensive generation. The total emissions are then reduced.

(ii) **Cost policy:** In this policy, the amount of Carbon Credits that are created is proportional to the electricity market price. The EVPP is considered to participate in the wholesale electricity markets in order to sell/buy its electricity. Since the electricity generation is directly proportional to the emissions, this policy drives the EVPP to generate more when the electricity price is high, to increase its revenue.

(iii) **Mixed policy (Cost & Emissions):** The above two policies are combined. The EVPP emissions production is driven by two objectives. This multi-objective strategy is defined by means of fuzzy inference methods (see Section 5.3.5).

The micro-generators make projections for the next operational period. The EVPP Aggregator collects these projections through intermediate, Micro-grid Aggregators. Thus, it has the following aggregated information available:

- **Lowest possible emissions:** the minimum amount of emissions that the micro-generators can produce without failing to supply thermal demand (micro-CHP) or without wasting renewable energy (wind turbines/photovoltaics).
- **Projected/Desired emissions:** the amount of emissions that the micro-generators would desire to produce, in order to satisfy their individual strategy. An example micro-CHP strategy is to maintain thermal storage above a given level (e.g. 75%) at all times. The amount of Carbon Credits that the EVPP Aggregator distributes to each micro-generator is in proportion to this number.

- **Highest possible emissions:** the maximum amount of emissions that the micro-generators can produce. For micro-CHP, it is the maximum amount of emissions without wasting co-produced heat. For wind turbines and photovoltaics, the maximum amount of emissions is limited by the actual output of the wind turbine or the photovoltaic.

5.2.4. EVPP Operation

The EVPP control mechanism can be described as an internal market, based on the concept of the Emissions Trading Scheme. Scaling it down to micro-generation level, the EVPP Aggregator plays the role of the regulator who issues the Carbon Credits to micro-generators, through the intermediate Micro-grid Aggregators. The micro-generators are the carbon emitters.

The EVPP Aggregator is operating on a repetitive basis, at predefined time steps (e.g. every 15 minutes). The sequence is shown in Fig. 5.2.

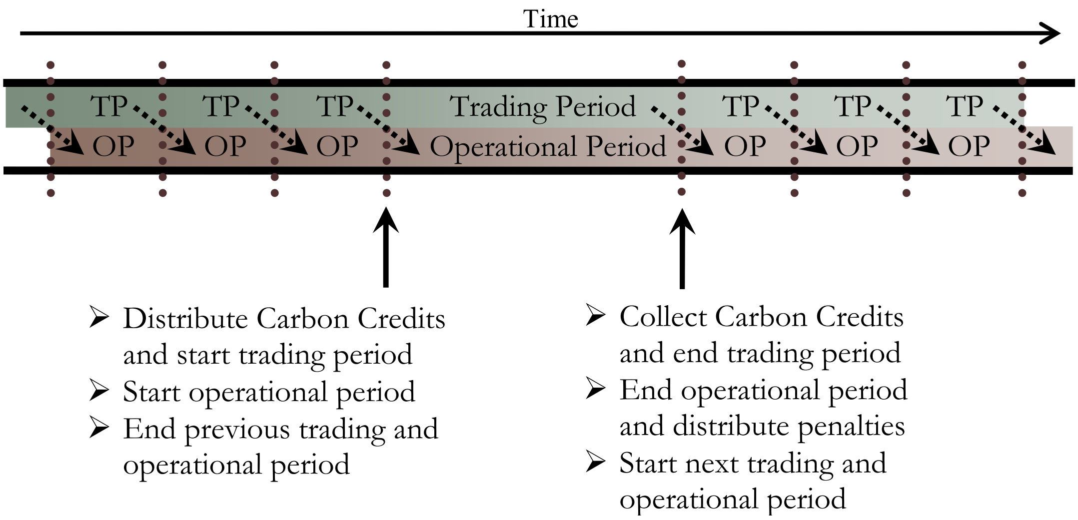

Fig. 5.2 Trading and operational periods of the EVPP

The main stages of the interaction between the EVPP participants at every time-step are the following (also see Fig. 5.3):

1) **The start** of the trading period, when the EVPP Aggregator distributes the Carbon Credits to the micro-generators, through the Micro-grid Aggregators.
2) **The trading period**, when the micro-generators trade Carbon Credits to match their needs.

3) **The end** of the trading period, when the micro-generators return their Carbon Credits to the EVPP Aggregator, through the Micro-grid Aggregators.
4) **Penalties** are imposed on the micro-generators, where necessary, to cover for Carbon Credit excess or shortfall.

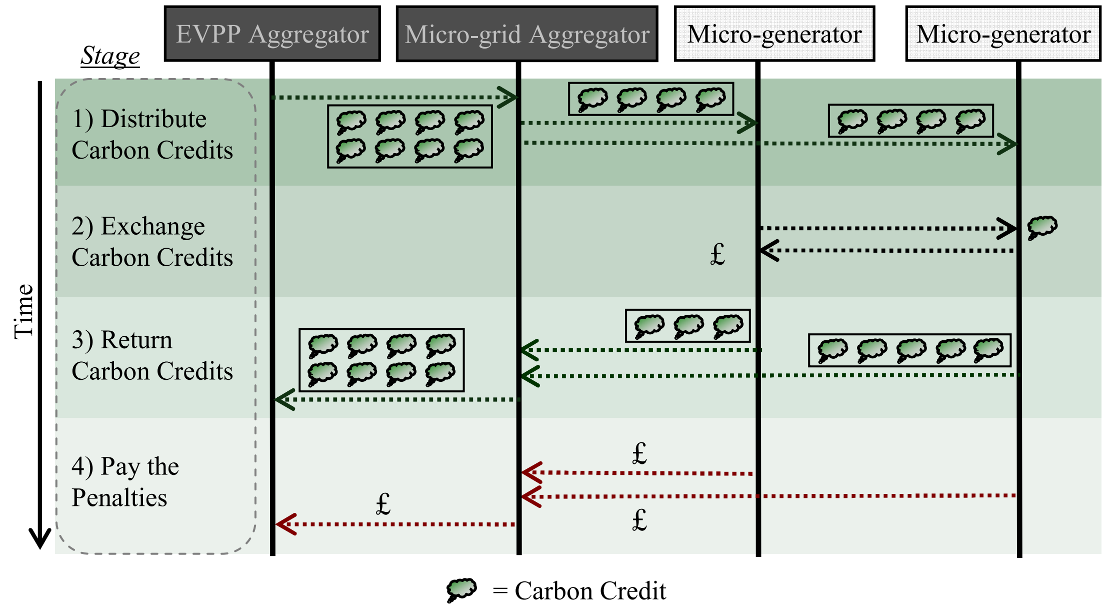

Fig. 5.3 Aggregator and micro-generators interaction stages at every time-step

Diagrams describing the aggregator/micro-generator interaction and micro-generation trading sequences can be found in Appendices E and F respectively.

The ideal outcome of the above balancing process is that all the micro-generators hold enough Carbon Credits to satisfy their emission needs, as illustrated in Fig. 5.4:

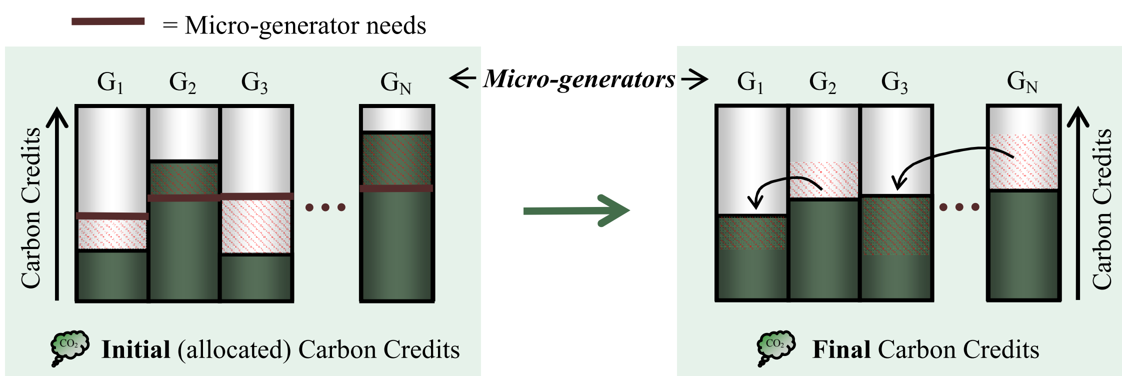

Fig. 5.4 Carbon Credit balancing among micro-generators

In Fig. 5.5, a high-level algorithm of the EVPP operation is presented:

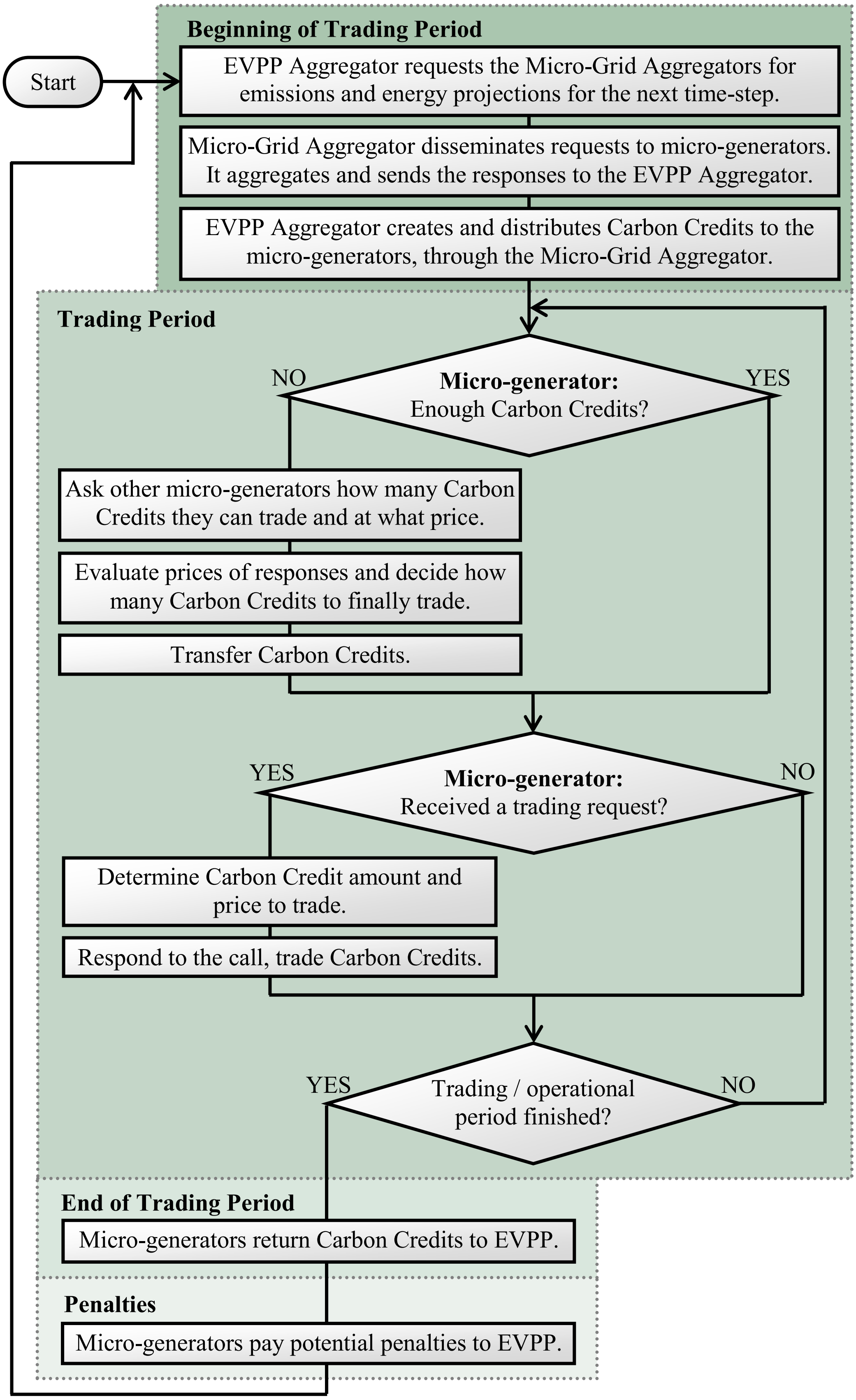

Fig. 5.5 EVPP algorithm.

5.3. Environmental Virtual Power Plant Multi-Agent System

5.3.1. System Structure – Architecture

In [43],[44] and [53], intelligent software agents have been introduced, for the design of an aggregation system. This approach is adopted in this chapter and a multi-agent system is designed.

The proposed system is designed using a hierarchical structure, as described in [44] and [57]. Two levels of aggregation are established: (i) at the micro-grid level and (ii) at the EVPP level. The micro-generator agents are aggregated by the Micro-grid Aggregator agents, which in turn are aggregated by the EVPP Aggregator agent. The hierarchy is shown in Fig. 5.6. The main reason for including the micro-grid intermediate level was to split the EVPP into micro-grids, which reduces the communicational requirements. The role and main purpose of each agent is briefly described below:

a) **The Environmental Virtual Power Plant (EVPP) Aggregator agent** is responsible for deciding upon the overall EVPP behaviour, using a given policy (see Section 5.2.3). It estimates control variables such as the electricity price and how much they should affect the EVPP output. It issues the Carbon Credits to the micro-generators.
b) **The Micro-grid Aggregator agent** is acting as an intermediary between the micro-generators and the EVPP Aggregator agent, mainly for reducing the communicational requirements. No decision making is done at this level. It transfers the Carbon Credits to the micro-generators and aggregates the micro-generator parameters that are requested by the EVPP Aggregator agent, such as the lower and higher operational limits.
c) **The Micro-generator agent** is located in the micro-generator controller. It has a representation of the parameters affecting the micro-generator emissions, its electrical or thermal storage capacity and the local electrical and thermal demand. It has an individual strategy that defines its behaviour. Based on this strategy, it determines the amount of Carbon Credits to request from the EVPP Aggregator agent, and/or trade with the other micro-generator agents.

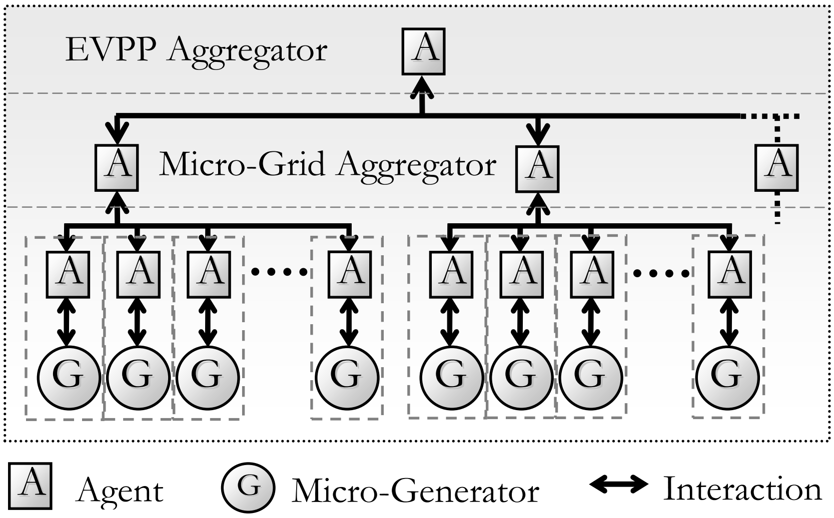

Fig. 5.6 Hierarchical structure of the multi-agent system

The Multi-Agent System was implemented in the JADE platform. This is a widely used tool in the implementation of software agents for power engineering [69][70]. JADE libraries implementing standard communication protocols from the Foundation for Intelligent Physical Agents (FIPA) were used [66].

5.3.2. Agent Interaction

According to [65], there are three aspects defining the agent interaction:

(i) **Goal compatibility:** The goals of the different micro-generator agents are compatible. They aim at independently satisfying their own need for Carbon Credits, regardless of the other agents. The fact that one agent possesses enough Carbon Credits does not necessarily mean that another will not.

(ii) **Access to resources:** Their access to resources (Carbon Credits) is usually limited by the EVPP Aggregator agent, since it regulates the supply of Carbon Credits. Most of the time, this leads to insufficient resources. Thus, the agents need to collaborate (trade) in order to satisfy the goals of each individual.

(iii) **Agent skills:** The skills of the agents for satisfying their goals are usually insufficient, in the sense that they cannot always match their emissions with their Carbon Credits, without trading Carbon Credits with other agents.

The above characteristics (compatible goals – insufficient resources – insufficient skills) lead the agent interaction to be described as Coordinated Collaboration [65]. The agents collaborate in order to exploit the advantages of working together both for the common (EVPP) as well as their individual (micro-generator) goals.

The developed trading procedure is an auction process, chosen due to its simplicity. According to the classification in [58], it is described as First-Price Sealed-Bid auction. In this type of auction, the agents bid according to their valuation of the commodity (Carbon Credit), which is finally sold to the highest bidder, at the price of this bid. Contrary to other types of auction, there is only one bidding round, and the agents do not know the bids of other agents. This can be implemented with FIPA protocols in JADE.

5.3.3. Agent Internal Architecture

The main elements of the agents that contain executable code are called behaviours [70]. The JADE platform enables the agents to execute behaviours as lumps of code for a specific action. Behaviours can be timed to repeatedly execute at intervals, or can be executed once. The FIPA communication protocols are also implemented as behaviours. A detailed description of the agent architecture and all the behaviours developed can be found in Appendices G, H, I and J.

The agent functionality can be described with operational modules, which are responsible for a given function inside the agent. The internal structure of the three types of agents is shown in Fig. 5.7. Fuzzy logic techniques were applied for the decision-making processes of the agents.

The agent functionality is different for each type of agent:

(i) The micro-generator agent communicates with (or is part of) the micro-generator controller.

(ii) The Micro-grid Aggregator agent has the aggregation functionalities of the EVPP Aggregator agent, but it is not actively controlling the signals, it just transfers them from and to the EVPP Aggregator agent.

(iii) The EVPP Aggregator agent aggregates all the micro-generator information and sends the appropriate signals, following a specific control policy.

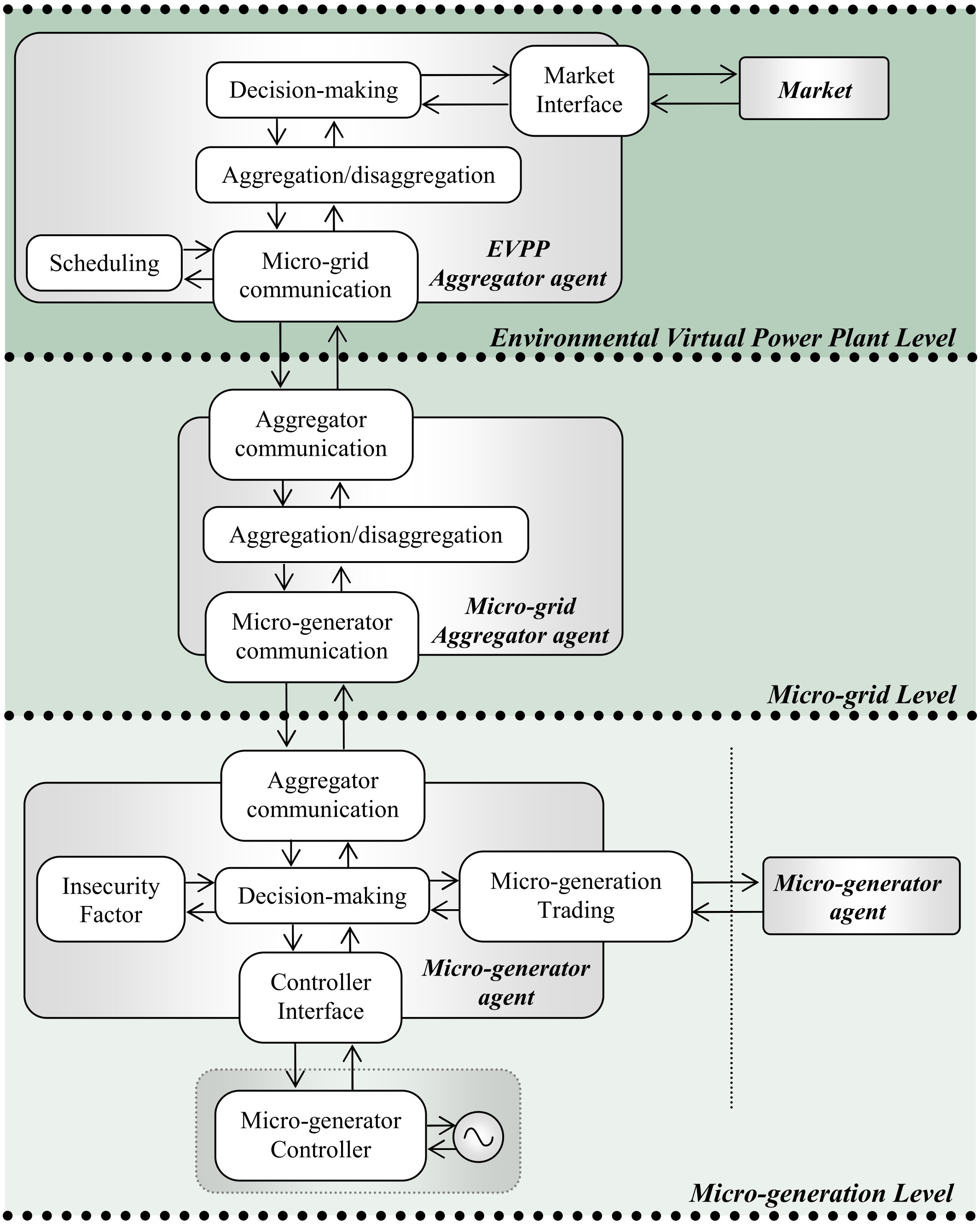

Fig. 5.7 Modular structure of the agents

5.3.4. Insecurity Factor

The insecurity factor is the core of the decision making in the micro-generator agent. It reflects the operational flexibility of the micro-generator. This factor is calculated by the agent and is used in conjunction with fuzzy logic functions (see Section 5.3.5) for the following purposes:

- To project the amount of energy that the micro-generator aims to generate during the next operational period.
- To derive a Carbon Credit price, when the micro-generator agent needs to provide a price in a trading proposal.
- To evaluate a Carbon Credit price, when the micro-generator agent receives a trading proposal, thus determining how many Carbon Credits to trade at this price.

5.3.4.1. Micro-CHP Insecurity Factor

For the micro-CHPs, the insecurity factor I is calculated using the following equations:

$$I_G = \frac{G_{MIN}}{G_{MAX}} \qquad \text{subject to } 0 < I_G < 1 \qquad (18)$$

$$I_S = \frac{S - E_P}{S} \qquad \text{subject to } E_P \geq U \qquad (19)$$

where: I_G is the generation insecurity factor.
I_S is the thermal storage insecurity factor.
G_{MIN} is the minimum generation limit coefficient (Equation 20).
G_{MAX} is the maximum generation limit coefficient (Equation 21).
S is the thermal storage capacity (kWh).
E_P is the stored heat projection for the next time step (kWh).
U is the unserveable thermal demand (Equation 22) in kWh.

The insecurity factor I is then found using fuzzy inference rules between I_G and I_S (see Section 5.3.5). G_{MIN} and G_{MAX} represent the operational limits of the micro-generator based on the availability of storage. They are determined as follows:

$$G_{MIN} = \frac{D_P - E_P}{G_R} \qquad \text{subject to } G_{MIN} > 0 \text{ and } E_P \geq U \tag{20}$$

$$G_{MAX} = \frac{D_P + (S - E_P)}{G_R} \qquad \text{subject to } G_{MAX} < 1 \text{ and } E_P \geq U \tag{21}$$

where: D_P is the projected thermal demand (kWh).

E_P is the stored heat projection for the next time step (kWh).

G_R is the generator rated energy (heat rating * time step duration).

U is the unserveable thermal demand (Equation 22) in kWh.

S is the thermal storage capacity (kWh).

The unserveable demand U is the proportion of the demand that exceeded the capacity of the micro-generator during the previous n time-steps (e.g. 24 hours):

$$U = \sum_{i=-n}^{0} (D_i - G_R) \qquad \text{subject to } D_i - G_R \geq 0 \tag{22}$$

where: D_i is the thermal demand at time-step i.

G_R is the generator rated energy (heat rating * time step duration).

5.3.4.2. Renewables Insecurity Factor

For the renewables (wind turbines, photovoltaics), the insecurity factor I is calculated as follows:

$$\text{If} \quad \frac{E_P}{S} > E_T \quad \Rightarrow \quad I = \frac{\left(\frac{E_P}{S} - E_T\right)}{E_T} \tag{23}$$

$$\text{If} \quad \frac{E_P}{S} < E_T \quad \Rightarrow \quad I = \frac{\left(\frac{S - E_P}{S} - E_T\right)}{E_T} \tag{24}$$

where: E_P is the battery level projection for the next time step.

S is the electrical storage capacity.

E_T is the target battery level, defined by the micro-generator strategy.

5.3.4.3. Collective Insecurity Factor (CIF)

The insecurity factor is also communicated to the EVPP Aggregator. The EVPP Aggregator calculates the average agent collective insecurity factor for the whole EVPP, and sends it back to the micro-generators. Therefore the micro-generator agents are aware of the overall level of insecurity, and take it into account when deciding upon prices using fuzzy inference rules (see Section 5.3.5).

When the EVPP Aggregator agent creates the Carbon Credits, it evaluates the current grid emission factor, or electricity market price, or both. It uses this evaluation together with the collective insecurity, to infer the amount of Carbon Credits that will be fed into the internal agent market. The Carbon Credits are distributed to the micro-generators proportionally to the amount they requested (Projected/Desired emissions).

5.3.5. Fuzzy Logic

5.3.5.1. Fuzzy sets

Fuzzy logic techniques were applied during agent development, to implement the agent intelligence processes. Fuzzy sets were derived for the insecurity factor, in a relatively simplified, uniform manner, as shown in Fig. 5.8. This enabled the utilisation of fuzzy inference rules for the decision-making of the agent, as described in Section 2.6.6.

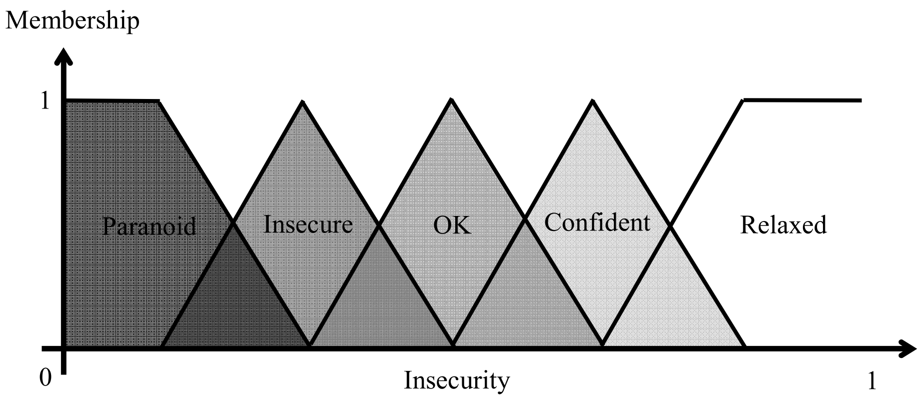

Fig. 5.8 Fuzzy sets for the insecurity factor

5.3.5.2. Fuzzy Clustering

The Fuzzy c-Means clustering algorithm is used by the agents to create fuzzy sets out of the following data [71]:

- Grid real-time emission factor (EVPP Aggregator agent).
- Electricity market price (EVPP Aggregator agent).
- Carbon Credit trading price (micro-generator agent).

These fuzzy sets are used for the decision-making. The fuzzy clustering algorithm runs every time new data points are added to the respective database:

- In the EVPP Aggregator agent, this occurs every time period (e.g. 15 minutes), when it receives data on the grid emission factor and/or the electricity market price.
- In the micro-generator agent, this occurs every time it receives a trading proposal with a Carbon Credit price from another agent.

This method enables the agent to retain a form of approximate "memory" of the data which can be used along with a fuzzy inference method for adaptive decision-making.

5.3.5.3. Fuzzy Inference

The implication matrix for inference between the agent individual insecurity factor and the collective EVPP insecurity factor is shown in Table 5.I:

TABLE 5.I: INDIVIDUAL INSECURITY – COLLECTIVE INSECURITY FACTOR (CIF) IMPLICATION MATRIX

Insecurity \ CIF	Paranoid	Insecure	OK	Confident	Relaxed
Paranoid	Paranoid	Paranoid	Insecure	Insecure	OK
Insecure	Paranoid	Insecure	Insecure	OK	Confident
OK	Insecure	Insecure	OK	Confident	Relaxed
Confident	Insecure	OK	Confident	Confident	Relaxed
Relaxed	OK	Confident	Relaxed	Relaxed	Relaxed

This inference procedure produces a combined micro-generator insecurity value, which encompasses the Collective Insecurity Factor. When a trading proposal is received, this combined insecurity factor is used together with the proposal price to infer the percentage of Carbon Credits that the agent will trade. The percentage of Carbon Credits is relative to the trading quantity proposed by the other agent. Different implication matrices were used for different proposal types. The implication matrix that was used in response to a proposal to sell Carbon Credits is shown in Table 5.II:

TABLE 5.II: INSECURITY – PRICE IMPLICATION MATRIX FOR A PROPOSAL TO SELL

Insecurity \ Price	Very Low	Low	Fair	High	Very High
Paranoid	0%	0%	25%	50%	75%
Insecure	0%	25%	50%	75%	100%
OK	25%	50%	75%	100%	100%
Confident	50%	75%	100%	100%	100%
Relaxed	75%	100%	100%	100%	100%

5.3.5.4. Defuzzification

The method of interpolation was used to find the inference result. However, the result is a fuzzy number, which cannot be used directly by the agent. Instead, a single real number is required, which is obtained by a defuzzification method.

Two defuzzification methods were used in this study, the Centre of Gravity and the Mean of Maxima [71]. The values were normally defuzzified with the Centre of Gravity, except when the result was close to the limits 0 and 1. For these boundary values, the Centre of Gravity method was found to be inaccurate, so the Mean of Maxima method was used instead. For example, with Paranoid insecurity and Very High price the Centre of Gravity result should be 100%, but instead it was close to 96%. Therefore, if the result was below 0.1 or above 0.9 it was defuzzified with the Mean of Maxima method.

5.3.5.5. Benefit of fuzzy logic

The main advantage offered by this combination of fuzzy inference and fuzzy clustering is that incomparable factors can be combined to draw a conclusion. This process can be described as learning, since it is adaptable to new data and the meaning of characterisations such as "high price" adjusts to the environment. The agent records the inputs from its environment (e.g. trading price) and plans its future actions according to this input, in order to achieve its design objectives.

5.3.6. Forecasting

In the proposed system, forecasting was done using the method of simple linear regression [110], for a set of variables. The agents have the ability to record and use past data. In order to plan their strategy accordingly, the agents need to have an indication of the future trends of the following variables:

- Grid real-time emission factor – EVPP Aggregator agent.
- Electricity market price – EVPP Aggregator agent.
- Customer demand (thermal/electrical) – micro-generator agent.
- Renewable generation (wind turbines/photovoltaics) – micro-generator agent.

The trend of these data is found and the value of the next point in the time-series is projected. The method is described in Appendix K.

Periodical effects were also taken into account. For the grid emission factor and the electricity price, a forecast was also performed using the data points from the same time of the day as the present time-step, in the previous seven days (1 week). The result was averaged with the normal sequential forecast, giving a more accurate prediction that takes into account long-term trends.

In the case of demand and renewable generation, the normal forecast is averaged with the value recorded at the same time, in the previous day.

The forecasting method is illustrated in Fig. 5.9:

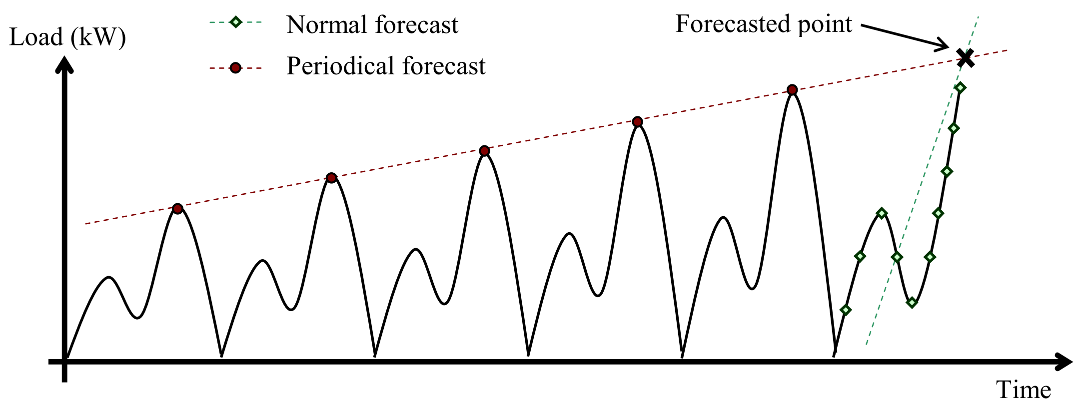

Fig. 5.9 Double linear regression

5.4. ENVIRONMENTAL VIRTUAL POWER PLANT CASE STUDY

5.4.1. Input data

A simulation of the EVPP operation was performed, in order to test its behaviour. The following data were used as inputs:

- **Grid real-time emission factor:** data were taken from RealtimeCarbon [96], for the first week of February 2010.
- **Electricity Market Price:** APX Power UK Reference Price Data (RPD) [111] were used, for one week.
- **Thermal demand data:** An average daily thermal load profile for winter was taken from [106].
- **Electrical demand data:** An average daily electrical load profile for winter was taken from [102].
- **Renewable generation data:** A typical daily profile for photovoltaic generation was taken from [87]. The wind generation profile of a random day in winter was also taken from [87].

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 [112]:

$$RF = 1 + D + Q \tag{25}$$

where: *RF* is the randomisation factor.

D is the daily randomisation (same for the whole day). It is a random number. In this study the range was -20% to 20%.

Q is the time-step randomisation (different for each data point). It is a random number. In this study the range was -10% to 10%.

Sample data for the grid emission factor are illustrated in Fig. 5.10. Sample data for the grid electricity market price are illustrated in Fig. 5.11.

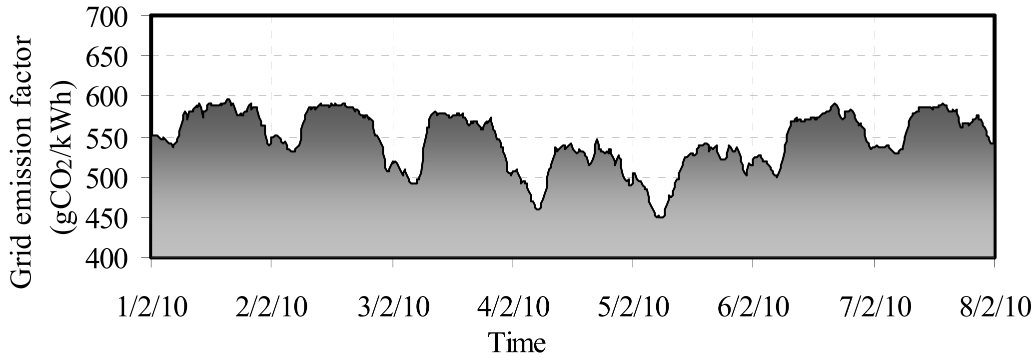

Fig. 5.10 Sample data for the grid emission factor [96]

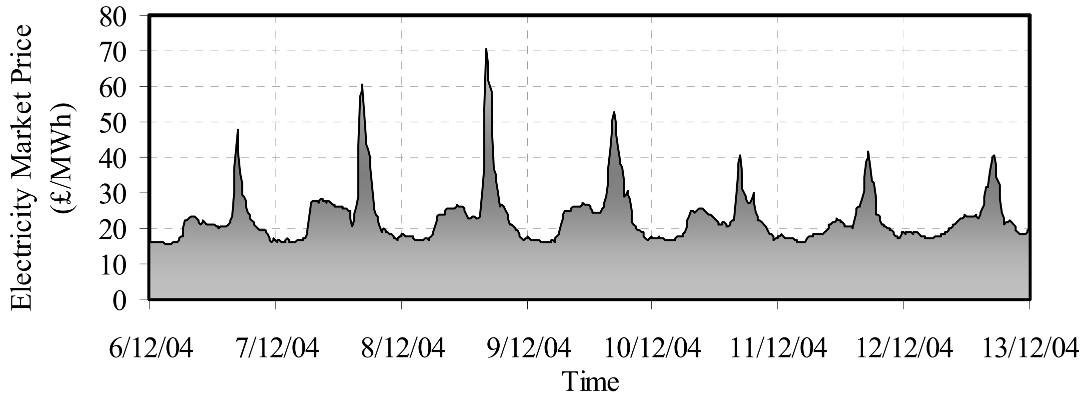

Fig. 5.11 Sample data for the electricity market price [111]

5.4.2. Part-load emission factors for micro-CHP

The emission factor of micro-CHP generators is not constant, but it varies with the generator loading [113]. The part-load emission curves calculated in Chapter 4 were used by the agents to determine their projected emissions according to the projected generator loading. The part-load emission factors are shown in Fig. 5.12.

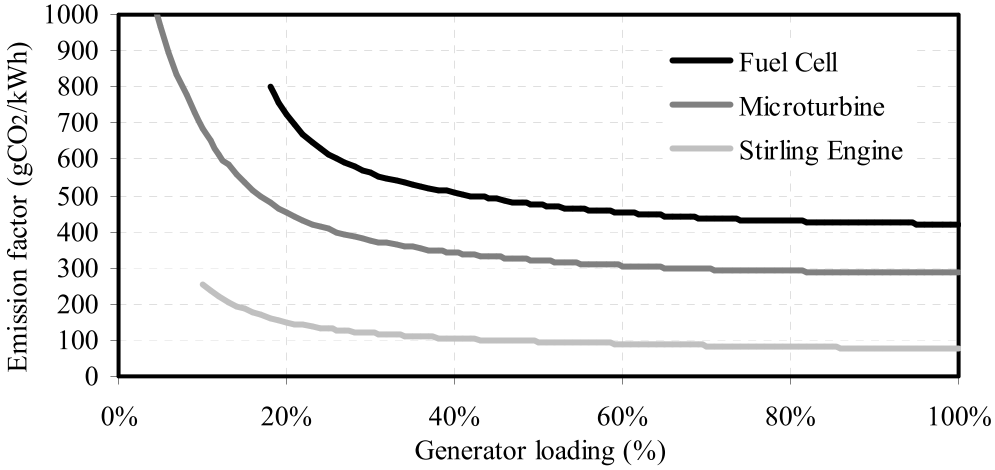

Fig. 5.12 Part-load emission factor curves for the micro-CHP

5.4.3. Simulated EVPP

The number of agents that were simulated is based on the case described in Chapter 4 [113]. In total, 48 micro-generators were simulated. Two micro-grids were simulated, each of them containing the following agents:

- 4 Wind Turbines,
- 2 Photovoltaics,
- 2 Microturbines,
- 3 Fuel Cells and
- 13 Stirling Engines.

Although the wind turbines and photovoltaics are renewable energy sources and are considered carbon-free, their life-cycle carbon emissions were also considered, as described in Chapter 3. This provides an emission factor for these sources as well. Electrical storage capacity of $20kWh_e$ was considered for the wind turbines and photovoltaics and 500L ($20kWh_{th}$) thermal storage for the micro-CHPs. One Carbon Credit was considered to be equal to 1 gCO_2-e.

5.5. SIMULATION RESULTS AND DISCUSSION

A simulation of the EVPP was performed using the Emissions Policy, enabling it to follow the grid emission factor. The EVPP was run using a trading period of 15 minutes, for 3 simulated days. A uniformly distributed random number was taken as the initial storage level of each micro-generator. The results are presented in the following sections.

5.5.1. Controllability

5.5.1.1. EVPP output deviation from Carbon Credits

The amount of Carbon Credits supplied by the EVPP Aggregator is compared with the actual emissions output in Fig. 5.13. A very close match can be observed, except for small inconsistencies such as the one depicted with the dotted circle.

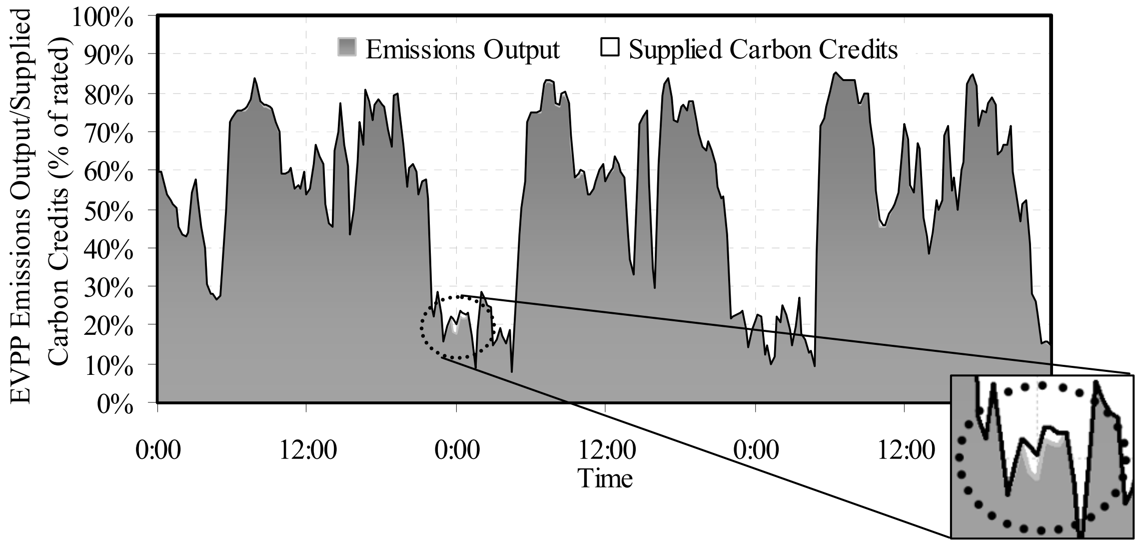

Fig. 5.13 EVPP emissions desired (Carbon Credits) and actual output.

In some trading sessions, the micro-generators were not able to acquire enough Carbon Credits to match their emissions, even after trading. This was due to the fact that the other agents also needed Carbon Credits. This is evident in Fig. 5.14, where the deviation between the Carbon Credits (set-point) and the actual emissions output is compared with the thermal demand. It was observed that most of the deviation occurrences were under two types of circumstances:

(i) **Immediately after a peak in thermal demand,** when the micro-CHP thermal storage level is normally low (see Fig. 5.17). Some micro-CHPs cannot reduce their production to meet their Carbon Credits, or they would fail to supply the domestic thermal load. The Carbon Credit availability is also low. Thus, they cannot buy Carbon Credits either, and a deviation occurs.

(ii) **At times when the thermal demand is very low** and the thermal storage level is high. When the micro-CHP storage levels are high and the EVPP supplies a lot of Carbon Credits, some micro-CHPs cannot increase their production to match their Carbon Credits. If they do, they would waste recovered heat, or overheat their storage tank. They cannot sell their Carbon Credits either, since the availability is high and the other agents are not interested in buying.

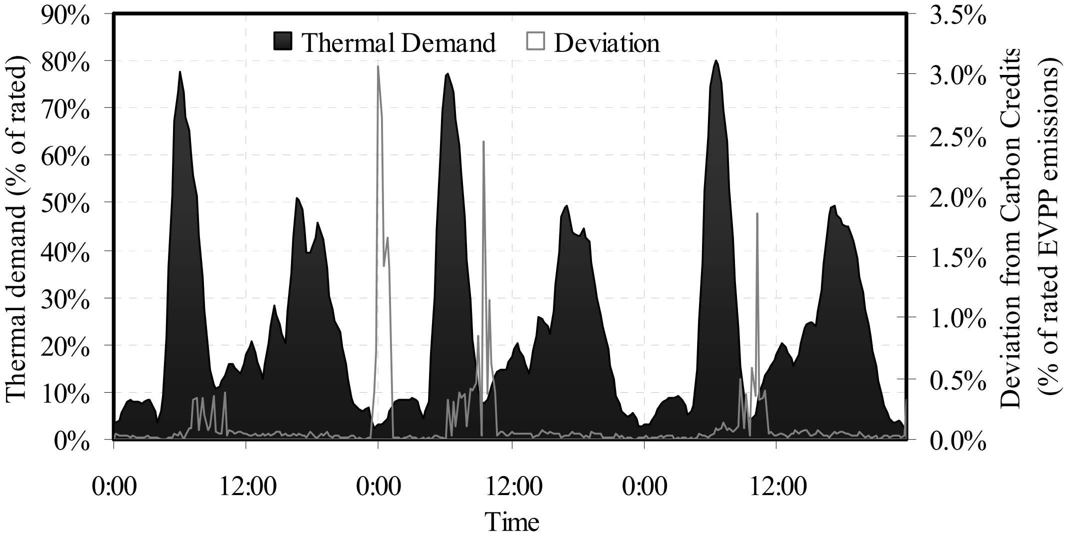

Fig. 5.14 EVPP emissions output deviation from Carbon Credits and total thermal demand.

5.5.1.2. Control policy effect on Carbon Credit trading

Fig. 5.15 compares the grid emission factor with the total number of Carbon Credits traded internally between the micro-generators. It can be seen that the pattern of the Carbon Credit trading is defined by the pattern of the control variable – in this case the Grid Emission Factor. It is also affected by the customer thermal load and storage levels, i.e. the micro-generator flexibility. Peaks and troughs can be observed, indicating Carbon Credit redundancy and shortage respectively.

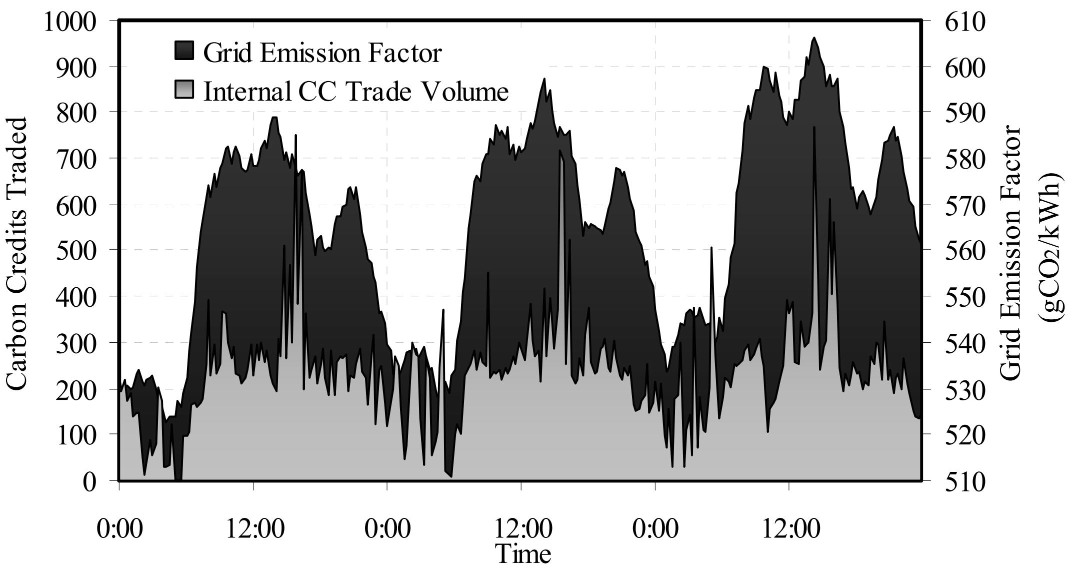

Fig. 5.15 EVPP Carbon Credits trading volume and grid emission factor.

5.5.2. Effect of thermal demand and storage on EVPP output

By comparing the EVPP emissions output with the overall thermal demand (see Fig. 5.16), the effect of the thermal demand on the emissions output is observed. It can be seen that the emissions output is slightly skewed by the thermal demand. This is because the micro-CHP units are heat-driven and utilise their thermal buffer to vary their production instead of following the thermal demand. However, the thermal storage level is significantly reduced during the peaks in demand, as can be seen in Fig. 5.17. This also reduces the flexibility of the micro-CHP units. Consequently, right after a peak in demand, the agents are driven towards resuming their flexibility. This is done by increasing micro-CHP production to raise the storage levels.

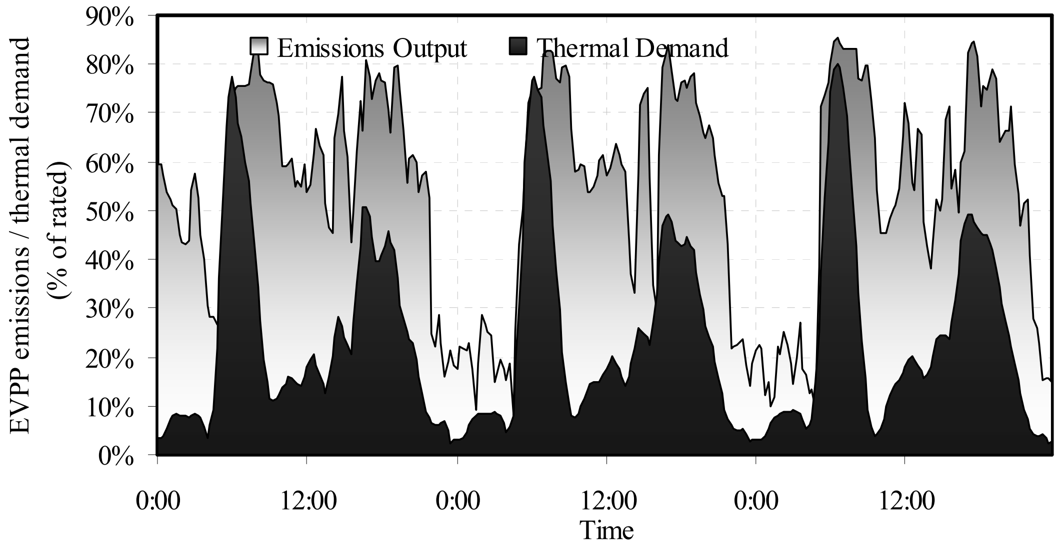

Fig. 5.16 EVPP emissions output and total thermal demand.

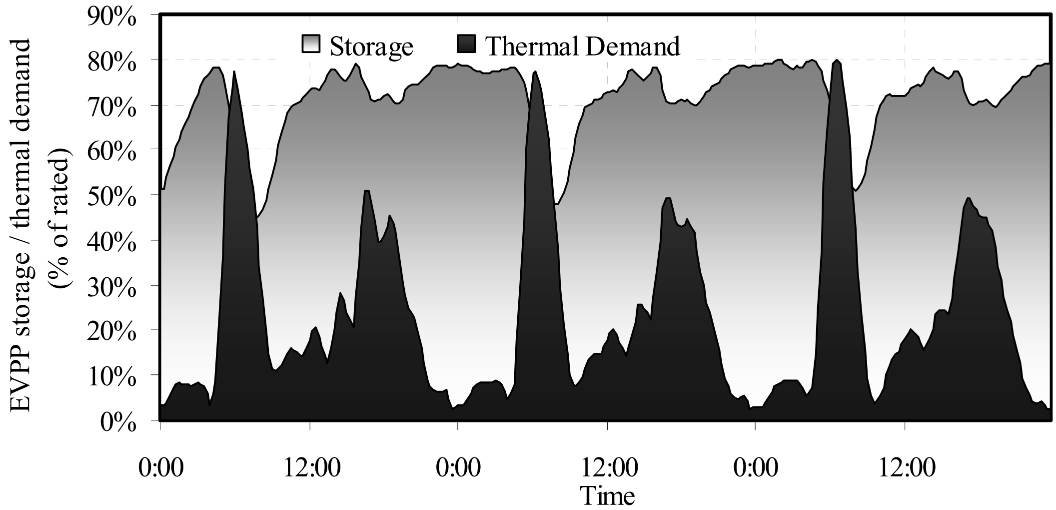

Fig. 5.17 EVPP overall storage level and total thermal demand.

5.5.3. EVPP emissions and energy output correlation

The emissions and energy output of the EVPP can be seen in Fig. 5.18. It is observed that they are directly proportional.

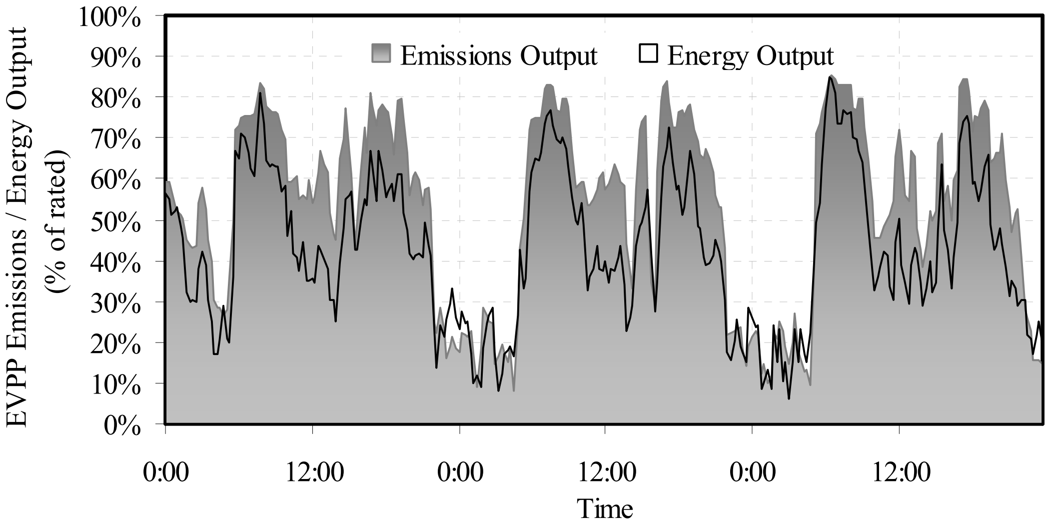

Fig. 5.18 EVPP emissions and energy output.

The data from Fig. 5.18 were used to plot a scatter plot, correlating EVPP generation and emission factor (see Fig. 5.19). This provides an indication of the aggregated part-load emission factor trend. It can be seen from Fig. 5.19 that this trend loosely follows the micro-CHP part-load emission factor curves presented in Fig. 5.12. The normalization was done with respect to the aggregated rated generation capacity of the EVPP.

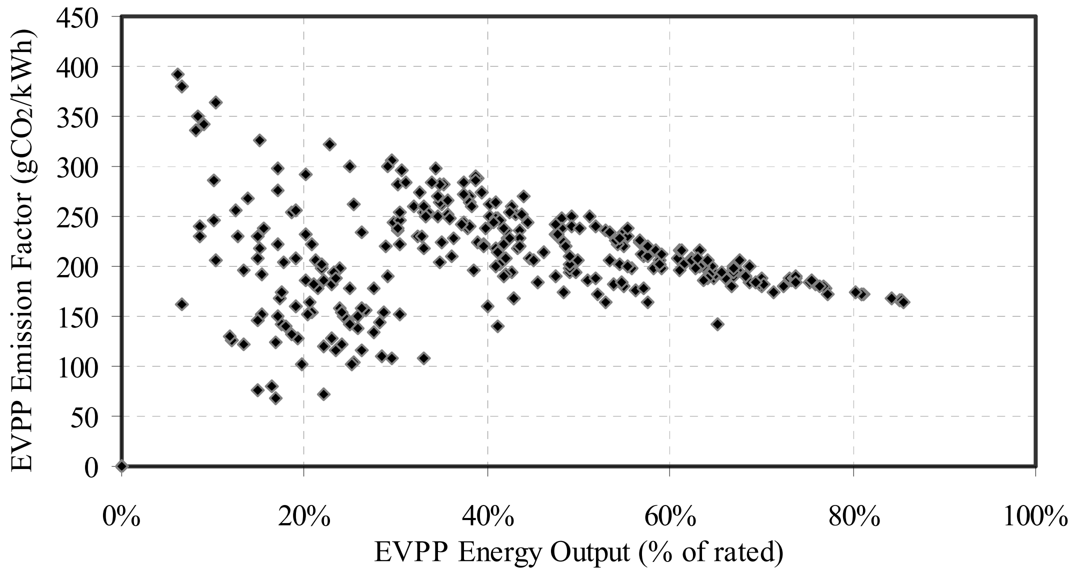

Fig. 5.19 EVPP average emission factor and energy output correlation.

5.5.4. Comparison with optimal case in Chapter 4

The EVPP control case that was simulated in this chapter has been compared with the VPP case that was theoretically optimised in Chapter 4. The results were scaled up to 48 micro-grids to match the VPP in Chapter 4 (see Section 4.3.1). In Table 5.III, a comparison between the two cases is given.

It can be seen that the total emissions incurred by the customer electrical and thermal demand are very similar between the two cases. It is observed that the EVPP produces slightly more savings than the optimised VPP case, because the assumptions were slightly different. The most significant inconsistency between the assumptions of the two studies is that the micro-generator agent in the EVPP does not consider the start-up and shut-down emissions of the micro-CHPs. If the start-up and shut-down emissions had been modelled into the agent, the emissions savings of the simulated EVPP would be less than the optimised VPP.

TABLE 5.III: COMPARISON BETWEEN OPTIMISED AND SIMULATED EVPP OUTPUT (10% MICRO-GENERATION PENETRATION – LOW EV PENETRATION – WINTER)

Indicator	Optimised VPP	Simulated EVPP
Base case emissions (tCO_2)	337.29	336.51
Total daily emissions (tCO_2)	325.48	324.67
Emission savings compared to base case (%)	3.50	3.52
Final electricity emission factor (gCO_2/kWh_e)	245.52	246.06
Final heat emission factor (gCO_2/kWh_{th})	194.44	194.39

5.6. SUMMARY

In this chapter, a multi-agent system has been described, for the control of the carbon emissions from aggregated micro-generators. The operation of the EVPP simulates an Emissions Trading Scheme.

A study case was built and simulations were performed. An Environmental Virtual Power Plant (EVPP) was defined, which comprises two aggregation levels. A hierarchical structure was adopted, for reducing communication requirements. The upper aggregation level is at the EVPP level and the lower is at the micro-grid level.

The simulation results show that the EVPP emissions can be consistently controlled within the operational limits of the micro-generators. Composite EVPP characteristics such as the part-load emissions were found to be consistent, increasing the predictability of the EVPP output. Since micro-CHP units were considered, peaks in thermal demand have an effect on the EVPP behaviour by reducing micro-CHP flexibility. When the results were compared with the optimised VPP case in Chapter 4, they were found to be similar.

The developed control system provides significant benefits:

- Micro-generators have the opportunity to collaborate in order to accommodate their individual limitations and to participate in electricity and/or emissions markets.
- The difference from a centralised solution is that the intelligence and decision making are mostly located at the micro-generator agents. This provides flexibility and extensibility to the control system.
- Micro-generators can be connected or disconnected at any time with little or no changes to the control system and without interruption of its operation.

This control system is especially suited for emissions market participation of micro-generators, since the market price can be transferred to them through the EVPP. Thus, the aggregator operation becomes almost transparent.

Finally, this control system can be used by an aggregation entity in order to control the emissions of its client micro-generators. The nature of this entity will depend on the business case. The aggregation entity may be the energy supplier, or a separate company.

Chapter 6

Environmental Virtual Power Plant Experimental Validation

6.1. Introduction

In Chapter 5, the control of VPP emissions by means of setting up an internal market has been proposed, based on the concept of the Emissions Trading Scheme. This approach was termed the Environmental Virtual Power Plant (EVPP).

An EVPP has been tested experimentally in two laboratories, in the National Technical University of Athens (NTUA) and the Centre for Renewable Energy Sources (CRES) in Greece. The outcome is presented in this chapter.

6.2. Experimental Setup

The EVPP comprises two micro-grids, installed in different laboratories. One is located in CRES and the other in NTUA, both in Greece. The agents communicate between the labs via the internet. The main agent platform is run on one dedicated computer, which also hosts the EVPP Aggregator agent. The other agents attach to this host platform through the network, utilising JADE functionality [70].

A diagram of the experimental EVPP is presented in Fig. 6.1:

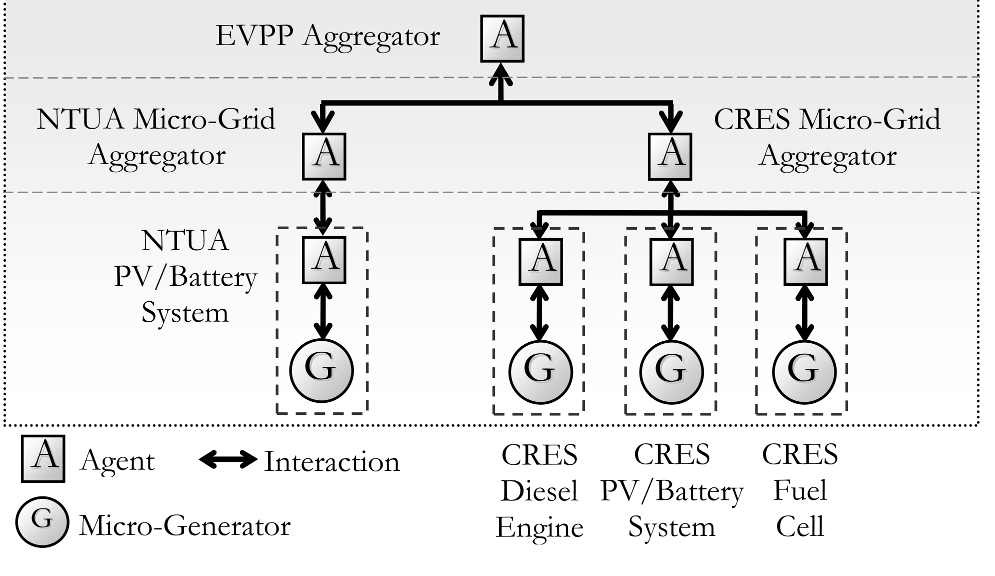

Fig. 6.1 Structure of the experimental EVPP

The NTUA laboratory includes one photovoltaic system, with battery storage. The CRES laboratory includes one Diesel engine, one photovoltaic system with battery storage and one fuel cell. The detailed configuration of each laboratory is described in the next sections.

6.2.1. NTUA Equipment

The laboratory facilities at the National Technical University of Athens include a PV generator, battery energy storage, controllable loads and a controlled interconnection to the local LV grid. Both the battery unit and the PV generator are connected to the AC grid via fast acting DC/AC power converters.

The battery unit power electronics interface consists of a Cuk DC/DC converter and a voltage source Pulse Width Modulation (PWM) inverter. They are both bi-directional, thus permitting charging and discharging of the batteries. The DC/DC converter provides constant 380 V DC voltage to the DC/AC converter input.

The laboratory components that were utilised in this study are described below:

- **PV generator**
  Modules: 10 modules, connected in series, mono-crystalline Si, 12V, 110W per module.
  Inverter: SMA Sunny Boy, 1100 W.
- **Batteries**
  Cells: Lead-acid, vented type, 30 cells, 2V, 250Ah.
  Inverter: SMA Sunny Island, 4.5kVA, bi-directional, suitable for grid-connected and islanded operation.
- **Grid:**
  Connection to local building distribution (laboratory switchboard).
  Miniature Circuit Breaker (MCB) for protection – Contactor for control.

A diagram of the laboratory components utilised in this experiment is shown in Fig. 6.2. Photographs of the photovoltaic and battery inverters can be seen in Fig. 6.3.

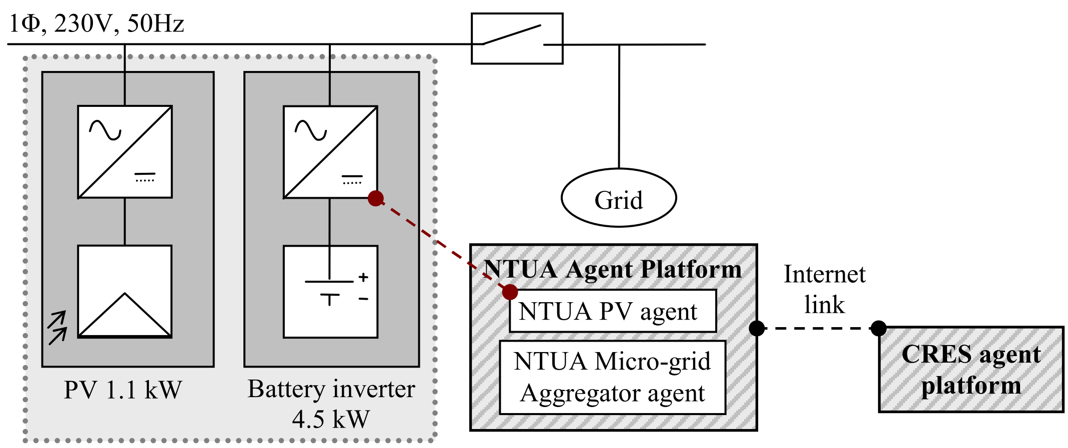

Fig. 6.2 NTUA laboratory setup

Fig. 6.3 NTUA equipment: PV inverter (left) and battery inverter (right)

6.2.2. CRES Equipment

The Hybrid Power Plant and Microgrid laboratory in CRES comprises a 3-phase electric network. All DER components can be connected either in a single phase or 3-phase configuration. In this experiment, only single-phase connections were employed. A block diagram of the most important equipment and the topology of the system is presented in Fig. 6.4. Photographs of the equipment are shown in Fig. 6.5.

The components that were utilised in this study are described below:

- **Photovoltaic:** A PV array with a capacity of 1.1kWp interconnected through a single phase PV inverter of 1.1kW nominal power.
- **Battery storage:** The lab is equipped with three single phase battery inverters of the same type as in NTUA (only one of them was used in the experiments):
    - SMA Sunny Island, 4.5kVA, 60VDC, 230VAC.
    - Bi-directional, suitable for grid-connected and islanded operation.

- **Diesel genset:** 400 VAC, 50Hz, 12 kVA. The purpose of this generator during the experiments was to simulate a residential CHP unit supplying 4 residences.
- **Loads:** The system includes a 20kW resistor load bank.
- **Proton Exchange Membrane (PEM) fuel cell:** The PEM fuel cell has a nominal capacity of 5 kW (DC). It was operated at 1.9kW to ensure sufficient H_2 supply. A DC/AC three-phase system is also integrated in the PEM fuel cell system in order to supply AC electricity to the micro-grid of the hybrid system. Micro-CHP operation and a reforming process for extracting hydrogen (H_2) from Natural Gas were simulated.

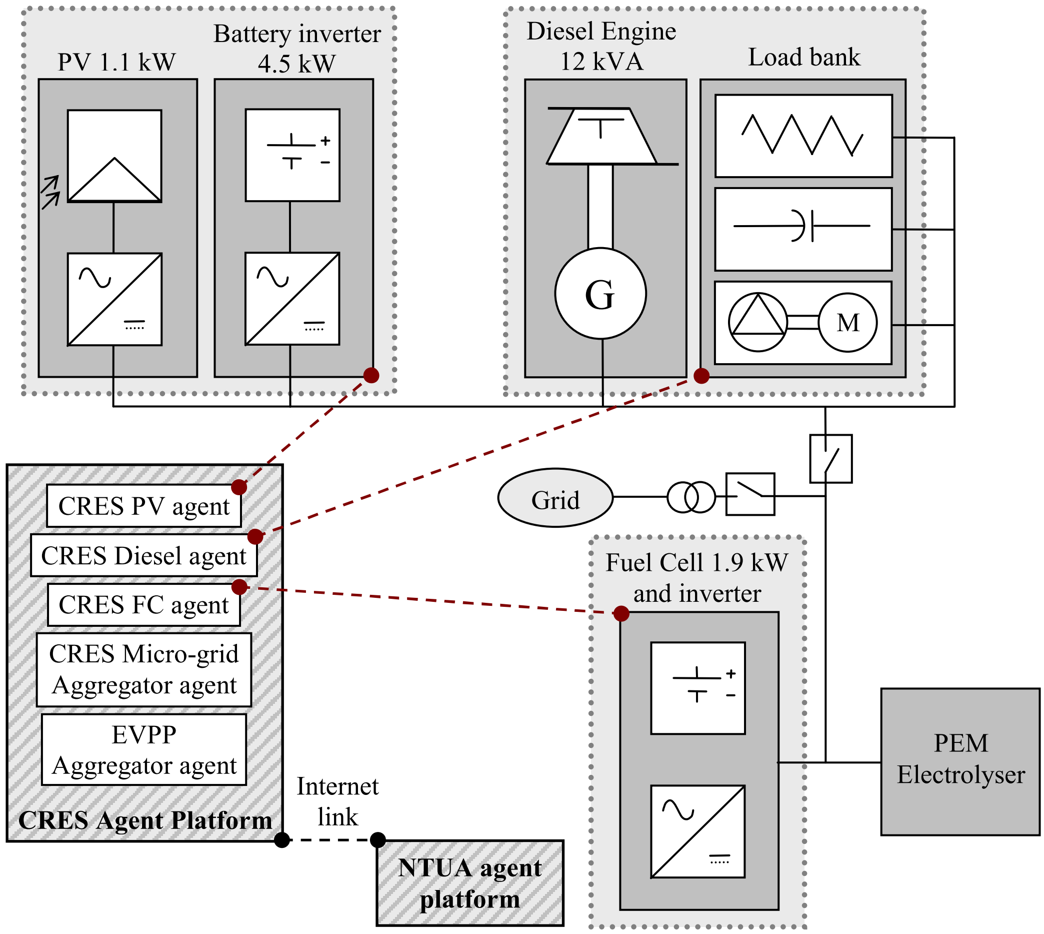

Fig. 6.4 Block diagram of the Hybrid system and Microgrid test site of CRES

The control and communication interfaces have been developed using National Instruments LabVIEW software platform. All the controls are fully automated. Security measures have been implemented. Emergency stop buttons were in place, both in the SCADA system and in the agent graphical user interfaces. The agent interfaces are described in Appendix L.

Fig. 6.5 CRES Diesel genset (upper left), fuel cell (upper right), photovoltaic (lower left) and battery inverters (lower right)

Neither the Diesel genset nor the fuel cell were capable of heat recovery for CHP operation. Therefore, heat recovery was simulated for the Diesel genset and the fuel cell, as follows:

$$H = \left(F \cdot E_f - E_{el}\right) \cdot \eta_{HR} \tag{26}$$

where: H is the heat recovered (kWh_{th}).

F is the fuel consumption measurement (L or m^3).

E_f is the energy content of fuel (kWh/L or m^3).

E_{el} is the electrical energy generated (kWh_e).

η_{HR} is the heat recovery efficiency (%).

6.3. MICRO-GENERATOR CONTROL METHODS

6.3.1. Diesel Engine (CRES)

The Diesel engine in CRES was isolated from the rest of the system, and the control of its output was done using a set of resistive loads. It was controlled by the agent through the SCADA system. The agent calculated a power set-point and was sending it to the SCADA system. The SCADA system would determine the combination of resistive loads that was closest to the set-point received by the agent and would connect them to the generator. In this manner, a discretised control of the power output was achieved. The step was roughly 0.25W, with a range of 0.5kW to 11kW. The values are shown in Appendix M. The Diesel engine was being shut down when the set-point was lower than 1.75kW, to prevent inefficient operation.

6.3.2. Fuel Cell (CRES)

The fuel cell did not have the capability of power output control. It only supplied the electrical load that it detected, working as a backup system. An ON/OFF control method was employed. The fuel cell was isolated from the rest of the system and was connected to a resistive load, controlled by the SCADA system. The amount of energy generated during each operational period was then regulated by adjusting the time that the load was connected, i.e. the time that the fuel cell was generating at a constant power level. In Fig. 6.6, the energy generation per period and the instantaneous power are compared.

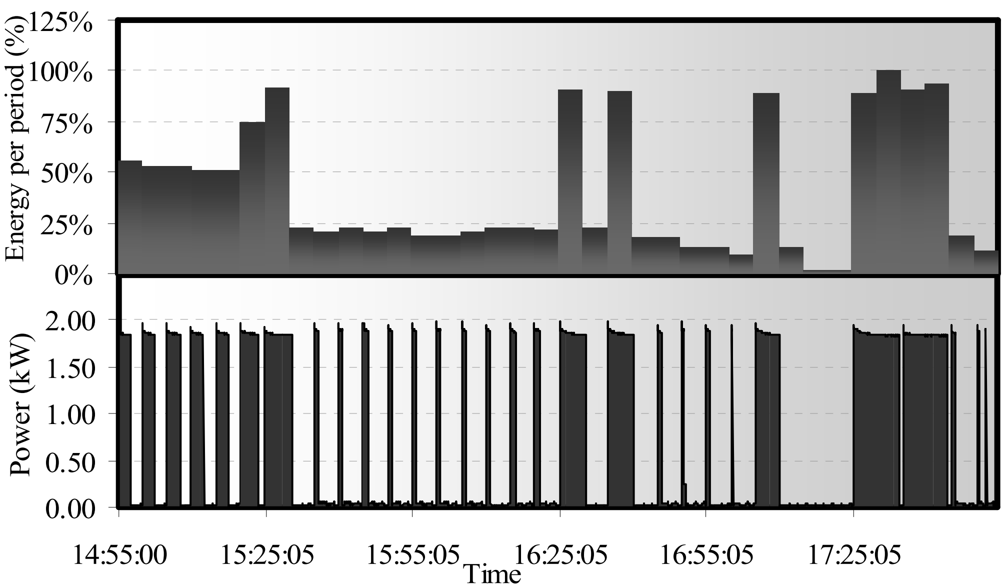

Fig. 6.6 Fuel cell example output: normalised energy per period (top), instantaneous power (bottom)

6.3.3. Photovoltaic/Battery Inverter (CRES)

The photovoltaic installation in CRES, along with the battery inverter, was controlled by one agent. This agent was calculating the total power output required and was sending this value to the SCADA system. The SCADA system was reading the output of the photovoltaic every second and was setting the battery inverter to produce the remainder, up to the set-point received:

$$P_{inverter} = P_{setpoint} - P_{PV} \tag{27}$$

where: $P_{inverter}$ is the battery inverter power output set-point.
$P_{setpoint}$ is the total power output set-point.
P_{PV} is the photovoltaic current power output.

The outcome of this process can be observed in Fig. 6.7. The total system power was the sum of the PV power and the battery inverter power. When the system set-point was lower than the photovoltaic output, the battery inverter absorbed the excess PV power. Such occurrences in Fig. 6.7 are indicated with red arrows.

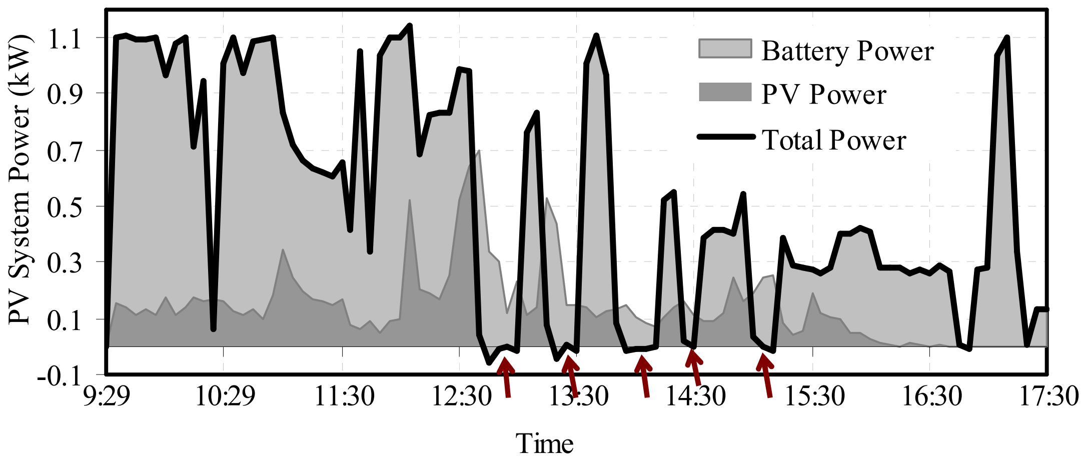

Fig. 6.7 Photovoltaic module and inverter contribution to total PV system power

The control of the battery inverter output was done by adjusting the idle frequency set-point with a control loop. The frequency set-point was adjusted with steps of 0.1Hz or 0.02Hz, depending on the difference between the desired and measured power [114].

6.3.4. Photovoltaic/Battery Inverter (NTUA)

The NTUA photovoltaic and battery inverter were also controlled by one agent. However, the photovoltaic measurement frequency was much lower than CRES, making it impossible to control the battery inverter adaptively, like in CRES. Thus, this agent calculated the battery inverter power set-point based on the photovoltaic production forecast. The power output of the battery inverter was kept constant for the whole duration of the operational period. The photovoltaic production was added to that. The battery inverter set-point was calculated as follows:

$$P_{inverter} = P_{desired} - P_{PVforecast\ ed} \quad (28)$$

where: $P_{inverter}$ is the battery inverter power output set-point.
$P_{desired}$ is the total power output set-point.
$P_{PVforecasted}$ is the photovoltaic forecasted power output.

By using this method, the deviations between projected and actual emissions were caused mostly by the inaccuracy of the photovoltaic output forecast.

The control of the battery inverter output was done with the same method as in CRES. However, the battery inverter frequency set-point steps in the control loop were not predetermined. They were calculated as proportional to the difference between the desired and measured power [115]. A gain factor was tuned by trial and error to link the two variables:

$$dF = K \cdot \left(P_{INVdesired} - P_{INVmeasured}\right) \quad (29)$$

where: dF is the frequency set-point step.
$P_{INVdesired}$ is the desired power output of the battery inverter.
$P_{INVmeasured}$ is the battery inverter current power output.
K is the gain factor.

An illustration of the battery inverter output along with the frequency set-point is shown in Fig. 6.8. It can be seen that although the frequency set-point varies, the power stays relatively constant.

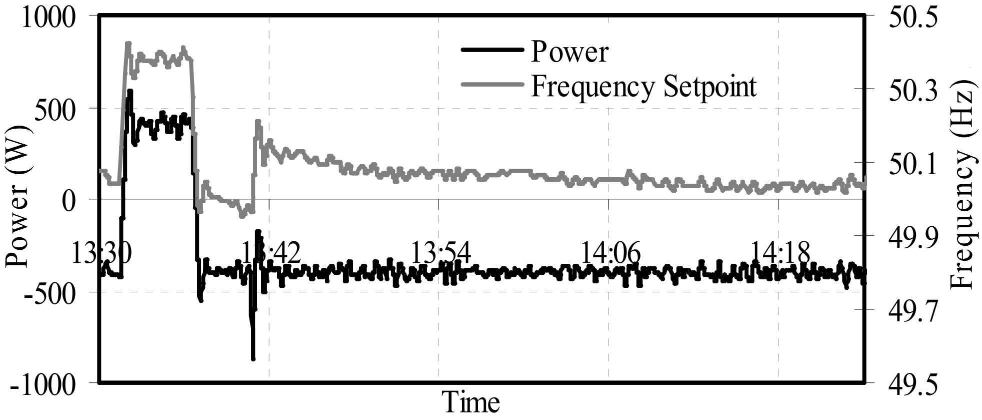

Fig. 6.8 NTUA inverter control output

The control loop has been created because the battery inverter output did not depend only on a constant droop curve. This is evident in the measurements, as can be seen in Fig. 6.9. At a certain frequency set-point, e.g. 50.0 Hz, the output power can fluctuate from 50W to -1000W. Therefore, the power needed to be constantly monitored and the set-point to be adjusted accordingly.

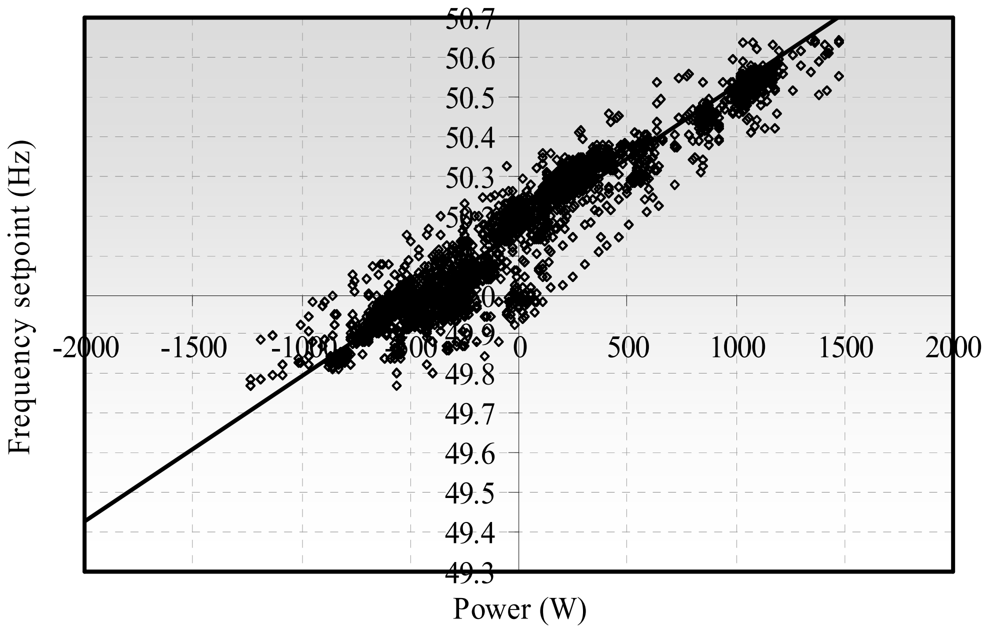

Fig. 6.9 NTUA inverter frequency set-point and power output scatter plot with trend line

6.4. Input Data

The following data were used as inputs:

- **Grid real-time emission factor:** hourly data were calculated using unit loading data from the Greek TSO [116], for the 7th November 2010.
- **Electricity Market Price:** Marginal Price Data from the Greek power system were used [116], from 10 to 20/10/2010.
- **Thermal demand data:** An average daily thermal load profile for November was taken from [117].
- **Electrical demand data:** An average daily electrical load profile for winter was taken from [102].
- **Renewable generation data:** The CRES photovoltaic generation was measured for one day and this was used as historical data for both photovoltaics. A wind generation profile at a random day in winter was taken from [87].
- **Life cycle emissions:** For the photovoltaics and wind turbines, an emission factor was derived using life-cycle data (see Chapter 3).

Sample data for the grid emission factor are shown in Fig. 6.10 and for the electricity market price in Fig. 6.11.

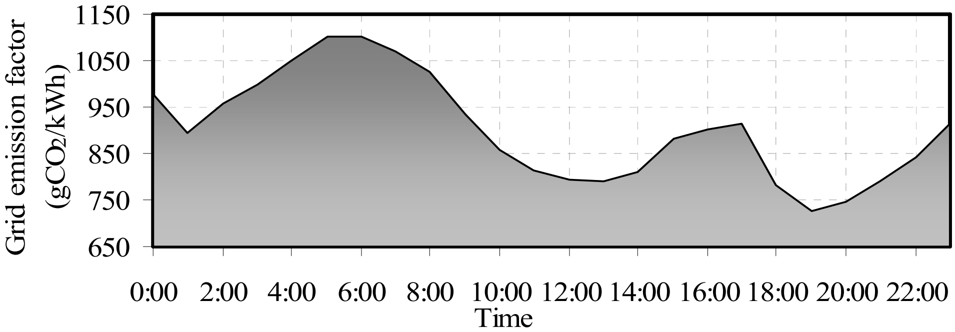

Fig. 6.10 Sample data for the grid emission factor [116]

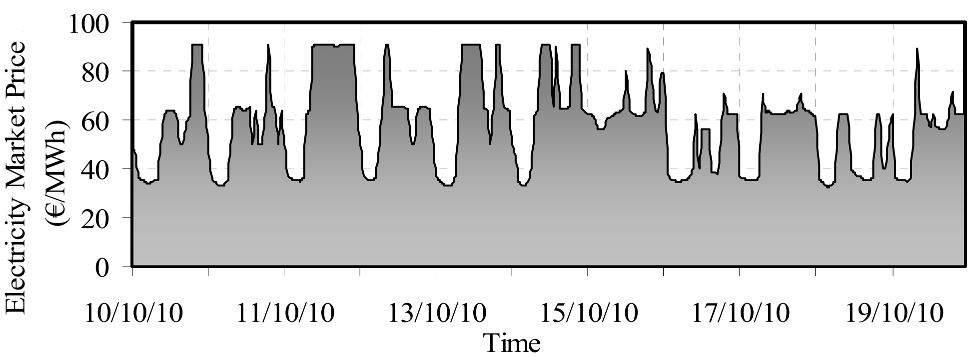

Fig. 6.11 Sample data for the electricity market price [116]

6.4.1. Part-load emission factors for micro-CHP

The emission factor of micro-CHP generators is not always constant, but it varies with the generator loading [113]. Part-load emissions for the CRES Diesel engine and the Fuel Cell were measured. Part-load curves were created and they were used by the agents to determine their projected emissions according to their loading. The part-load emission factor curves are shown in Fig. 6.12.

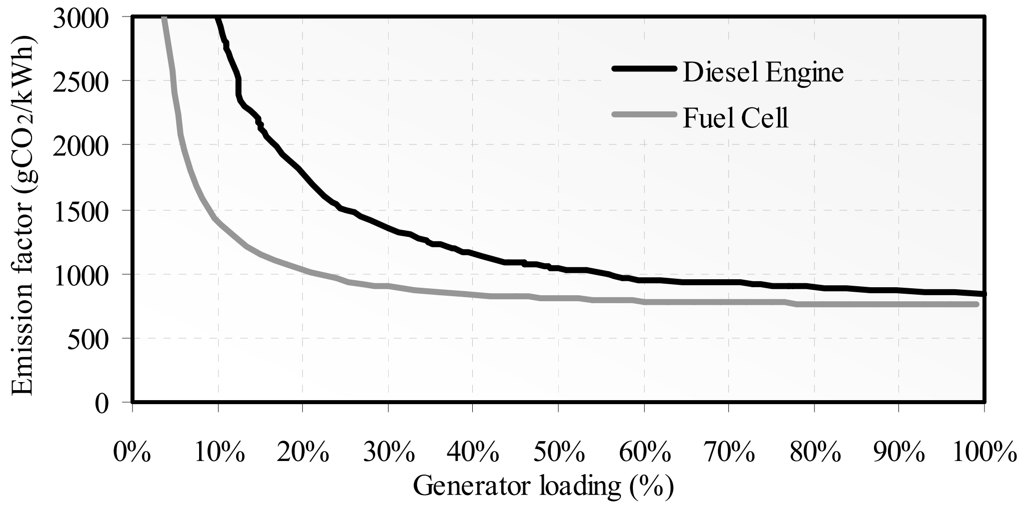

Fig. 6.12 Fuel cell and Diesel engine part-load emission factor curves

6.5. EXPERIMENTAL PROCEDURE

The objective of the experiments was to perform tests with all four generators operating simultaneously, for as long as possible. Two days (8 hours 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 simulated sources with their corresponding agents.

The purpose of the second day was to determine if the EVPP proves to be more stable and controllable by increasing the number of sources that are participating. A number of additional micro-generation sources were simulated. The penetration scenario was based on the benchmark micro-grid in [50]. Table 6.I shows the configuration in both experiments.

TABLE 6.I: MICRO-GENERATION SOURCES FOR THE TWO EXPERIMENTS

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

* One of them is a real installed micro-generation source

The host JADE platform was run on a computer located in CRES. The control policy that was followed by the EVPP Aggregator agent was the Mixed Policy (see Section 5.2.3), which takes into account both the electricity price and the grid real-time emission factor. The EVPP Aggregator agent, the CRES Micro-grid Aggregator agent and the three CRES micro-generator agents were initiated on that platform.

Another platform was run in a computer located in NTUA. The NTUA micro-grid and photovoltaic agents were initiated on that platform. The NTUA agents communicated with the agents located in CRES via an internet connection.

6.6. EXPERIMENTAL RESULTS

6.6.1. Micro-generator power and emissions output

The total emissions and energy output of the EVPP, along with the average storage level of its sources can be seen in Fig. 6.13, for Experiment I. The cumulative emissions output, broken down to the contribution of each of the four sources in Experiment I is shown in Fig. 6.14. The cumulative power output of the NTUA and CRES photovoltaic systems is shown in Fig. 6.15.

In all three figures, the periods that the Diesel engine requested Carbon Credits are shaded in red. The Diesel engine was operating (i) from the beginning of the experiment until around 12:15 and (ii) for two short periods around 13:45 and 17:15.

6.6.1.1. Diesel engine emissions dominance resulted in deviation

Shortly before the two afternoon spikes in Diesel operation, the output of the other sources was altered significantly (see indent detail and red dotted circles in Fig. 6.14). At this transitional point the Diesel engine requested an amount of Carbon

Credits, but the EVPP provided less than that. The Carbon Credits provided were not sufficient for the Diesel engine to start up, therefore the 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 CRES and NTUA photovoltaics received as many Carbon Credits as they could accommodate, raising their output to the maximum (see red dotted circles in Fig. 6.15). The Fuel Cell agent refused to support the Diesel engine by receiving excess Carbon Credits, due to its internal decision-making. The Diesel engine still had excess Carbon Credits that it could not dissipate, thus a deviation from the EVPP desired output occurred (see two spikes in Fig. 6.17).

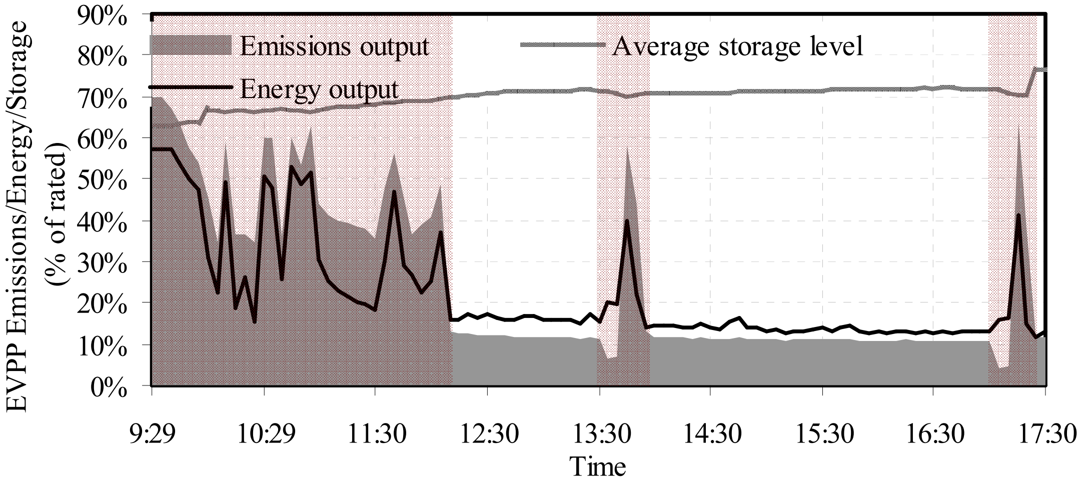

Fig. 6.13 EVPP emission and energy output, and total storage capacity (Experiment I)

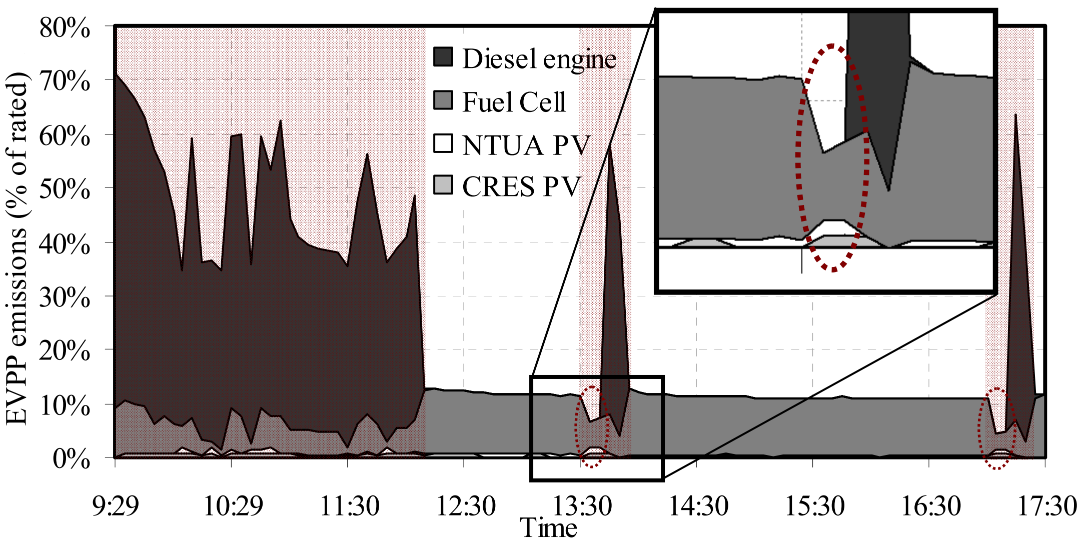

Fig. 6.14 Cumulative diagram of EVPP emissions output breakdown per source (Experiment I)

6.6.1.2. Photovoltaic and fuel cell behaviour

During the periods when the Diesel engine was not operating, the EVPP had a very low upper operational limit, compared to its rated capacity (see Fig. 6.16). For this reason, the aggregator provided as many Carbon Credits to the fuel cell and photovoltaics as they could handle. During these periods the fuel cell was producing constantly at its rated capacity, as can be seen in Fig. 6.14. Likewise, the NTUA and CRES photovoltaic systems produced as much as possible. Their internal energy storage targets were not compromised, though. This can be observed in Fig. 6.15, since the output gradually reduces, reflecting the photovoltaic panel output reduction.

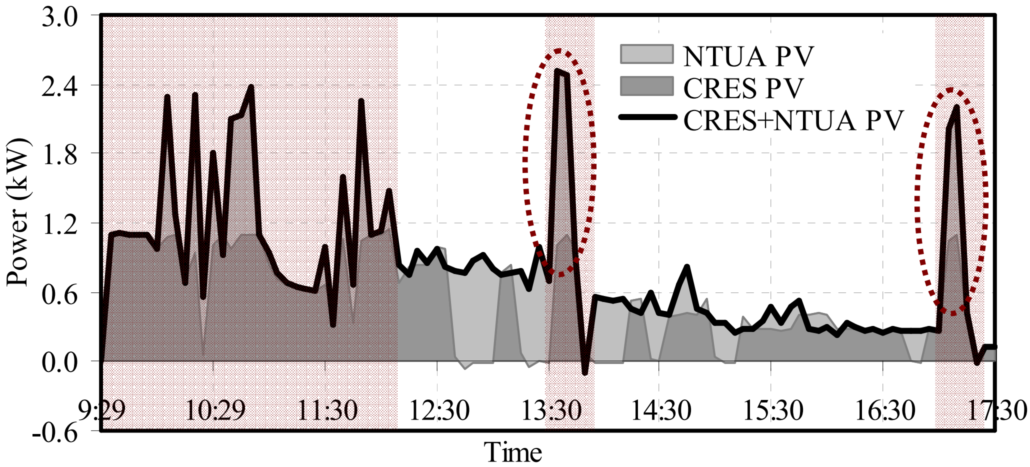

Fig. 6.15 Cumulative diagram of NTUA and CRES Photovoltaic-Battery Inverter systems power output (Experiment I)

6.6.2. Controllability

6.6.2.1. Deviation of EVPP emissions output from Carbon Credits

The EVPP desired emissions are defined by means of the Carbon Credits. The Carbon Credits are compared in Fig. 6.16 with the actual EVPP emissions output, as well as the upper emissions limit set by the generators. A close match can be seen, except for two transitional periods around 13:30 and 17:00. These two points of discrepancy can be seen as two deviation spikes in Fig. 6.17.

In the periods from 12:10 to 13:30 and 14:00 to 17:00, the Carbon Credits provided to the Diesel engine were not enough for it to be started. This limits the maximum output of the EVPP as shown in Fig. 6.16.

The diagram in Fig. 6.17 illustrates the deviation of the actual EVPP emissions from the total Carbon Credits sent by the EVPP Aggregator agent. A comparison is made between Experiments I and II. It can be seen that in Experiment II, the deviation is significantly reduced. Apart from the effect described in Section 6.6.1.1, most of the deviation is due to the errors in the agent's estimation of the micro-generator output.

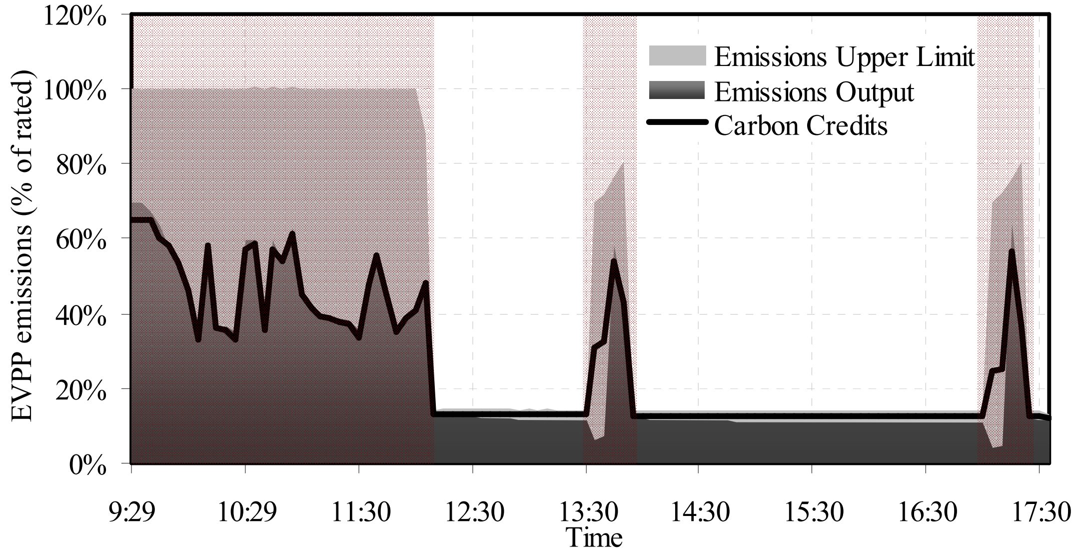

Fig. 6.16 EVPP emissions upper limit, actual output and total Carbon Credits (Experiment I)

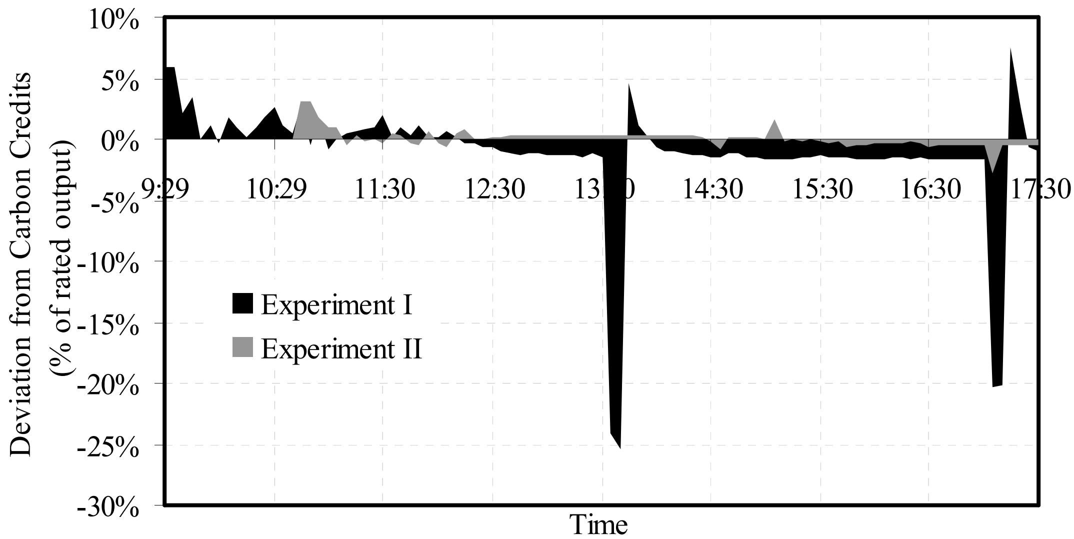

Fig. 6.17 Deviation of EVPP emissions output from supplied Carbon Credits

6.6.2.2. Effect of the number of micro-generators on controllability

In Fig. 6.18, the values from Fig. 6.16 are plotted as a correlation between the EVPP Carbon Credits and the actual EVPP emissions output. The spikes of the Experiment I deviation in Fig. 6.17 can be identified as the few points which are most distant downwards of the trend line.

The same plot was drawn in Fig. 6.19 with the data from Experiment II, which included the additional simulated agents. The correlation is better, with only a few points deviating slightly. Therefore, by increasing the number of participating micro-generators, the emissions controllability of the EVPP increased as well. Considerably fewer deviations were recorded. It was observed that when simulated agents were added to the EVPP, more agents were available to compensate an agent's potential Carbon Credit excess or shortfall.

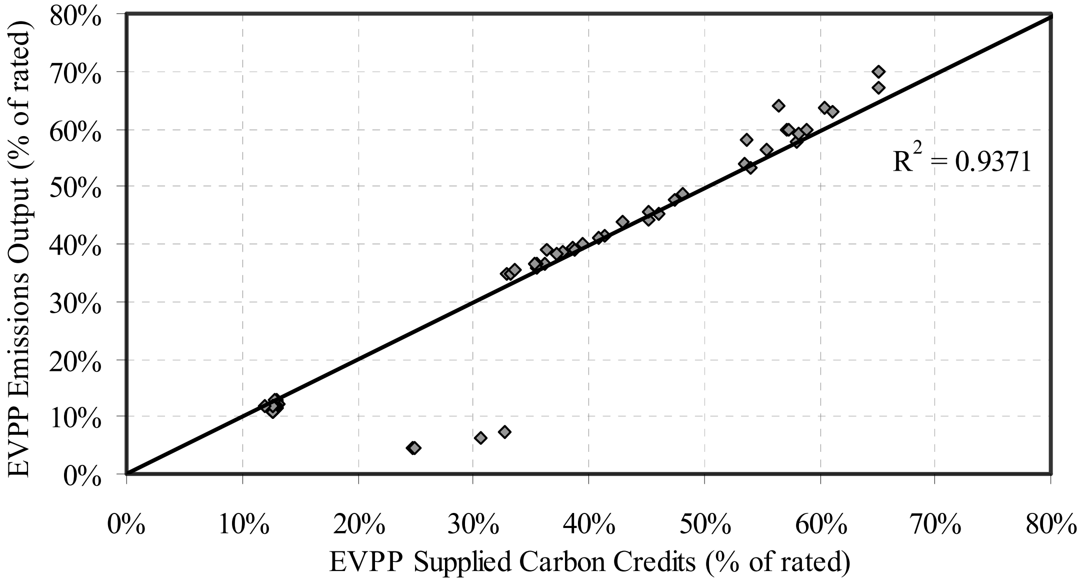

Fig. 6.18 Correlation between EVPP total Carbon Credits and total emission output in **Experiment I**

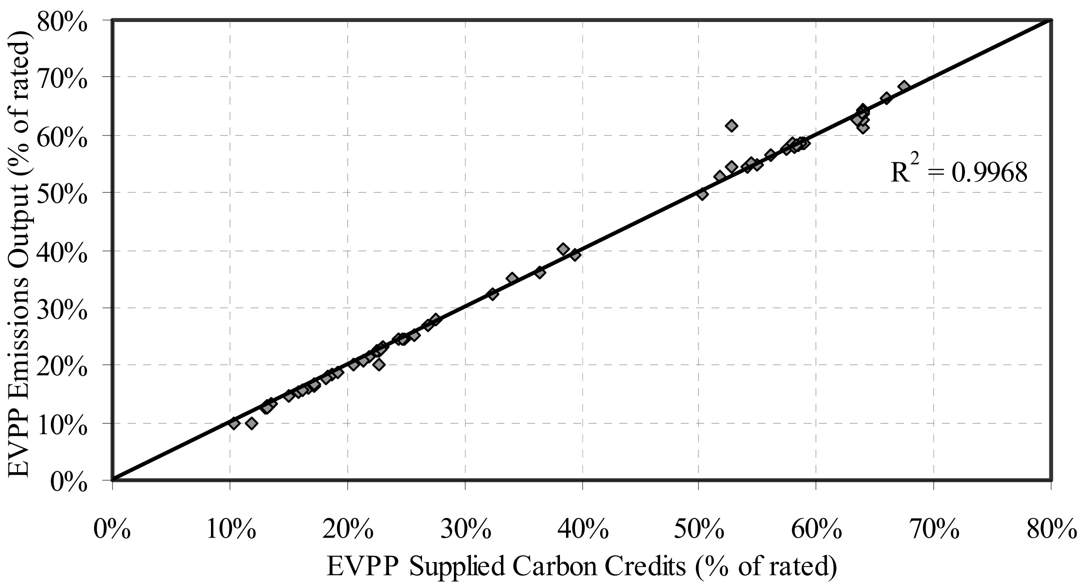

Fig. 6.19 Correlation between EVPP total Carbon Credits and total emission output in **Experiment II**

6.6.3. Composite EVPP part-load emission factor

The correlation between EVPP generation and emission factor provides an indication of the aggregated part-load emission factor curve. This correlation is shown in Fig. 6.20, for Experiment I. This diagram resembles the part-load emission factor curves presented in Fig. 6.12. The influence of the Diesel engine on the overall EVPP emissions can be observed, as indicated with the dotted circles.

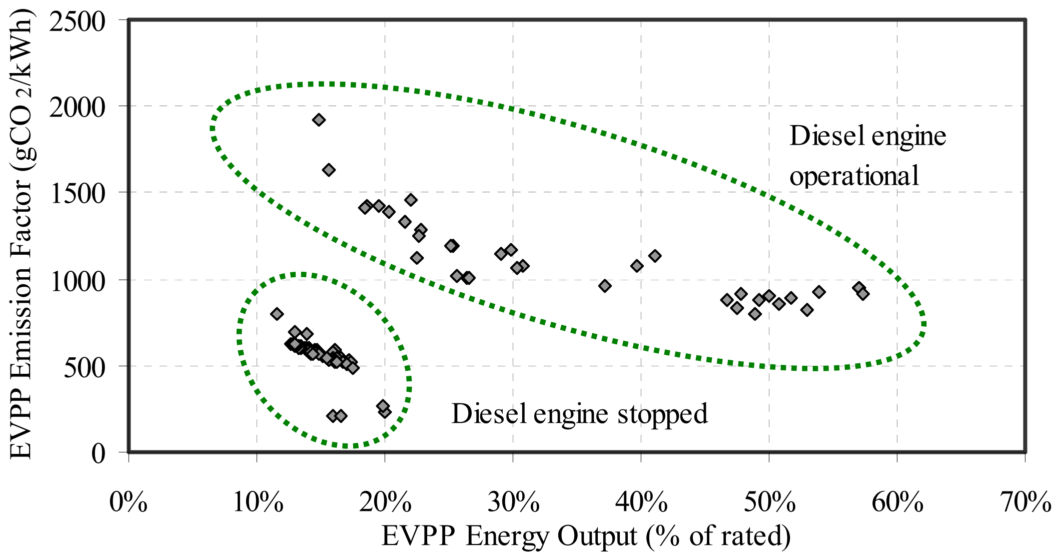

Fig. 6.20 Correlation between EVPP emission factor and energy output (Experiment I)

6.6.4. Fuel cell start-up emissions

The fuel cell produces increased emissions with the same power output for a short time after start-up (see Section 4.2.2.2). The main reason is that part of the fuel is consumed for the operation of ancillary systems, e.g. for heating up the membrane. This effect has been recorded during the experiments and is depicted in Fig. 6.21. It is also described in the literature [6].

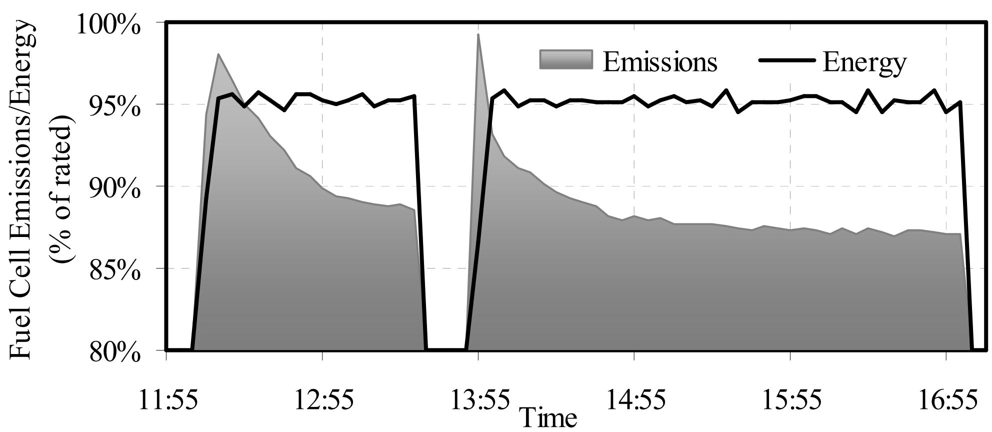

Fig. 6.21 Fuel cell start-up emissions (Experiment I)

6.7. SUMMARY

In Chapter 5, a multi-agent system was developed, based on a simulated emissions trading scheme. This system was tested experimentally, using three (3) micro-generation sources installed in CRES and one (1) in NTUA. The generic agents developed in Chapter 5 were adapted to each of the available micro-generation sources. Equipment-specific data were measured: (i) photovoltaic output historical data and (ii) Diesel engine and fuel cell part-load emissions. Data from the Greek power system were used.

Two experiments were conducted. Experiment I included the four real micro-generation units in the laboratories, while Experiment II included 55 simulated micro-generators, in addition to the real units.

The experimental results demonstrate the collaborative nature of the EVPP. This system enables the micro-generators to be controlled from a single point (EVPP), acting as a single entity. The main findings are as follows:

- Limited computational resources were necessary. All the agents were running on two personal computers.
- The fact that the Diesel engine was producing about 80% of the EVPP emissions resulted in a deviation from the supplied Carbon Credits when its agent decided to shut down the Diesel engine and dissipate the Carbon Credits.
- The controllability of the EVPP has been demonstrated. Apart from the above event, a close match between the desired and actual emissions output has been observed.
- It has been shown that by increasing the number of participants in the EVPP scheme, the emissions controllability increases significantly. This is mostly due to the fact that the micro-generation sources compensate for each other's limitations.
- The composite EVPP part-load emission factor was determined. It was found that it resembles the individual part-load emission factor curves of the micro-generators.
- Finally, the additional start-up emissions of the fuel cell were measured, as suggested in [6].

Chapter 7

Conclusions and Further Work

7.1. Contribution

Through this research, the following were accomplished:

- The potential of micro-generation sources in saving domestic carbon emissions was evaluated.
- The benefit of controlling aggregated micro-generators and optimising their emissions was assessed.
- An agent-based control system was designed and developed to control aggregated micro-generator emissions.
- The developed control system has been tested experimentally.

7.2. Carbon emissions

Emission factors were calculated for selected micro-generators. The life-cycle emissions associated with the manufacturing, transport, operation and disposal of micro-generators were assessed.

Two case studies were conducted, looking at the emissions saving potential of micro-generators (i) during their operation and (ii) during their whole life-cycle.

7.2.1. Operational emissions case study

The operational emissions of (i) fuel cells, (ii) Diesel engines and (iii) microturbines were examined against the UK grid electricity and gas boiler heat. All of the micro-generators were considered to be micro-CHP units.

It was found that emissions associated with domestic electrical and thermal demand would be reduced by approximately **13-41%**, depending on the technology, fuel and penetration level. Biomass fuels would achieve similar reduction levels to fossil fuels with a quarter of the penetration. Taking into account that network losses would be avoided increases the emissions savings by approximately **1-3%**.

7.2.2. Life-cycle emissions case study

A case study was constructed, based on the literature, including (i) wind turbines, (ii) photovoltaics, (iii) fuel cells and (iv) microturbines. Fuel cells and microturbines were considered to be micro-CHP units.

It was found that the overall emissions would be reduced by approximately **30%**. If it is assumed that a Combined Cycle Gas Turbine would be forced to operate part-loaded, the additional incurred emissions would reduce the savings to **25%**.

It was observed that life-cycle emissions from biomass-fuelled micro-generators were lower than conventional generation, but also significantly higher than zero.

7.3. VIRTUAL POWER PLANT EMISSIONS OPTIMISATION

A Virtual Power Plant was defined, using micro-generation penetration projections for the year 2030 from the literature. An optimisation problem was described, where the goal was to minimise the carbon emissions from aggregated micro-generators. The types of micro-generators that were considered were: (i) wind turbines (ii) photovoltaics (iii) fuel cells (iv) microturbines and (v) Stirling engines. The fuel cells, microturbines and Stirling engines were considered to be micro-CHP units. Only the micro-CHP profiles were optimised, by using thermal storage as a buffer for varying the micro-CHP output.

The results were indicative of the amount of emissions that would potentially be reduced by managing an existing micro-generation portfolio in a VPP. These reductions would be achieved with minimal modifications and cost. Controllers would need to be installed on the micro-generators and the points of aggregation.

7.3.1. Optimal micro-CHP profiles

The micro-CHPs were found to produce fewer emissions when they were operating constantly, with minimal interruptions, at full capacity. This is due to two factors; both of them lead to increased emissions due to additional fuel consumption:

(i) At start-up and shut-down, additional fuel is consumed for auxiliary functions, such as heating/cooling of components.

(ii) Their conversion efficiency is lower when operating part-loaded.

7.3.2. Emission savings

The emissions savings of the optimised VPP were evaluated against the baseline of having no micro-generation installed. The customer electricity would be supplied by the UK grid and thermal demand would be covered by a standard boiler. It was found that total customer emissions were reduced by up to:

(i) **44%** by the VPP with optimised profiles, utilising thermal storage.
(ii) **42%** by the VPP without optimised profiles, utilising thermal storage.
(iii) **41%** by the VPP without optimised profiles, not utilising thermal storage.

7.3.3. Emission factor daily variation

The overall emission factor of the electricity supplied to the customers was not constant throughout the day. Further variations were introduced by the operation of the VPP. Due to the optimisation, most of the micro-CHPs were started simultaneously. The additional micro-CHP start-up emissions resulted in significant instantaneous increase of the VPP average emission factor.

7.4. ENVIRONMENTAL VIRTUAL POWER PLANT

A distributed control system for a Virtual Power Plant was designed. The principle of operation was based on the EU Emissions Trading Scheme. Carbon Credits were used to balance the micro-generator emissions within the VPP. This system was termed Environmental Virtual Power Plant (EVPP), after the Commercial and Technical VPP described in [41]. A hierarchical structure was defined. Three types of intelligent agents have been used: (i) the EVPP Aggregator agent, (ii) the Micro-grid Aggregator agent and (iii) the Micro-generator agent.

The main benefit of the proposed control system is that it enables the participation of micro-generators in electricity and emissions markets. Their integration in the power system is also facilitated, which brings improvements in the overall emissions performance of the power system. The benefits of distributed systems are inherited, allowing the addition or removal of micro-generators to the EVPP at any time and with little or no cost.

7.4.1. Simulated operation – controllability

It was observed that the EVPP can regulate the emissions of micro-generators with a high precision within the operational limits of the micro-generators.

One limitation was that the operational limits determine the EVPP flexibility. This distinguishes the controllability of the EVPP from that of a real power plant.

One advantage was that the EVPP ramp rate was defined by the length of the operational period, which would normally be in the scale of minutes. Another advantage was that micro-generators could be connected or disconnected at any time, without any changes to the control system or any interruption of the EVPP operation.

The number of Carbon Credits, and therefore the EVPP output, was determined by the EVPP control policy. It could also be defined by an external entity, such as the system operator. Small deviations from the EVPP desired emissions output were observed under the following circumstances:

(i) Immediately after a peak in thermal demand and

(ii) At times when the thermal demand was very low.

The emissions savings achieved by the EVPP operation were calculated. They were scaled up to be comparable with the optimisation study. The emissions savings were found to be very similar with the corresponding optimisation study case.

7.4.2. Experimental operation

The EVPP control system was tested using equipment from two laboratories, installed in NTUA and CRES, in Greece. The NTUA equipment was a photovoltaic system (PV panel and battery inverter). The CRES equipment included a similar PV system, a Diesel genset and a fuel cell. The developed control methods provided the agents of each generator with the capability to regulate the energy output. Data from the Greek power system were used in the experiments.

Two experiments were performed. During both experiments, an EVPP was operated for approximately 8 hours, using the mixed control policy (emissions and cost). In Experiment I, the EVPP included only the four sources installed in the two laboratories. In Experiment II, 55 additional sources were simulated. The purpose was to test the controllability of the EVPP with regards to the number of the participating sources.

7.4.2.1. Deviation from EVPP Carbon Credits

In 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. During certain transitional periods in Experiment I, the Diesel engine agent decided to switch off the generator and sell the Carbon Credits to the other sources. The other sources were only capable to increase their output to accommodate a small amount of these Carbon Credits, so most of them were left unsold.

Consequently, the actual EVPP output was significantly less than planned by the EVPP Aggregator agent. As a consequence, some Carbon Credits that the EVPP Aggregator would have purchased from the external emissions market were redundant, thus wasted. This can be taken as a penalty caused by the deviation, despite the fact that the emissions were actually lower than required. This reveals an inherent limitation of the emissions market, which is that market participants can be "penalised" if they are over-contributing to the purpose of reducing emissions.

7.4.2.2. Increasing the number of sources

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:

- The Diesel engine had access to much more micro-generator agents that could buy or sell Carbon Credits. Thus, incidents such as the deviation peaks in Experiment I were avoided.
- Most of the sources (55 out of 59) were simulated, therefore lacking the limitations of real systems.

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 is inversely proportional to the number of sources.

7.5. FURTHER WORK

7.5.1. Emissions optimisation

The optimisation method used for the VPP could be extended to include network constraints, such as (i) voltage limits (ii) transformer limits and (iii) current thermal limits. The resulting method would constitute a "Carbon Optimal Power Flow (Carbon OPF)".

Randomisation factors could also be included, for more realistic inputs.

7.5.2. Environmental Virtual Power Plant control system

The agent-based control system could be developed further by:

- Using more advanced artificial intelligence methods for internal agent operation and decision-making.
- Using a more accurate forecasting method.
- Extending the EVPP control policies, or adding new policies.

The operation and behaviour of the control system could be further tested by:

- Measuring the controllability of the EVPP with a more diverse range of micro-generators included. A curve can be drawn, correlating the number of sources with the EVPP controllability.
- Testing for longer periods and in different seasons.
- Measuring and evaluating the operation of real micro-CHP sources.

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Appendix A – Fuzzy Logic examples

- **Fuzzy sets**

As an example, the price of a kWh is considered. Fuzzy sets can be defined as shown in Fig. A.1. A price of €0.10 would be considered definitely average, a price of €0.20 definitely expensive, and a price of €0.02 definitely cheap. However, a price of €0.15 is considered 50% average and 50% expensive.

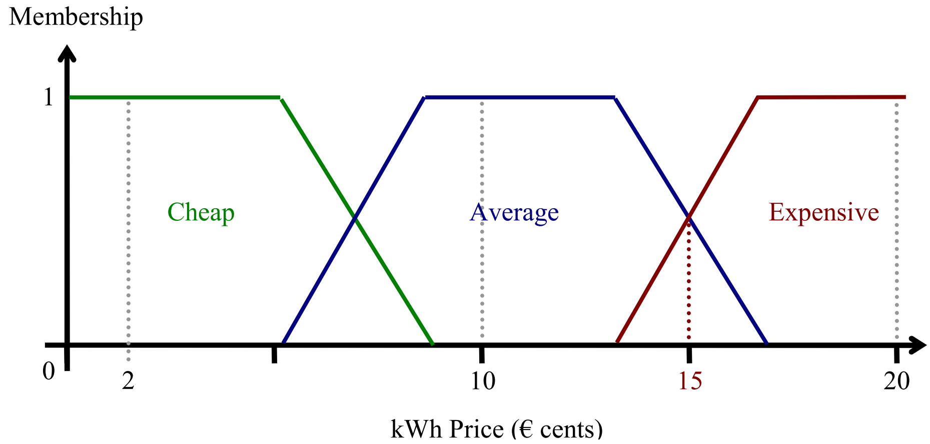

Fig. A.1 Fuzzy sets for the price of a kWh

Every number has a degree of membership in each of the three sets: Cheap, Average and Expensive. Therefore, the aforementioned prices would be represented as fuzzy numbers (fuzzy membership) in the following way:

TABLE A.I: EXAMPLES OF FUZZY MEMBERSHIPS

Price	Cheap	Average	Expensive
€0.02	1	0	0
€0.10	0	1	0
€0.15	0	0.5	0.5
€0.20	0	0	1

- **Fuzzy clustering**

An example of fuzzy clustering is illustrated in Fig. A.2 and Fig. A.3. In Fig. A.2, a domestic load profile is shown, taken from UKERC [102]. This set of data can be clustered in fuzzy sets by the Fuzzy c-Means algorithm. The resulting sets are shown in Fig. A.3.

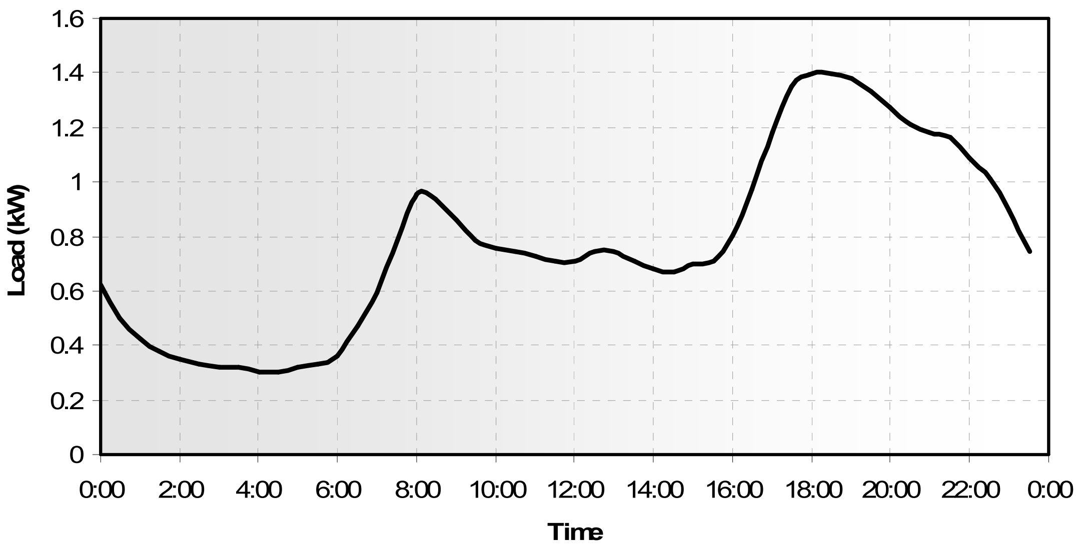

Fig. A.2 Domestic load profile

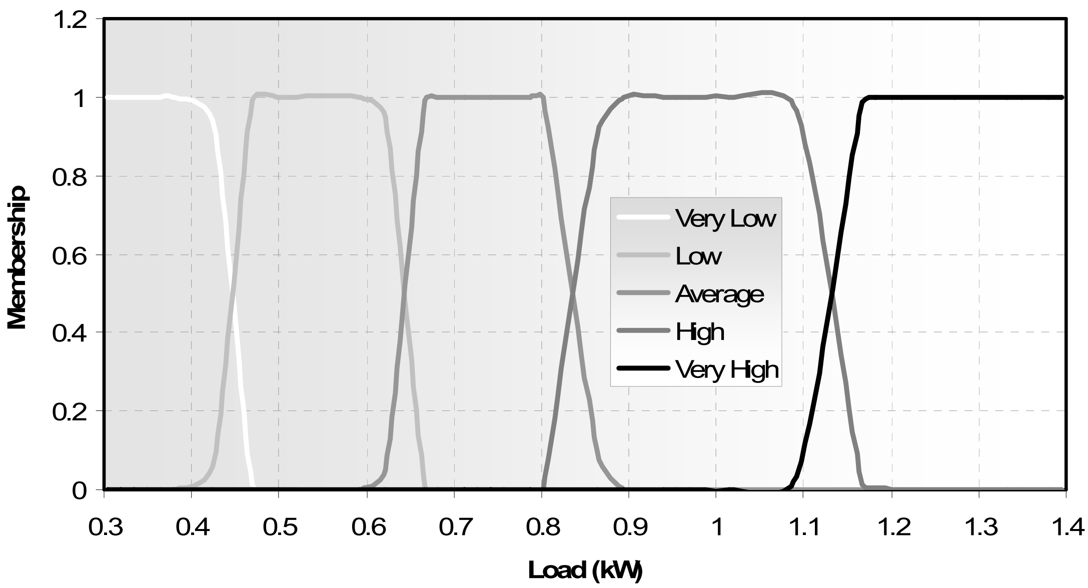

Fig. A.3 Fuzzy clusters for the domestic load profile

- **Fuzzy inference (interpolation method)**

(i) Calculate the height of the intersection of X in set A, and then truncate the set B at that height:

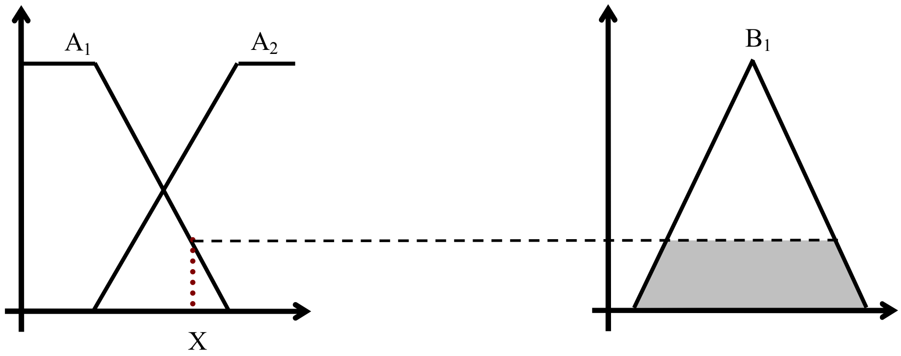

Fig. A.4 Fuzzy rule 1

(ii) Do the same for every other rule:

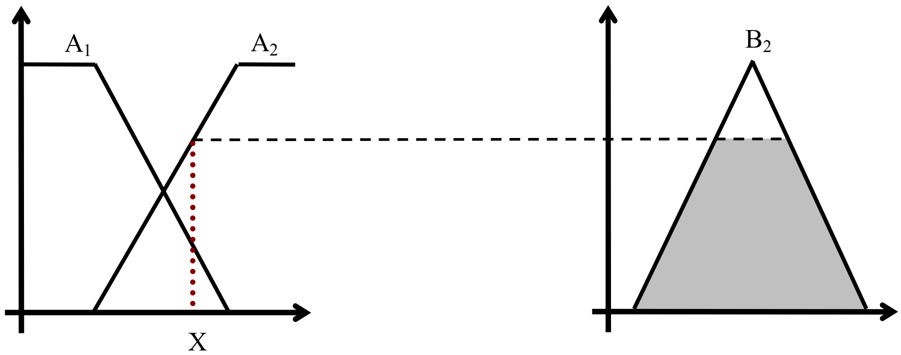

Fig. A.5 Fuzzy rule 2

(iii) Take the union of the two truncated sets to come up with the result:

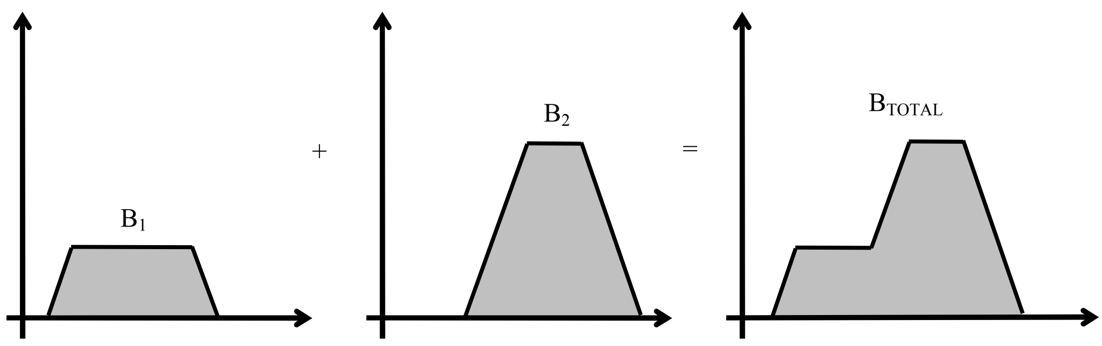

Fig. A.6 Result of the interpolation method for fuzzy rules 1 and 2

Appendix B – RETScreen inputs

TABLE A.II: RETSCREEN INPUT PARAMETERS.

Parameter	Value	Unit	Source
Location	Cardiff, UK	-	-
Electrical demand profile	-	-	UKGDS [87]
Heat demand profile	-	-	UKGDS [87]
Electrical peak load	125	kW	UKGDS [87]
Total heat demand	1728	MWh/yr	[88]
Micro-CHP availability	7455	h/yr	UKGDS [87]
Micro-CHP capacity factor	85.1	%	UKGDS [87]
Electrical efficiency - Fuel Cell	40.4	%	[13], [14], [15], [16]
Electrical efficiency - Microturbine	25.9	%	[13], [14], [15], [16]
Electrical efficiency - Diesel ICE	37.5	%	[13], [14], [15], [16]
Conversion efficiency - Boiler	90	%	[13]
Heat Rate - Fuel Cell	8916	kJ/kWh	[13], [14], [15], [16]
Heat Rate - Microturbine	13913	kJ/kWh	[13], [14], [15], [16]
Heat Rate - Diesel ICE	9600	kJ/kWh	[13], [14], [15], [16]
Heat Rate - Boiler	4000	kJ/kWh	[13]
Peak demand source - Electricity	UK grid	-	-
Peak demand source - Heat	Gas boiler	-	-
Emission factor - Natural Gas - CO_2	50.49	kg/GJ	[1], [30]
Emission factor - Natural Gas - CH_4	1	kg/GJ	[1], [30]
Emission factor - Natural Gas - N_2O	0.1	kg/GJ	[1], [30]
Emission factor - Biogas - CO_2	0.0 [a]	kg/GJ	[1], [30]
Emission factor - Biogas - CH_4	1	kg/GJ	[1], [30]
Emission factor - Biogas - N_2O	0.1	kg/GJ	[1], [30]
Emission factor - Diesel - CO_2	68.913	kg/GJ	[1], [30]
Emission factor - Diesel - CH_4	3	kg/GJ	[1], [30]
Emission factor - Diesel - N_2O	0.6	kg/GJ	[1], [30]
Emission factor - Biodiesel - CO_2	0.0 [a]	kg/GJ	[1], [30]
Emission factor - Biodiesel - CH_4	3	kg/GJ	[1], [30]
Emission factor - Biodiesel - N_2O	0.6	kg/GJ	[1], [30]
Transmission and distribution losses	7.04	%	[86]

[a] due to the carbon cycle [31]

- RETScreen requires the user to input the location of the project so that the climate statistics can be determined. RETScreen incorporates a complete database of climate statistics, most of which are acquired from NASA.
- The generators are considered to operate at full capacity, not in load following mode. Excess power is being exported to the grid. Excess heat is considered to be dissipated.

- For the micro-CHP system, RETScreen requires the heat rate (HR) of the system, in kJ/kWh. This is found from:

$$HR = \frac{3600}{\eta} \tag{30}$$

where: *HR* is the heat rate (kJ/kWh).
η is the electrical efficiency.

- The Higher Heating Value (HHV) was used for all fuels. For the HHV, the heat rate includes the heat lost for the vaporisation of water contained in the fuel. Otherwise, the heat rate is expressed as the LHV (Lower Heating Value). In hydrocarbons, HHV from LHV have a difference of approximately 7% to 11%

Appendix C – Homer inputs

TABLE A.III: HOMER INPUT PARAMETERS.

Parameter	Value	Unit	Source
Electrical demand profile	-	-	UKGDS [87]
Profile daily perturbation	8	%	-
Profile hourly perturbation	16	%	-
Biomass resource	unlimited	-	-
Natural Gas - Energy Content (LHV)	50.380	MJ/kg	[30], [112]
Natural Gas - Carbon Content	67.062	%	[1], [112]
Natural Gas - Density	0.790	kg/m^3	Homer [112]
Natural Gas - Sulphur Content	0.000	%	Homer [112]
Biogas - Energy Content (LHV)	48.740	MJ/kg	[30], [112]
Biogas - Carbon Content	0.062	%	[1], [112]
Biogas - Density	0.720	kg/m^3	Homer [112]
Biogas - Sulphur Content	0.000	%	Homer [112]
Diesel - Energy Content (LHV)	45.600	MJ/kg	[30], [112]
Diesel - Carbon Content	88.296	%	[1], [112]
Diesel - Density	852.676	kg/m^3	[30], [112]
Diesel - Sulphur Content	0.330	%	Homer [112]
Biodiesel - Energy Content (LHV)	43.296	MJ/kg	[30], [82], [112]
Biodiesel - Carbon Content	0.296	%	[1], [112]
Biodiesel - Density	880.000	kg/m^3	[83]
Biodiesel - Sulphur Content	0.330	%	Homer [112]
Heat recovery - Fuel Cell	95	%	[13]
Heat recovery - Microturbine	91	%	[13]
Heat recovery - Diesel ICE	96	%	[13]
Heat to Power Ratio (HPR) - Fuel Cell	1.4	-	[13]
Heat to Power Ratio (HPR) - Microturbine	2.6	-	[13]
Heat to Power Ratio (HPR) - Diesel ICE	1.6	-	[13]
Grid emission factor	544	gCO_2/kWh	Carbon Trust [30]

- Homer requires the part-load efficiency curve for each fuel/technology. This was approximated for each technology, and scaled so that the resulting annual average efficiency would equal the one shown in Table 3.X.
- Homer calculates the grid exports. Using the grid emission factor, it counts these as negative emissions or, otherwise, avoided emissions.
- Homer does not have a specific input for the transmission and distribution losses. Therefore, all sources were assumed to be in DC mode, and they were put behind a converter (inverter and rectifier). The converter was given an efficiency of 93%, to emulate 7.04% transmission and distribution losses [86].

APPENDIX D – OPERATIONAL EMISSIONS CALCULATION METHOD INPUTS

In this method, data from [87] were used to calculate the annual energy generation values for each micro-generation mix. Then, the emission factors were calculated from data from the Intergovernmental Panel on Climate Change (IPCC) [1] and were multiplied with the energy produced from each micro-generation technology, so that the total annual emissions were obtained. The displaced (avoided) grid emissions were calculated by multiplying the total energy produced in each case with the grid emission factor. The displaced emissions from the boiler were calculated with the same procedure. Finally, the displaced emissions were subtracted from the micro-grid emissions to find the emission savings. The emission factors used are presented in Table A.IV:

TABLE A.IV: FUEL EMISSION FACTORS

Fuel	Technology	Fuel emission factor (gCO_2/kWh)	Electrical Efficiency	Micro-CHP Emission Factor (gCO_2/kWh)
Natural Gas	Fuel Cell	183.770	40.375%	455.2
Biogas	Fuel Cell	0.170	40.375%	0.4
Natural Gas	Microturbine	183.770	25.875%	706.8
Biogas	Microturbine	0.170	25.875%	0.7
Diesel	Diesel ICE	250.146	37.5%	667.1
Biodiesel	Diesel ICE	0.838	37.5%	2.2
Natural Gas	Boiler	183.770	90.00%	204.2

The micro-CHP emission factors were calculated by dividing the fuel emission factor by the efficiency of the technology.

Appendix E – Aggregator / Micro-generator interaction

The interaction sequence between the micro-generators and the aggregators is illustrated in Fig. A.7. It is described as follows:

(i) ***(Once)*** The micro-generator agents register with their corresponding Micro-grid Aggregator agent. The Micro-grid Aggregator agent updates the total power and aggregated emission factor of the micro-grid.

(ii) ***(Once)*** Similarly, the Micro-grid Aggregator agents register with the EVPP Aggregator agent. The EVPP Aggregator agent updates the total power and aggregated emission factor of the EVPP.

(iii) The EVPP Aggregator agent announces the start of the new trading period and the end of the previous trading and operational periods.

(iv) The micro-generator agents complete any pending transactions and then return their final Carbon Credits to the EVPP Aggregator agent, through the Micro-grid Aggregator agent. They also return information on the last operational period as well as projections for the next operational period.

(v) The EVPP Aggregator agent calculates the penalties based on the data it received from the agents. It sends the possible penalties to the Micro-grid Aggregator agents for distribution to the micro-generator agents.

(vi) The EVPP Aggregator agent generates a new set of Carbon Credits and distributes them to the micro-generator agents proportionally, according to their projections. The amount of Carbon Credits it creates is based on two factors: (a) the projections of the micro-generator agents and (b) the control policy of the EVPP. The policy defines how favourable it is for the EVPP to produce carbon emissions at the current time step.

(vii) The micro-generator agents receive the Carbon Credits and start trading, if necessary.

(viii) The process repeats from step III at the next time step.

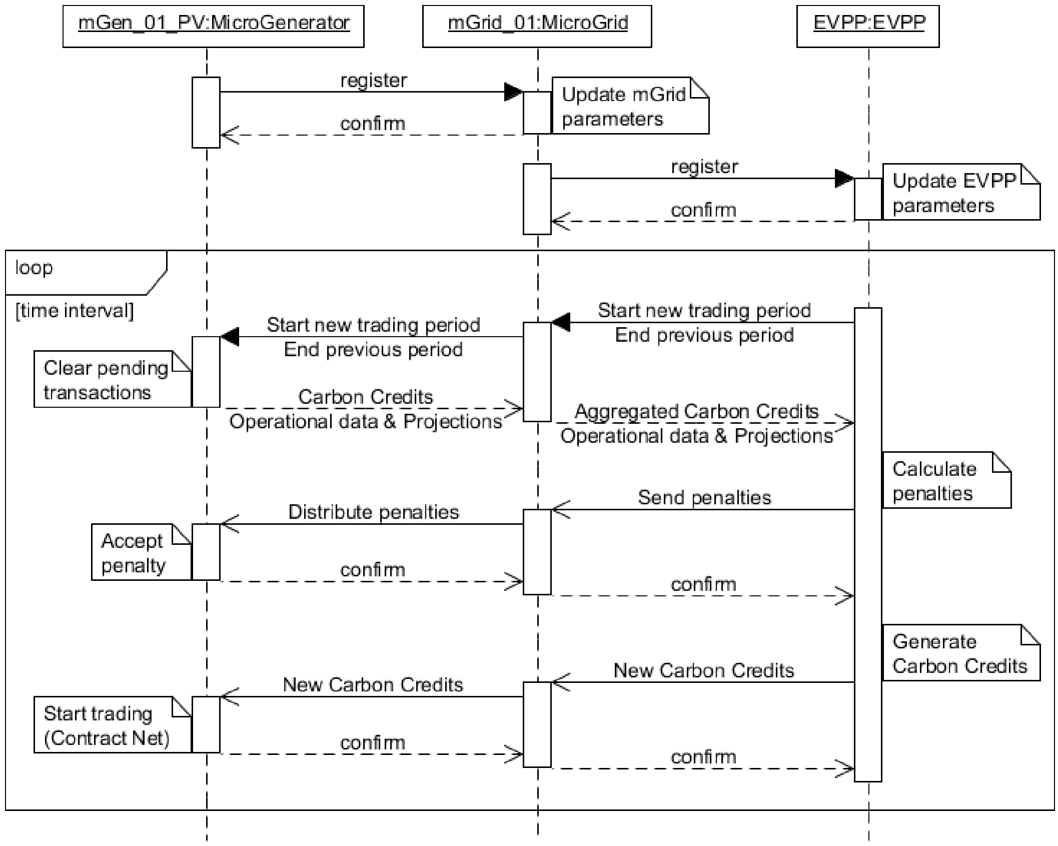

Fig. A.7 Unified Modelling Language (UML) sequence diagram showing the interaction between aggregator and micro-generator agents

Appendix F – Micro-generator / Micro-generator interaction

Once the micro-generator agents have received the Carbon Credits from the Micro-grid Aggregator agents, they calculate the difference between the emissions justified by the Carbon Credits and their projected emissions. Then, if they find a discrepancy, they start trading Carbon Credits with other agents, in order to match their projected emissions.

They do this by using the Contract Net agent interaction protocol [65][66][70]. This interaction is drawn in a Unified Modelling Language (UML) sequence diagram in Fig. A.8. It is described as follows:

(i) Every few seconds (e.g. 5 seconds) the agent checks if the trading period has started. It also checks if it has a Carbon Credit deficit or excess.

(ii) If it needs to trade, then it prepares and sends out Call For Proposal (CFP) messages to the other micro-generator agents. This agent is called the initiator agent, since it initiates the protocol. To prepare CFP messages, the agent:

a. Discovers the other agents that are actively trading Carbon Credits.

b. Derives the amount of Carbon Credits it needs to trade.

(iii) If an agent receives a CFP message, it decides (a) how many Carbon Credits it wants to trade and (b) a reasonable price for them. If it decides that it is willing to trade Carbon Credits, it returns a Propose message to the initiator, which contain the proposed number and price of the Carbon Credits. Otherwise, it returns a Refuse message. This agent is called the responder agent, since it responds to a call from an initiator agent.

(iv) If a proposal is returned to the initiator agent, it evaluates the proposal price and quantity.

(v) If the initiator decides to accept the proposal, then it prepares an Accept message, which it sends to the responder. There are two possibilities:

a. If the intent was to sell, it retrieves the Carbon Credits from its database and includes them in the Accept message.

b. If the intent was to buy, it includes in the message the number of Carbon Credits it will finally buy.

(vi) The responder agent then updates its money total. It prepares an Inform message, to confirm that the transaction has been successful. Depending on the type of the transaction, it also:

a. Inserts the received Carbon Credits in its database.

b. Retrieves the Carbon Credits from its database and includes them in the Inform message.

(vii) The protocol ends.

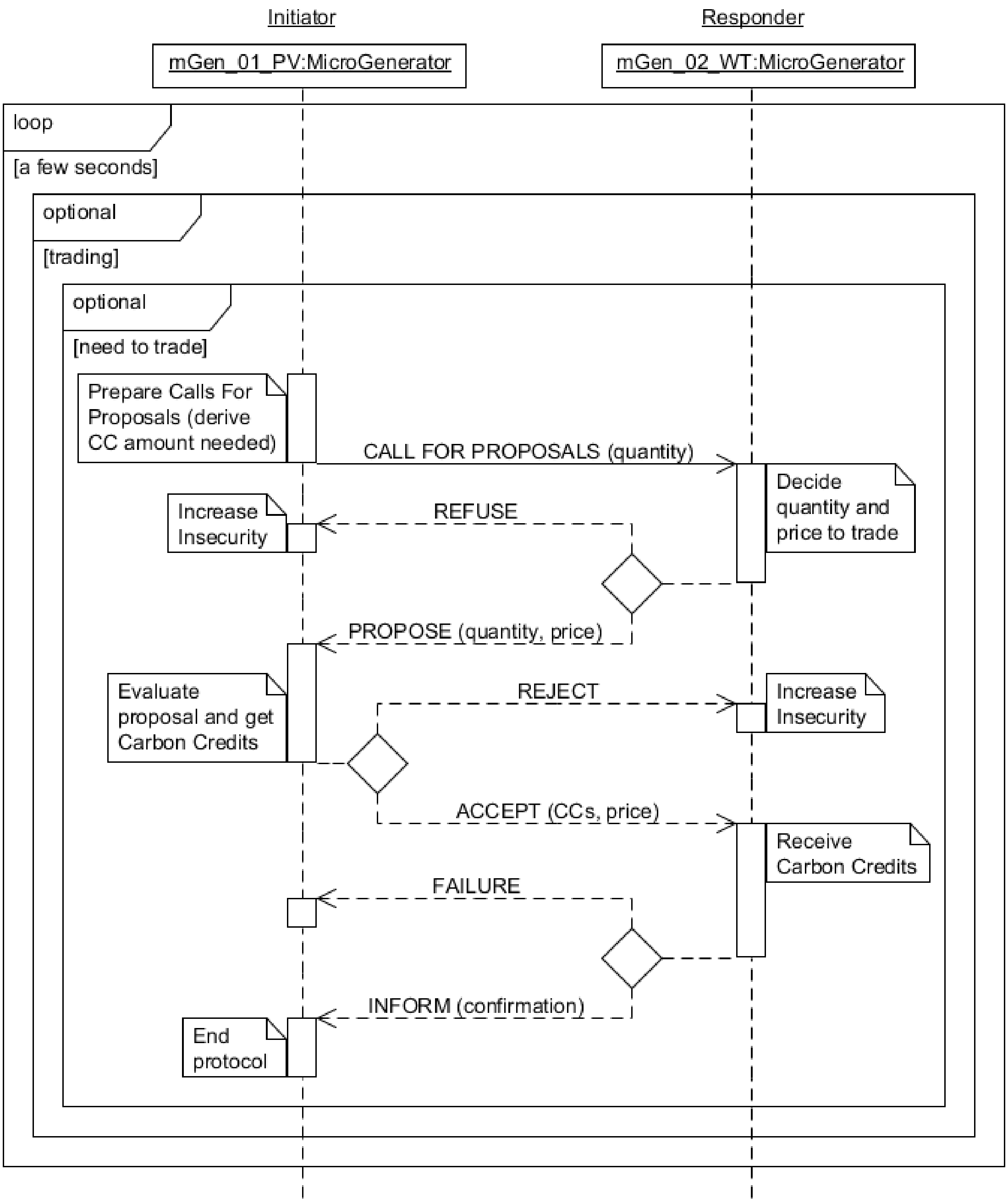

Fig. A.8 UML sequence diagram showing the trading interaction between micro-generator agents

If a Call For Proposals is refused, the initiator agent increases its insecurity factor (see Section 5.3.4). Likewise, the responder increases its insecurity factor if a Proposal is rejected by the initiator.

Appendix G – Multi-agent System structure

The following JADE classes are used (Fig. A.9):

- ✓ **TickerBehaviour**, which executes every predefined time interval
- ✓ **WakerBehaviour**, which executes after a given time
- ✓ **SubscriptionManager**, to register the micro-generators to the aggregator
- ✓ **SubscriptionInitiator**, to send registration requests to the aggregator
- ✓ **AchieveREInitiator**/**AchieveREResponder**, to implement the FIPA Request and FIPA Query interaction protocols
- ✓ **ContractNetInitiator/SSContractNetResponder**, to implement the FIPA Contract Net interaction protocol (SS stands for single session)

For the EVPP Aggregator agent:

- ✓ A **SubscriptionManager** (registerMicrogrid) is used to keep a database of the micro-grids that are aggregated under this VPP agent.
- ✓ A **Ticker** behaviour (StartTradingPeriod) is used to iterate through the trading sessions, and call the behaviours necessary to initiate the trading sessions.
- ✓ An **AchieveREInitiator** behaviour (TradeInitiator) is used to initiate the trading session, send the corresponding initiation messages to the agents and generate the Carbon Credits.
- ✓ An **AchieveREInitiator** behaviour (SendCCs) is used to send the Carbon Credits to the agents.
- ✓ A **Waker** behaviour (ClearPendingTransactions) is added by the StartTradingPeriod to notify the agents shortly before the trading period ends, in order for them to clear any pending trading transactions.

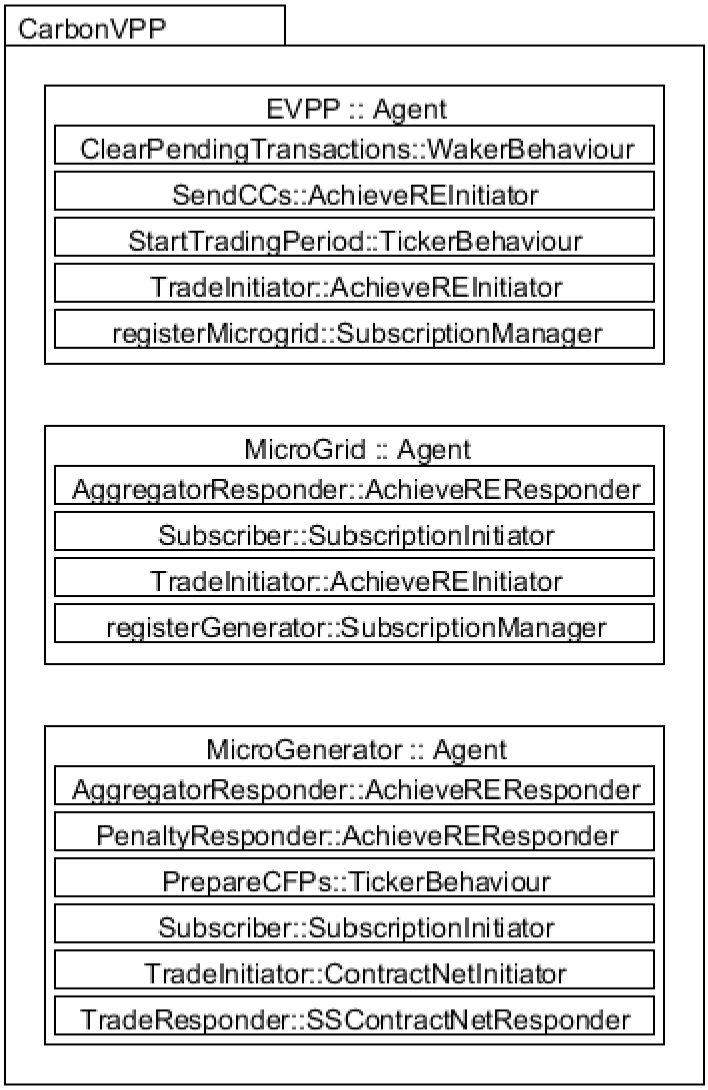

Fig. A.9 Class diagram of the multi-agent system

For the MicroGrid agent:

- ✓ A **SubscriptionManager** (registerGenerator) is used to keep a database of the micro-generators that are aggregated under this Micro-grid Aggregator agent.
- ✓ A **SubscriptionInitiator** behaviour (Subscriber) is used to send subscription/registration requests to the EVPP.
- ✓ An **AchieveREResponder** behaviour (AggregatorResponder) is used to notify micro-generators based on EVPP Aggregator requests (e.g. start trading) and relay the information necessary between the micro-generators and the EVPP Aggregator (e.g. Carbon Credits).

- ✓ An **AchieveREInitiator** behaviour (TradeInitiator) is used to initiate the trading session and send the corresponding initiation messages to the agents.

For the MicroGenerator agent:

- ✓ A **SubscriptionInitiator** behaviour (Subscriber) is used to send subscription/registration requests to the MicroGrid.
- ✓ An **AchieveREResponder** behaviour (AggregatorResponder) is used to receive aggregator notifications (e.g. start/stop trading) and respond with the information necessary (e.g. final emissions). It also receives the Carbon Credits.
- ✓ A **Ticker** behaviour (PrepareCFPs) is used to check is the agent needs to trade Carbon Credits and if it does, prepare messages for Calls For Proposals and initiate trading interaction protocols.
- ✓ A **ContractNetInitiator** behaviour (TradeInitiator) is used to initiate the FIPA Contract Net interaction protocol. It sends the CFPs regarding Carbon Credits trading and responds to proposals submitted from the other agents.
- ✓ An **SSContractNetResponder** behaviour (TradeResponder) is used to respond to FIPA Contract Net CFPs from other agents. It also sends/receives the Carbon Credits from/to the other agents.
- ✓ An **AchieveREResponder** behaviour (PenaltyResponder) is used to receive and process penalties that the micro-generator agent may receive from the aggregator.

Appendix H – Micro-generator agent internal architecture

As soon as the agent starts, it adds the necessary behaviours in the agent behaviour pool [70]. This includes:

- ✓ the *AggregatorResponder*
- ✓ the *PenaltyResponder*
- ✓ the *PrepareCFPs*
- ✓ the *Subscriber*, that registers the micro-generator to the aggregator, and
- ✓ a *Dispatcher* behaviour that adds a *TradeResponder* every time a CFP message is received.

The *AggregatorResponder* behaviour receives the messages that are sent by the aggregator (MicroGrid agent). These are of three types:

- ✓ *Clear Pending Transactions*: The agent stops initiating trading sessions with other agents, and finishes the ones that are pending.
- ✓ *Trade*: The agent returns to the MicroGrid agent:
  1. the Carbon Credits,
  2. the operational data of the previous operational period:
     - o Final emissions
     - o Final generation
     - o Final thermal demand
     - o Unserved heat
     - o Thermal storage level
  3. projections on the next operational period parameters:
     - o Lower emissions bound
     - o Projected (desired) emissions, based on its needs
     - o Upper emissions bound
     - o Insecurity factor
- ✓ *Carbon Credits*: The agent receives the Carbon Credits from the aggregator, and it can start initiating trading sessions with other agents.

The *PrepareCFPs* behaviour runs every 10 seconds. If the agent status is at Trading (i.e. the trading period has started), it calculates its need for Carbon Credits. If it needs to trade, it creates the Call For Proposal messages and adds the TradeInitiator behaviour, which sends the CFP messages to the other agents, initiating trading sessions with them.

The *TradeInitiator* behaviour initiates trading sessions with other micro-generator agents. It includes call-back methods that are invoked during specific events:

- ✓ *prepareCfps*: It is called when the behaviour is started. It discovers the recipients' addresses and prepares and sends the CFP messages (adding recipients, setting parameters).
- ✓ *handleAllResponses*: It is called when all the responses (PROPOSE, REFUSE) are received from all the agents, or a predefined deadline has passed. It sorts all the proposals according to the price. Then, based on the best price, it determines the quantity of Carbon Credits it wants to trade. It processes the responses one by one, starting with the ones with the best price. It replies with ACCEPT messages until the amount of Carbon Credits it decided to trade is covered. The rest of the proposals are rejected. If a response is not a PROPOSE, but a REFUSE message, then the agent increases its insecurity factor by a given amount.
- ✓ *handleInform*: It is called when an INFORM message is received, which ends the protocol. If Carbon Credits are included in that message, it incorporates them into its existing set of Carbon Credits.

The *TradeResponder* behaviour is added by a Dispatcher behaviour every time a CFP message is received. It includes call-back methods that are invoked during specific events:

- ✓ *handleCfp*: It is called when the behaviour is added (a CFP message is received). It derives the amount to trade, according to the message and the availability of Carbon Credits. It also decides on a good price to propose. For that, it takes into account its insecurity, the overall agent community insecurity (see Section 5.3.4) as well as previous Carbon Credit prices that other agents have proposed. Finally, it sends the proposal message.

- ✓ *handleAcceptProposal*: It is called when an ACCEPT message is received. If it includes Carbon Credits, it incorporates them to its existing set. Otherwise, it checks that it actually has the agreed Carbon Credits, and puts them in the INFORM message. It then sends the message.
- ✓ *handleRefuse*: It is called when a REFUSE message is received. The agent insecurity factor is increased by a predefined amount.

The *PenaltyResponder* behaviour receives the messages that contain a penalty. It subtracts the amount of the penalty from the variable that corresponds to the agent money.

The Unified Modelling Language (UML) activity diagrams describing the functionality of the MicroGenerator agent are illustrated in Fig. A.10, Fig. A.11 and Fig. A.12.

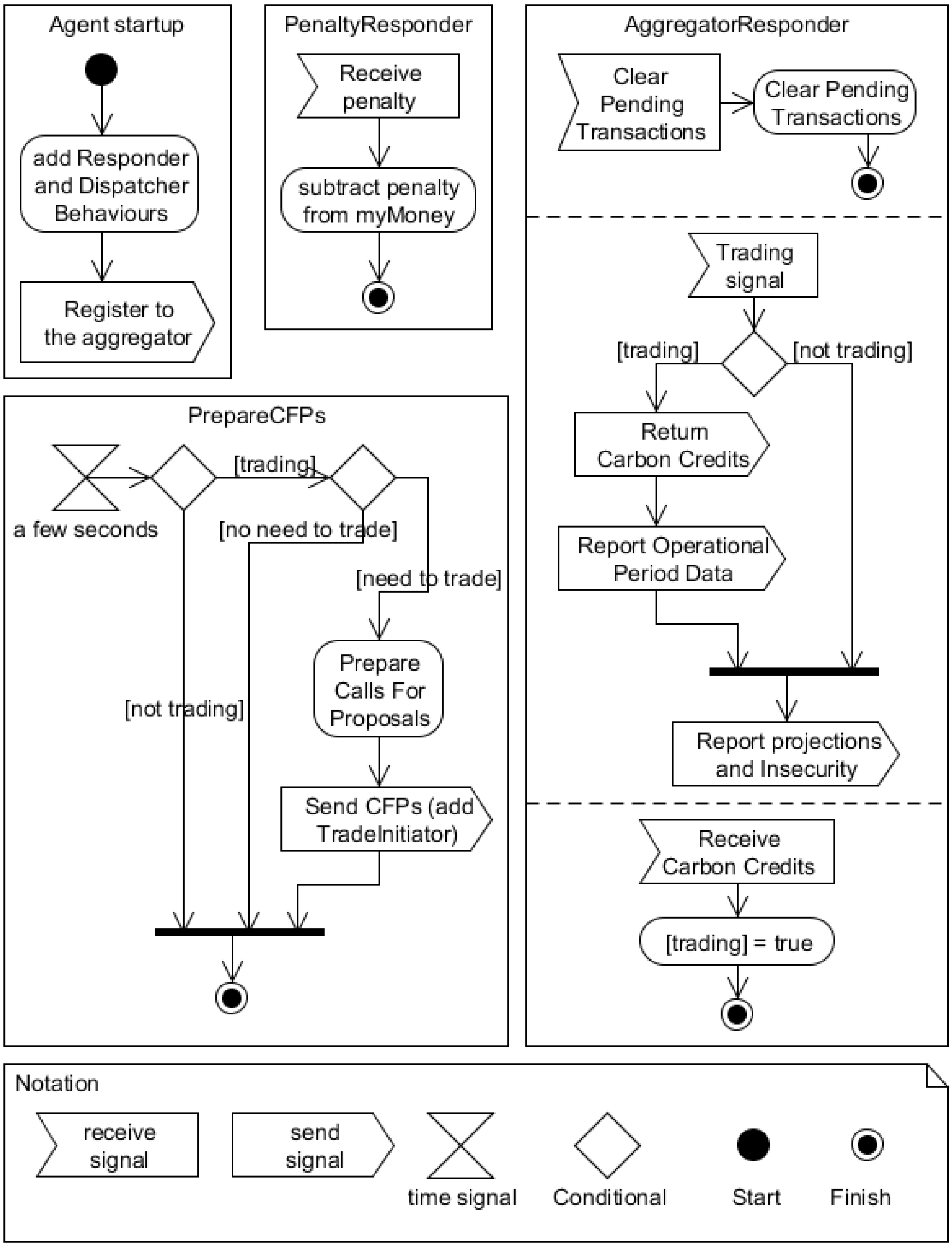

Fig. A.10 UML activity diagram showing the agent actions during start-up, as well as the function of *PenaltyResponder*, *PrepareCFPs* and *AggregatorResponder* behaviours

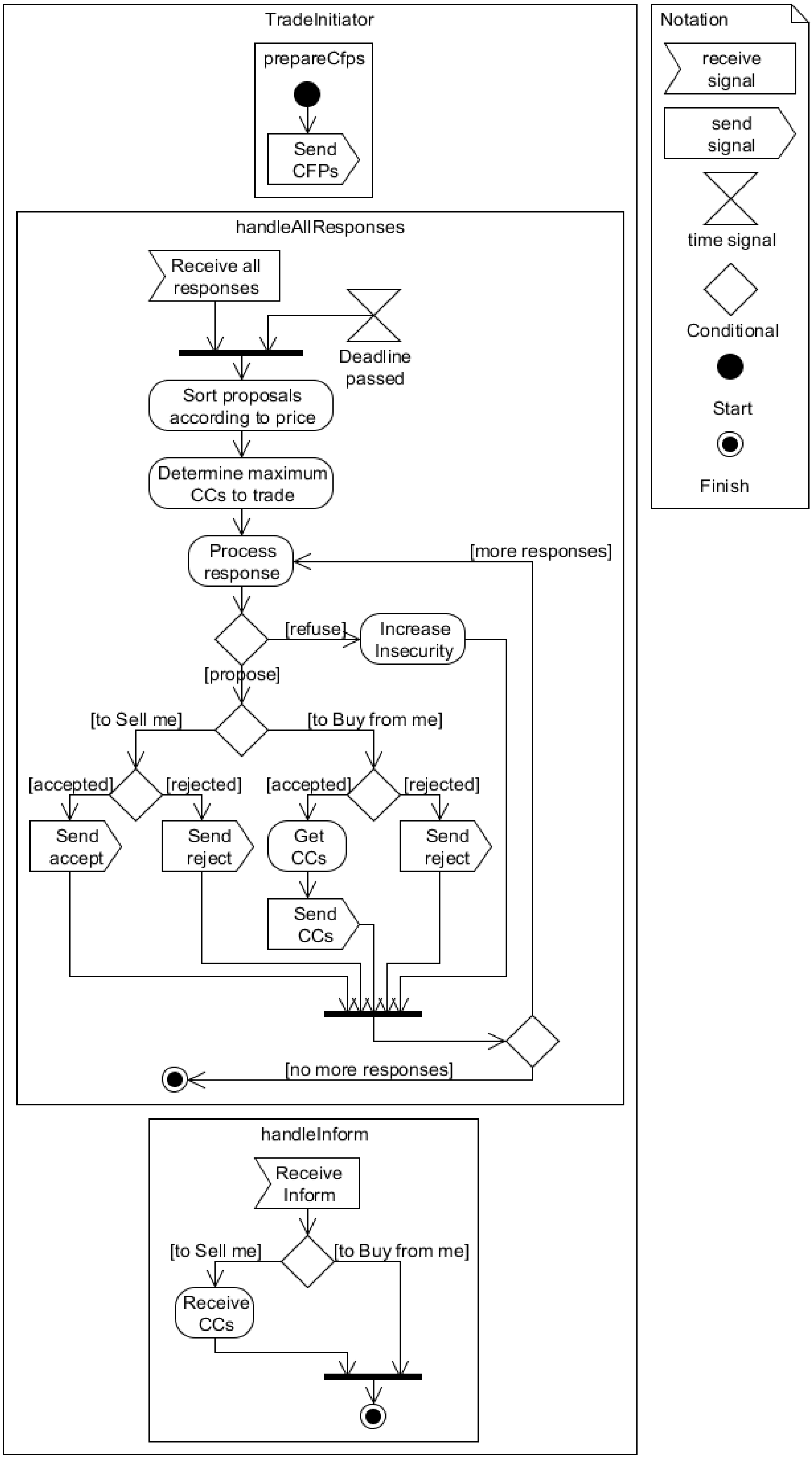

Fig. A.11 UML activity diagram showing the functionality of the *TradeInitiator* behaviour

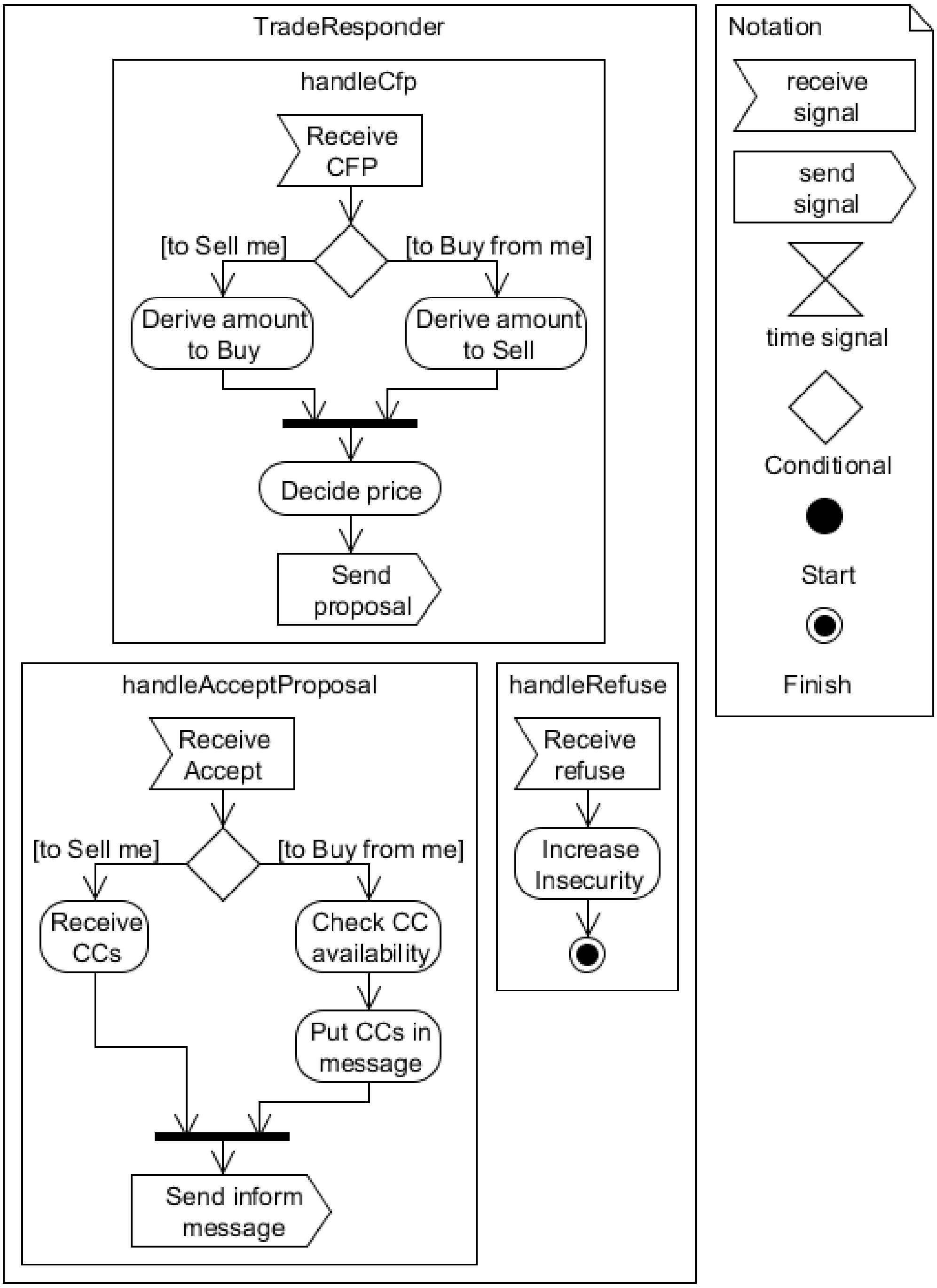

Fig. A.12 UML activity diagram showing the functionality of the *TradeResponder* behaviour

APPENDIX I – MICRO-GRID AGGREGATOR AGENT INTERNAL ARCHITECTURE

As soon as the agent starts, it adds the necessary behaviours in the agent behaviour pool [70]. This includes:

- ✓ the *AggregatorResponder*
- ✓ the *registerGenerator* and
- ✓ the *Subscriber*, that registers the micro-generator to the aggregator.

The Unified Modelling Language (UML) activity diagram describing the functionality of the MicroGrid agent is shown in Fig. A.13.

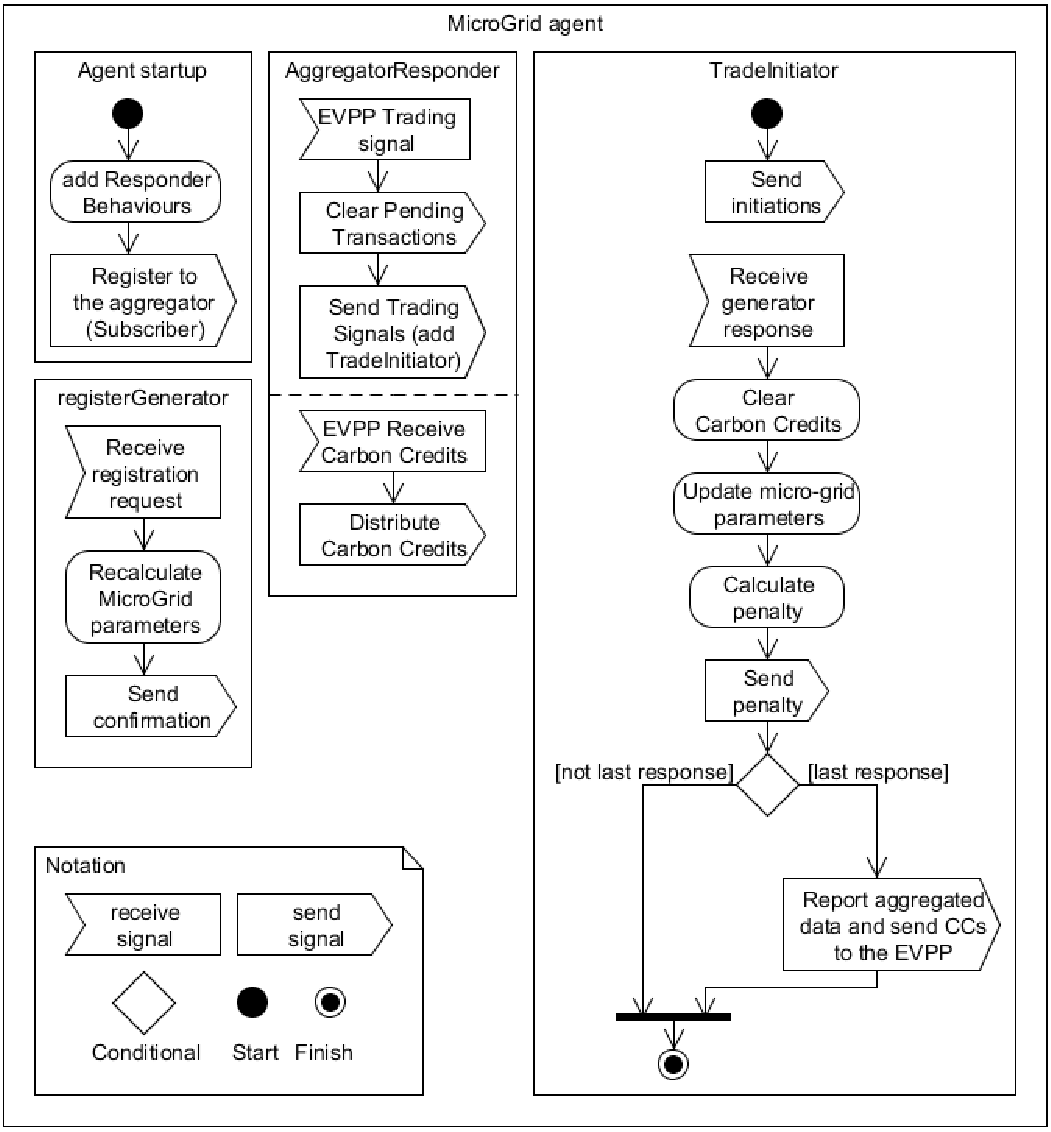

Fig. A.13 UML activity diagram showing the functionality and behaviours of the MicroGrid agent

The *registerGenerator* behaviour receives subscription messages from the MicroGenerator agents, registering them to the micro-grid. It then updates the following micro-grid parameters: (i) total power, (ii) total maximum emissions and (iii) average emission factor.

The *AggregatorResponder* behaviour receives the messages that are sent by the aggregator (EVPP Aggregator agent). These are of three types:

- ✓ *Clear Pending Transactions*: The agent forwards the message to the MicroGenerator agents.
- ✓ *Trade*: The agent sends trade initiation messages to the MicroGenerator agents by adding the TradeInitiator behaviour. When it receives the replies from the MicroGenerator agents, it returns to the EVPP Aggregator agent: (i) the aggregated Carbon Credits, (ii) the aggregated operational data of the previous operational period and (iii) aggregated projections on the next operational period parameters.
- ✓ *Carbon Credits*: The agent receives the Carbon Credits from the EVPP Aggregator agent and it distributes them to the MicroGenerator agents, proportionally to their projected emissions.

The *TradeInitiator* behaviour sends trade initiation messages to the MicroGenerator agents. When it receives a response from a micro-generator, then:

- ✓ It clears the Carbon Credits, confirming that they are valid and removes them from its database.
- ✓ It updates the aggregated micro-grid parameters (e.g. projected emissions at the next operational period, final generation at the previous operational period).
- ✓ It calculates and sends possible penalties, by comparing the Carbon Credits that the micro-generator sent back previously with their actual emissions.
- ✓ When responses from all micro-generators are received, the following aggregated parameters are sent to the EVPP Aggregator agent:

1. Total cleared Carbon Credits
2. Aggregated parameters of the previous operational period:
    - Emissions
    - Generation
    - Thermal Demand

- Unserved Heat
- Heat Storage Level

3. Aggregated projections for the next operational period:
    - Lower emissions bound
    - Projected (desired) emissions
    - Upper emissions bound
    - Micro-grid collective (average) insecurity factor

Appendix J – Environmental Virtual Power Plant agent internal architecture

As soon as the agent starts, it adds the necessary behaviours in the agent behaviour pool [70]. This includes:

✓ the *StartTradingPeriod* and
✓ the *registerMicrogrid*

The Unified Modelling Language (UML) activity diagram describing the functionality of the EVPP Aggregator agent is shown in Fig. A.14.

The *registerMicrogrid* behaviour receives subscription messages from the MicroGrid agents, registering them to the EVPP. It then updates the following EVPP parameters: (i) total power, (ii) total maximum emissions and (iii) average emission factor.

The *StartTradingPeriod* behaviour executes every predefined time period (preferably set to 15 minutes). It resets the current trading and operational session parameters, discovers the MicroGrid agents under the EVPP and it sends them trade initiation messages, by adding the TradeInitiator behaviour.

The *TradeInitiator* behaviour sends trade initiation messages to the MicroGrid agents. When it receives a response from a MicroGrid agent, then:

- ✓ It clears the Carbon Credits, confirming that they are valid and removes them from its database.
- ✓ It updates the aggregated EVPP parameters (e.g. projected emissions at the next operational period, final generation at the previous operational period).
- ✓ When responses from all micro-generators are received, the following aggregated parameters are recorded:
  1. Emissions
  2. Deviation of emissions from the Carbon Credits amount
  3. Generation
  4. Thermal Demand
  5. Unserved Heat
  6. Heat Storage Level
  7. Total maximum emissions/power/demand
  8. Number of micro-generators
  9. Market price data
  10. Real-time grid emission factor
- ✓ Then, a new trading session is initiated. The MicroGrid agents are discovered.
- ✓ New Carbon Credits are generated, according to the control policy of the EVPP (see Section 5.2.3), and they are sent to the MicroGrid agents for further distribution to the micro-generators. This is being done by adding an auxiliary behaviour called *SendCCs*.

The *ClearPendingTransactions* behaviour is added by the *StartTradingPeriod* behaviour every time it runs, and it is executed shortly before the trading period ends. It sends notifications to the MicroGenerator agents (via the MicroGrid agents) that the end of the trading period is imminent. This means that they should not initiate any more trading protocols and finish the ones that are pending.

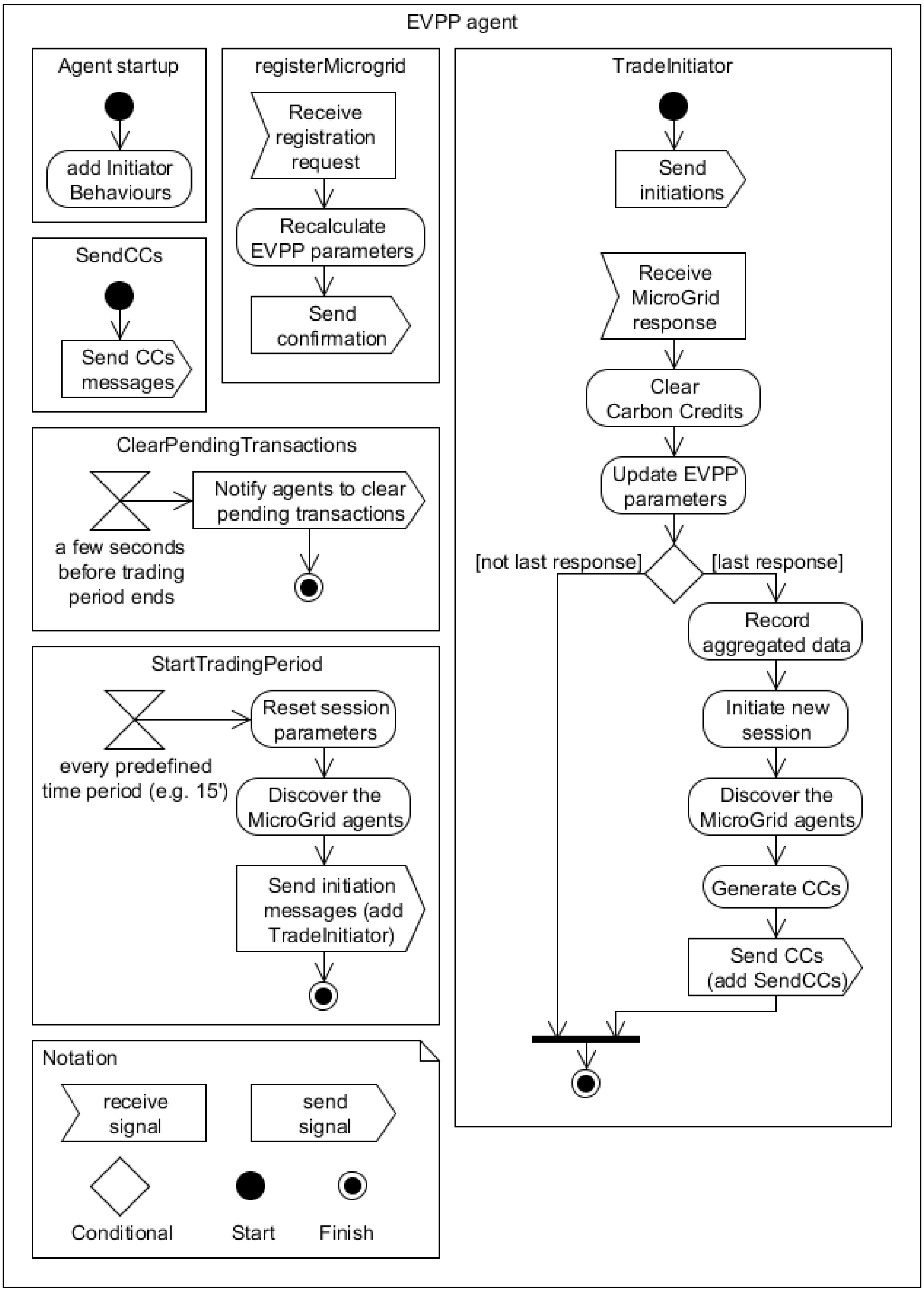

Fig. A.14 UML activity diagram showing the functionality and behaviours of the EVPP Aggregator agent

Appendix K – Forecasting method

Simple linear regression is a method of estimating the parameters of a line that describes the trend of a set of *n* data points and is of the form:

$$y = a + b \cdot x \tag{31}$$

The parameters *a* and *b* are estimated using the following equations [110]:

$$b = \frac{n \cdot \sum_{i=1}^{n} x_i - \sum_{i=1}^{n} x_i \cdot \sum_{i=1}^{n} y_i}{n \cdot \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i \right)^2} \tag{32}$$

$$a = \frac{\sum_{i=1}^{n} y_i}{n} + b \cdot \frac{\sum_{i=1}^{n} x_i}{n} \tag{33}$$

When the trend line is found, the value of the next point in the time-series is calculated using (31).

Appendix L – Agent Graphical User Interfaces

A Supervisory Control And Data Acquisition (SCADA) interface was designed for the EVPP Aggregator agent, which has the following capabilities:

Control:

- ✓ Manual setting of the emissions level for the next time period
- ✓ Choice between the three control strategies: (i) Grid Emission Factor, (ii) Electricity Market Price and (iii) Mixed (Emissions & Price)

Diagnostics:

- ✓ Emissions indicator (%)
- ✓ Generation indicator (%)
- ✓ Deviation indicator (%)
- ✓ Demand indicator (%)
- ✓ Storage indicator (%)
- ✓ Unserved Heat value (kWh)
- ✓ EVPP Emission Factor value (gCO_2/kWh)
- ✓ Grid Emission Factor value (gCO_2/kWh)
- ✓ Electricity Price value (€)
- ✓ Trading/Operational Session counter
- ✓ Simulated Time counter

A SCADA interface was also designed for the NTUA photovoltaic agent. This interface relates to the operation of the Sunny Island inverter. It has the following capabilities:

Control:

- ✓ Power and frequency set-points limits adjustment. The agent will not send a frequency set-point and will not target a power level outside those limits.
- ✓ Panic button. When clicked, resets the frequency set-point to 50.0 Hz and suppresses agent set-points.

Diagnostics:

- ✓ Power set-point (W)
- ✓ Actual measured power (W)
- ✓ Maximum measured power (W)
- ✓ Minimum measured power (W)
- ✓ Grid frequency measurement (Hz)
- ✓ Last frequency set-point sent (Hz)

✓ Waiting/Value Changed!/OK indicator. Shows whether a set-point value has been sent, accepted, or nothing has been sent recently.

A snapshot of the EVPP SCADA graphical user interface is shown in Fig. A.15 and a snapshot of the Sunny Island interface is shown in Fig. A.16.

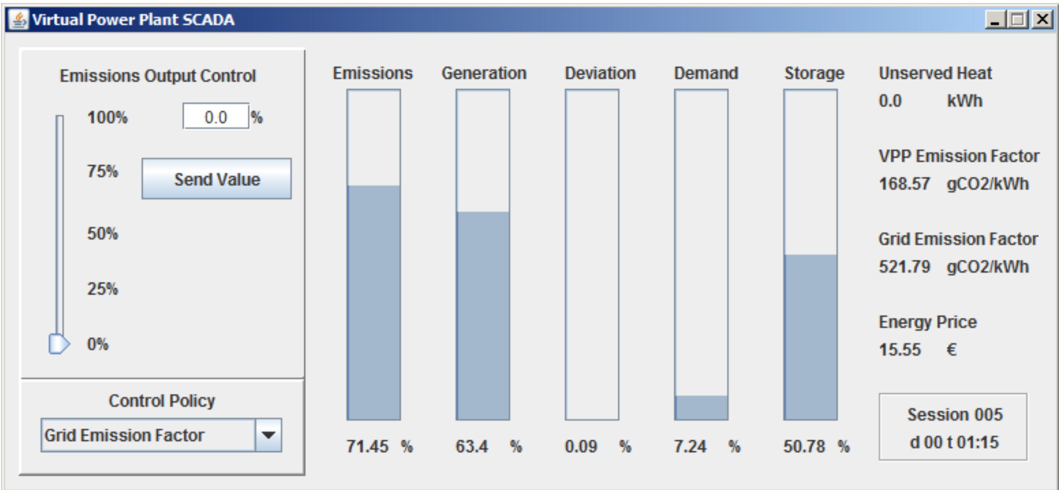

Fig. A.15 Environmental Virtual Power Plant SCADA interface snapshot

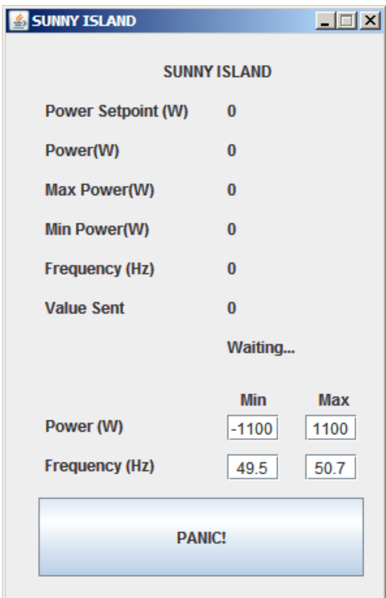

Fig. A.16 NTUA Sunny Island inverter agent interface snapshot

Appendix M – CRES Diesel generator output control

The Diesel genset installed in CRES has been controlled in a stepwise manner, using a set of resistive loads. Their values are shown in Table A.V. According to these values, the estimated output and the measured output of the generator, compared to the set-point given by the agent, is shown in Table A.VI.

TABLE A.V: CRES RESISTIVE LOADS

Resistance	Value (kW)	Resistance	Value (kW)
R1	2.3	R6	0.5
R2	1.4	R7	2.3
R3	0.5	R8	0.5
R4	2.3	R9	0.75
R5	1.4	R10	0.75

TABLE A.VI: CRES DIESEL SETPOINT AND ACTUAL OUTPUT

Set-point (kW)	Estimated (kW)	Measured (kW)	Set-point (kW)	Estimated (kW)	Measured (kW)
0.50	0.50	0.52	**6.50**	6.10	6.19
0.75	0.75	0.83	**6.75**	6.35	6.31
1.00	1.00	1.02	**7.00**	6.60	6.64
1.25	1.25	1.31	**7.25**	6.85	6.72
1.50	1.40	1.48	**7.50**	6.90	6.97
1.75	1.75	1.79	**7.75**	7.25	7.13
2.00	1.90	1.95	**8.00**	7.40	7.45
2.25	2.15	2.22	**8.25**	7.65	7.73
2.50	2.30	2.33	**8.50**	7.90	7.89
2.75	2.65	2.68	**8.75**	8.15	8.16
3.00	2.80	2.84	**9.00**	8.40	8.30
3.25	3.05	3.06	**9.25**	8.65	8.59
3.50	3.30	3.25	**9.50**	8.90	8.97
3.75	3.55	3.52	**9.75**	9.15	9.12
4.00	3.70	3.67	**10.00**	9.30	9.22
4.25	4.05	4.03	**10.25**	9.55	9.50
4.50	4.30	4.47	**10.50**	9.80	9.81
4.75	4.45	4.49	**10.75**	10.05	9.98
5.00	4.70	4.63	**11.00**	10.30	10.60
5.25	4.95	4.96	**11.25**	10.45	10.61
5.50	5.20	5.07	**11.50**	10.70	10.70
5.75	5.45	5.40	**11.75**	10.95	11.02
6.00	5.70	5.76	**12.00**	11.20	11.30
6.25	5.85	5.90			