OPERATIONAL COST AND EMISSIONS MINIMISATION OF A MULTI-MICROGRID SYSTEM THROUGH ENERGY MANAGEMENT

by

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Submitted in partial fulfillment of the requirements for the degree
Master of Engineering (Electrical Engineering)

in the

Department of Electrical, Electronic and Computer Engineering
Faculty of Engineering, Built Environment and Information Technology

UNIVERSITY OF PRETORIA

December 2019

SUMMARY

OPERATIONAL COST AND EMISSIONS MINIMISATION OF A MULTI-MICROGRID SYSTEM THROUGH ENERGY MANAGEMENT

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Keywords:	Networked microgrids, operational cost, emissions, energy management system, optimisation.

Existing energy management problems for a multi-microgrid (MMG) system only minimise the operational cost. This study proposes a multi-objective operational cost and emissions minimisation (OCEM) problem for a grid-tied MMG system. The energy management strategy provided by the OCEM problem takes into account the power sharing among all the microgrids (MGs) as well as a price-based demand response programme. The benefits of the OCEM problem are demonstrated by comparing its results with those of a single-objective operational cost minimisation (OCM) problem reported in the literature. These results are obtained by applying both problems to the same MMG case study, which consists of three interconnected MGs and solving these two optimisation problems with a hybrid optimisation algorithm between the genetic algorithm and sequential quadratic programming in MATLAB. When compared to the best solution provided by the OCM problem, the optimal trade-off solution (OTS) provided by the OCEM problem decreases the emissions by 73.07% with a 18.86% increase in the operational cost. The OCEM problem does provide a decision maker with the flexibility to choose the best solution according to the trade-off between the emissions and operational costs, which are competing objectives.

The OTS provided by the OCEM problem has several advantages in comparison to the best solution provided by the OCM problem, namely:

1. Increase in the utilisation of the distributed energy resources in particular, the energy generated by the micro-turbines increased by 80.94%.
2. The energy imported from and exported to the main grid decreased by 52.52% and increased by 7.64%, respectively. As a result, the net energy imported from the main grid is negative, which contributes towards emission reduction and main grid support in terms of energy generation.
3. Reduction in the maximum demand of the MMG system from the main grid as the maximum power flow from the main grid to the MMG system decreased by 32.31%.

The MMG case study demonstrates the capability of the OCEM problem in designing an energy management strategy, which is cost-effective and minimises the emissions.

ACKNOWLEDGMENTS

I would like to thank my supervisor, Prof. Lijun Zhang and co-supervisor, Dr. Xianming Ye for their guidance, advice and support during my postgraduate studies at the University of Pretoria.

I would like to thank my mother, René Gildenhuys, father, Stephan Gildenhuys, and sister, Suné Gildenhuys for their loving encouragement and support during my postgraduate studies at the University of Pretoria.

I would like to thank Rohan Goddard and the postgraduate students at the Centre of New Energy Systems at the University of Pretoria for their support, excellent advice and for making my postgraduate studies an unforgettable experience.

The author would like to thank Eskom for providing him with the opportunity to use their weather data in this study.

This work is supported by the Centre of New Energy Systems and the National Hub for the Postgraduate Programme in Energy Efficiency and Demand Side Management at the University of Pretoria. The work is also supported by the Royal Academy of Engineering under the Industry-Academia Partnership Programme 17/18 scheme.

LIST OF ABBREVIATIONS

BESS	Battery energy storage system
CCHP	Combined cooling, heating and power
CHP	Combined heat and power
CO_2	Carbon dioxide
EDLC	Electric double layer capacitor
ESS	Energy storage system
EUETS	European Union Emissions Trading Scheme
FESS	Flywheel energy storage system
MG	Microgrid
MMG	Multi-microgrid
NOCT	Normal operating cell temperature
NO_x	Nitrogen oxides
OCEM	Operational cost and emissions minimisation
OCM	Operational cost minimisation
OTS	Optimal trade-off solution
PV	Photo-voltaic
SO_2	Sulfur dioxide
STC	Standard test conditions

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

1.1.1 Context of the problem

Centralised generation is the concept of supplying power from a central point through large-scale power plants, which are usually far away and rely on distribution and transmission systems to deliver power to the point of demand [1]. Decentralised generation is the concept of supplying power from distributed small-scale generation units, which can be installed close to the point of demand [2]. There are several advantages associated with distributed power generating units, namely: they emit fewer emissions in comparison to large-scale power plants [3–5]; reduce the power losses associated with as well as the voltage drop over transmission and distribution systems [1, 6]; and with their low capital cost, provides small companies and corporations with the opportunity to invest in power systems [6]. However, the behaviour of a power system could become unpredictable when multiple uncoordinated distributed power generating units are connected to it [7], especially, if there is a large presence of renewable generating units as their output power is uncertain and intermittent [4, 8]. This problem can be solved with an microgrid (MG) that refers to a low/medium voltage distribution system, which consists of a collection loads and distributed energy resources that together form a single controllable system used to supply power and sometimes also heat to a local area [9, 10]. A distributed energy resource refers to an energy storage system (ESS) as well as a power generating unit such as a diesel generator, fuel cell, micro-turbine, photovoltaic (PV) module, wind turbine, etc. An MG prevents any catastrophic abnormalities by integrating distributed energy resources efficiently into a power system and ensuring that they operate cooperatively as a single system [1, 4, 11]. An MG that operates in grid-tied mode is connected to and can share electricity with the main grid (national grid or utility grid) whereas in island mode an MG is isolated from the main grid [12]. There is a limit to the number of distributed energy resources that can be included in an MG [13]. As a result, it is not recommended to develop an MG, which includes a large number of distributed energy resources and loads but rather to divide such a large MG into multiple MGs [14]. These MGs can then be connected to one another to form an multi-microgrid (MMG) system, which allows the MGs to share power with each other [15]. The concept of dividing a large MG into multiple MGs improves the reliability and operation of the distribution system and avoids considerable complexity [14, 16]. In comparison to an isolated MG, an MMG system improves the operational stability and increases the penetration of renewable energy as well as the reliability of the power supply, while reducing the operation cost, occurrence of load-shedding, pollutant emissions, grid power losses, and the required capacity of the ESS [13, 15, 17–19]. An MMG system is also commonly known as networked MGs or cooperative MGs [20].

1.1.2 Research gap

The power generating units within an MG can either be controllable such as diesel generators, fuel cells, micro-turbines, etc. or uncontrollable in the sense that they rely upon the availability of natural resources such as PV modules, wind turbines, etc. As such, coordinated control of the distributed energy resources within an MG and the associated distribution system is essential. This coordination problem can be treated as a three-level hierarchical system where the first is the droop-control of the power electronics, the second is the control for frequency/voltage regulation, and the third is the control of the reactive and active power flowing within an MG, dealing with energy management [21, 22]. The scope of this dissertation is focused on the third level, which is energy management.

The advanced features of an MMG system are achieved via an energy management system that optimises the power flows between the distributed energy resources and loads. However, all the optimisation problems developed for an MMG system identify an energy management strategy, which primarily minimises the operational cost (note that the term “operational cost” in this study includes the cost of generation, maintenance and purchasing energy from other entities as well as the income received for selling energy to other entities). This is essential for the economic operation and to promote the market uptake of MGs; however, none of these problems take the emissions of an MMG system into account. Faced with the more and more severe environmental problems, all countries over the world are forced to pay attention to emission reductions of all sectors because many studies, such as [23] reported the correlation between the greenhouse gas concentration in the atmosphere as a result of human activities and the global temperature increase (it was observed that the average global temperature has increased by 0.7°C within the last 50 years and it is expected that by the year 2100 there will be an additional increase between 1.8°C and 4°C).

The transition of the power supply sector into a green and sustainable one is an important contributor to carbon footprint mitigation. Many countries around the world have made strides to reduce emissions of emission-intensive sectors. For this purpose, many countries introduced carbon taxes and national targets for emission reduction, including the European Union Emissions Trading Scheme (EUETS) [24, 25]. The European Union has set several targets for 2020, namely, a 20% decrease in emissions in comparison to the emission levels in 1990 and a 20% increase in energy efficiency [26]. The EUETS operates with a trade and cap concept in which the total emissions emitted by all the participating companies has a cap or maximum value assigned to it [25]. Each year a participating company can avoid an emission fine by covering its emissions with its emission allowance [25]. Emission allowances are provided for free or bought by the participating companies and can also be auctioned and traded amongst the companies [25]. Under these schemes in countries all over the world, a power system that emits fewer greenhouse gas emissions will benefit from trading its excess allowances to others.

Studies on reducing the emissions of MGs, however, have been focused on single MGs. For instance, the optimisation problems developed in [27, 28] can identify an energy management strategy for a single MG system, which minimises the operational cost and emissions simultaneously. On the other hand, this problem has not been investigated for MMG systems as mentioned earlier. The energy management strategies presented for MMGs in the literature primarily minimise the operational cost and neglect the emissions. This implies that these problems could possibly identify strategies, which minimise the operational cost by limiting the utilisation of the distributed energy resources and by promoting the import of electricity from the utility grid. This would have a negative contribution to greenhouse gas emissions because of the following two reasons. Firstly, 64% of the power generated within the utility grid is generated through the use of fossil fuels [29]. Secondly, the fossil fuel based power generators in the utility grid emit more emissions in comparison to the distributed energy resources [4, 5, 28].

1.2 RESEARCH OBJECTIVE AND QUESTIONS

In this study, the research objective is to formulate an energy management problem that identifies an energy management strategy for an MMG power supply system, which minimises the operational cost and emissions simultaneously. Several questions will be answered through this study, namely:

1. How will the operational cost of an MMG system be affected if the optimisation problem minimises the operational cost and emissions simultaneously in comparison to when the optimisation problem only minimises the operational cost?
2. How will the power flow from and to the distributed energy resources be affected if the optimisation problem minimises the operational cost and emissions simultaneously in comparison to when the optimisation problem only minimises the operational cost?
3. How will the power flow between the main grid and MGs be affected if the optimisation problem minimises the operational cost and emissions simultaneously in comparison to when the optimisation problem only minimises the operational cost?

1.3 RESEARCH APPROACH

Existing energy management problems for an MMG system only minimise the operational cost. This study proposes a multi-objective operational cost and emissions minimisation (OCEM) problem for an MMG system, which minimises the operational cost and emissions simultaneously. The effectiveness of the OCEM problem is demonstrated by comparing its results (energy management strategies) with those of a single-objective operational cost minimisation (OCM) problem reported in the literature, which only minimises the operational cost. These results are obtained by applying both problems to the same MMG case study, which consists of three interconnected MGs and solving these two optimisation problems with a hybrid optimisation algorithm between the genetic algorithm and sequential quadratic programming in MATLAB. This research approach is shown in Figure 1.1.

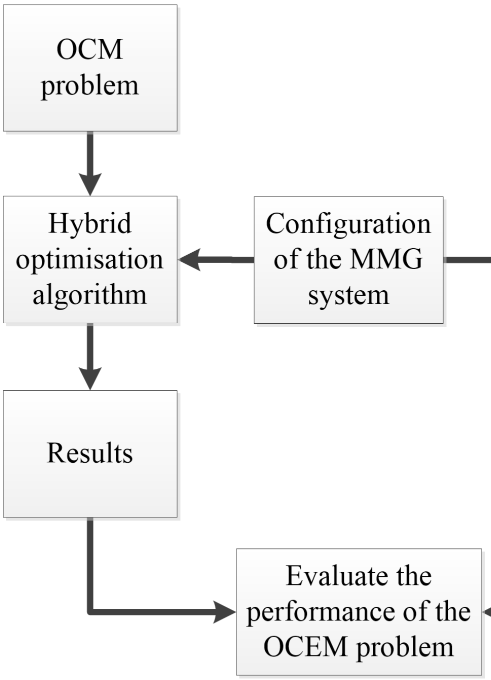


Figure 1.1. Research approach.

1.4 RESEARCH CONTRIBUTIONS

This study has several research contributions, namely:

1. In comparison to existing energy management problems presented in the literature, the problem developed in this study has the advantage of reducing the operational cost of an MMG system to promote its wide adoption and reducing the carbon footprint of the power supply sector by increasing the utilisation of renewable generating units, thus minimising the operational cost and emissions simultaneously.
2. Because an MMG system is targeted, the problem developed in this study is also a valuable addition to the field of MG energy management system design, which extends the energy management problems designed for single MGs and introduces a new dimension on emission reduction to the problems for MMG systems.
3. The problem developed in this study enables an MMG system to be coordinated optimally to reduce the emissions and operational costs of an MMG system by means of better utilisation

of the renewable generating units and ESSs and better power flow management between the individual MGs and main grid considering a price-based demand response programme.

4. The problem developed in this study also provides a power system operator the flexibility to find a solution that achieves the desired trade-off between the emissions and operational costs.

1.5 RESEARCH OUTPUTS

This study has provided several conference contributions and journal publications, namely:

1. T. Gildenhuys, L. Zhang, and X. Ye, "Energy management of a multi-microgrid system," in *Control Conference Africa*, Johannesburg, South Africa, 2017.
2. T. Gildenhuys, L. Zhang, X. Ye, and X. Xia, "Optimization of the operational cost and environmental impact of a multi-microgrid system," in *10th International Conference on Applied Energy*, Hong Kong, China, 2018, pp. 3827-3832.
3. L. Zhang, T. Gildenhuys, X. Ye, and X. Xia, "Energy management of a multi-microgrid system minimizing operational cost and emissions," *Applied Energy*, 2019. (under construction)

1.6 OVERVIEW OF THIS STUDY

This dissertation consists of five chapters, namely:

- Chapter 1 is the introduction and provides a brief overview of the research gap, research objective, research questions, research contributions, and research approach.
- Chapter 2 is the literature study that provides a summary and a critical evaluation of the previous work that has been done in the field of MG and MMG systems.
- Chapter 3 provides an overview of the objective functions, decision variables and constraints of the OCEM problem.
- Chapter 4 assesses the performance of the OCEM problem by comparing its results with those of the OCM problem. This chapter consists of three sections, the first presents the configuration of the MMG system, the second provides an overview of the optimisation algorithms used to solve the optimisation problems, and the third presents the results as well as a discussion thereof.

- Chapter 5 provides a conclusion to this dissertation as well as recommendations for future work.

CHAPTER 2 LITERATURE STUDY

2.1 CHAPTER OVERVIEW

The previous chapter introduces the concept of an MMG system and indicates that the research objective of this study is to formulate an energy management problem that identifies an energy management strategy for an MMG power supply system, which minimises the operational cost and emissions simultaneously. This chapter provides an overview on the previous studies that have proposed energy management problems for single MG and MMG systems. This chapter also identifies and evaluates several research gaps in the energy management field, which includes the research gap that is addressed by this study. This chapter consists of several sections, namely Section 2.2 focuses on grid-connected MGs, Section 2.3 focuses on grid-isolated MGs, Section 2.4 focuses on the voltage stability within MGs, Section 2.5 focuses on the operational uncertainties within MGs, Section 2.6 focuses on the power and heat distribution systems within MGs, and Section 2.7 focuses on the emissions of MGs.

2.2 GRID-CONNECTED SYSTEMS

As stated previously, an MG system can operate in grid-connected mode, which implies that the system can export electricity to as well as import electricity from the main grid [12, 30]. This allows the distributed energy resources to received support from the main grid if they are unable to satisfy the demand during the peak load periods [9]. On the other hand, an MG can also receive financial income for selling the surplus electricity generated by its distributed energy resources to the main grid during the off-peak load periods [9].

2.2.1 Single MG system

Energy management problems were developed in [2, 31–35] for a grid-connected single MG system. These problems minimise the operational cost by optimising the power flow within the MG as well as the power flow between the MG and main grid whilst considering the thermal limits of the power lines [36]. However, the problem presented in [33] also considers a limit on the rate in change of the power flow between the main grid and an MG, which is derived according to the capacity of the MG.

2.2.2 MMG system

Similar to the single MG system, energy management problems were also developed in [37–40] for a grid-connected MMG system. These problems minimise the operational cost by optimising the power flow within each MG, power flow between the MGs as well as the power flow between each MG and the main grid.

The economic dispatch problem of an MG can be solved in a centralised manner in which the local controller of each distributed energy resource considers the generating capacity of the distributed energy resource as well as the market price before it provides a bid (generation level and generation price) to the MG central controller [12]. The MG central controller then considers these bids, as well as the network constraints, market prices and predictions of the output power of the renewable generating units and electrical demand to identify the optimal energy management strategy. The MG central controller then sends the operational set point of each distributed energy resource to its respective local controller [11, 12]. A drawback of a problem that minimises the overall operational cost of an MMG system in a centralised manner is that it could identify an energy management strategy, which minimises the overall operational cost but increases the operational cost of certain MGs in comparison to when those MGs operate on their own. This is not a drawback if each MG has the same owner; however, if each MG has a different owner, then an MG owner will not be motivated to participate in an MMG system if there is a possibility that the operational cost of their MG will increase [41]. A solution was proposed in [42] where an optimisation constraint ensures that the operational cost of an MG within an MMG system is always less or equal to the operational cost when that MG is operating on its own outside of the MMG system.

On the other hand, the economic dispatch problem of an MG can also be solved in a decentralised manner in which the local controllers have the responsibility of determining their own operational set points based on their operational objectives [11, 12]. The MG central controller then obtains and evaluates these set points and provides the local controllers with adjusted set points according to the reliability and economy of the entire system [11]. In this control strategy, the local controllers compete against one another to maximise the output power of their distributed energy resources and maximise the electricity exported to the main grid, whilst considering the market prices [43, 44]. The advantage of decentralised control is that it allows decisions to be made independently and locally when the loads and distributed energy resources have different owners [44].

2.3 GRID-ISOLATED SYSTEMS

As stated previously, if an MG operates in grid-isolated mode, then that system is isolated from the main grid and unable to export electricity to and import electricity from the main grid [12]. There are several reasons why an MG would operate in island mode, namely:

1. maintain the reliability and power quality when a disturbance occurs outside of the MG [30],
2. operation of the main grid has been suspended [6],
3. power quality of the electricity supplied by the main grid is unacceptable [41], and
4. the MG is located in a remote location and unable to share electricity with the main grid [9].

The ability to operate in island mode is considered to be an advantage and key characteristic of an MG as it allows the demand to be satisfied regardless of whether the main grid is operational [1].

2.3.1 Single MG system

Energy management problems were developed in [4, 45–47] for a grid-isolated single MG system. These problems minimise the operational cost by optimising the power flow within the MG. A drawback of the problems in [4, 46, 47] is that they assume that the distributed energy resources are always able to satisfy the demand, which requires a grid-isolated system to include generating and storage units with large capacities to ensure that the system is robust against uncertainties and able to satisfy the peak demand [33]. This is not a cost-efficient solution and the supply could be insufficient if there is a change in the demand profile [33]. This problem is addressed by the optimisation problem in [45], which considers a demand response programme in which curtailable loads are disconnected to ensure the balance between demand and supply and to guarantee the voltage stability of the system [12, 17]. The non-critical loads are the first loads to be disconnected and if the demand is still unsatisfied, then certain critical loads are also disconnected.

2.3.2 MMG system

Energy management problems were also developed for a grid-isolated MMG system in [41, 48]. These problems minimise the operational cost by optimising the power flow within each MG as well as the power flow between the MGs. Similar to the drawback of the single MG problems, these MMG problems also assume that the distributed energy resources are always able to satisfy the demand; however, this problem is addressed by the MMG problem in [14], which is similar to the single MG problem in [45] as it also considers a demand response programme in which curtailable loads can be disconnected to ensure the balance between demand and supply. The MMG problem in [49] is similar to the MMG problem in [14]; except, it also considers shiftable loads, which can be shifted out of the peak load periods to decrease the peak demand and operational cost [49]. Shiftable loads can also be shifted into periods where there is an abundance of renewable energy to effectively utilise that energy [49].

A multi-objective problem is developed for a grid-isolated MMG system in [17]. The primary objective of this problem is to maximise service reliability whereas the secondary objective is to minimise the operational cost. The service reliability is maximised by minimising the load curtailment and the load curtailment is minimised by minimising the penalty cost associated with the load curtailment. The drawback of this problem is that it ensures that the service reliability has priority over the operational cost by assuming that the penalty cost associated with the load curtailment is always higher than the operational costs of the distributed energy resources. However, if this assumption is not true, then this problem could identify an energy management strategy in which the operational cost has priority over service reliability. A solution to this problem is to adopt the weighted sum method, as shown by (2.1) [50], which allows the user to adjust the priority between the service reliability and operational cost regardless of the magnitude of the penalty cost.

$$\text{Minimise} \quad \gamma = \lambda\sigma + (1-\lambda)\tau, \tag{2.1}$$

where

$$0 \leq \lambda \leq 1, \tag{2.2}$$

where γ is the fitness value of the combined objectives, σ is the operational costs of the distributed energy resources, τ is the magnitude of the load curtailment, and λ is a weight, which is selected by the user.

2.4 VOLTAGE STABILITY

All of the energy management problems developed for an MG and MMG system consider the distribution network constraints, which limit the power flow between the main grid and an MG, limit the power flow between MGs, etc. However, the majority of these problems do not consider the upper and lower boundaries of the voltage at each bus as they do not consider a multi-bus MG system but rather assume that the distributed energy resources and loads are all connected to one bus. This implies that energy management strategies identified by these problems could be unfeasible in practical applications, compromise the reliability of the system and would not necessarily provide secure voltage to the consumers [11, 43].

For a single MG system, this drawback is addressed by the energy management problems in [4, 11, 51], which manages the power flow within an MG whilst ensuring that the voltage at each node remains within the specified limits. Similarly, an energy management problem was also developed for an MMG system in [52], which manages the power flow within each MG as well as the power flow between the MGs whilst ensuring that the voltage at each node remains within the specified limits. The objectives of this problem are to minimise the operational cost and voltage deviation simultaneously. This implies that it can identify an energy management strategy, which minimises the operational cost whilst ensuring that the voltage at each node is not only within the specified limits but also as close as possible to the desired voltage. This problem also utilises the stability index presented in [53], which ensures that an MG operates with a predefined voltage security margin. If a power system has a low voltage security margin and it becomes heavily loaded, then voltage instability could occur, which could cause the system to become unstable and compromise its reliability [43, 52].

2.5 OPERATIONAL UNCERTAINTIES

The majority of energy management problems developed for an MG and MMG system utilise a future prediction of the demand profile, renewable resources, and market prices to identify the optimal energy management strategy. A strategy identified with this static method might no longer be optimal when there are unexpected fluctuations in the predictions, which implies that the validity of the strategy is dependent on the accuracy of the predictions [11, 54]. This drawback has been addressed by several problems, namely:

1. Energy management problems were developed for a single MG system in [33–35] that consider a power reserve, which allows an MG to respond to sudden and unexpected variations in the predictions [47]. The power in reserve in an MG is the difference between the power that is actually supplied and the maximum power that can be supplied [47]. Similar to the single MG problems, an energy management problem has been developed in [16] for an MMG system, which also considers a power reserve. The drawback of a power reserve is that it requires an MG to include additional distributed energy resources or distributed energy resources with larger capacities to ensure that the system is robust against uncertainties; however, this is not a cost-efficient solution and the supply could be insufficient if there is a change in the demand profile [33].
2. A single MG problem is developed in [4] that considers stochastic scenarios and identifies a strategy, which is a good solution for all of the possible scenarios [11]. Utilising a large set of scenarios will increase the number of uncertainties considered by the problem, which allows it to identify an efficient strategy; however, this also increases the computational effort [4, 18]. This computational effort problem can be addressed by a reduction technique that reduces the total number of scenarios by excluding the low probability scenarios [18]. Similar to the single MG problem, a stochastic scenario-based MMG problem has also been developed in [18].
3. A rolling optimisation problem is proposed for a single MG system in [11]. This problem utilises the future predictions to identify the optimal energy management strategy; however, this problem also continuously updates and corrects this strategy in real-time according to the latest future predictions and current state of the system.

2.6 POWER AND HEAT DISTRIBUTION SYSTEMS

MGs not only include a power distribution system, which is used to transmit power to the electrical demand but can also include a heat distribution system, which is used to transmit heat, usually in the form of steam or warm water, to the thermal demand [1]. Heat is usually provided by an on-site heat production facility such as a boiler; however, it can also be provided by a distributed multi-generation system, which captures the waste thermal energy of a distributed energy resource (usually a gas turbine) and uses that energy to satisfy the thermal demand [1, 55]. A distributed multi-generation system can increase the efficiency of a distributed energy resource to a value greater than 80%, which in turn decreases the operational cost and emissions [3, 55]. There are several different types of distributed multi-generation systems, namely [55]:

1. Combined heat and power (CHP) system, which can provide power and heat.
2. Combined cooling, heating and power (CCHP) system, which can provide power, heat and cooling.
3. Poly-generation system, which can provide power, heat, cooling, as well as products such as hydrogen, etc.

2.6.1 Single MG system

Energy management problems were developed in [11, 32, 56] for a single MG system, which includes a power and heat distribution system. These problems can identify an energy management strategy, which minimises the operational cost whilst ensuring that the power and thermal demands are satisfied. In these problems, the thermal demand is satisfied by a CHP system, which captures the waste thermal energy of an micro-turbine.

2.6.2 MMG system

Similar to the single MG system, an energy management problem was also developed in [20] for an MMG system, which includes a power and heat distribution system. In comparison to the single MG problems, there are several advantages associated with this problem. Firstly, it increases the utilisation of thermal energy by managing the transfer of thermal energy within each MG as well as between the MGs. Secondly, it considers a thermal energy storage system (TESS), which stores the surplus thermal energy and supplies it once it is required. Thirdly, the problem also considers boilers, which assist the CHP systems during the peak thermal demand. The drawback of this problem is that it does not consider the transfer of electrical power between the MGs; however, if it did, then it would increase the penetration of renewable energy as well as the reliability of the power supply, while reducing the operational cost [15, 17].

2.7 EMISSIONS

As stated previously, it is essential that an energy management problem should identify an energy management strategy, which not only considers the operational cost but also the emissions.

2.7.1 Single MG system

Most of the problems developed for a single MG system only minimise the operational cost; however, there are a few problems such as the problems in [27, 46], which minimise the operational cost and emissions simultaneously. However, the drawback of these two problems is that they only consider the emissions from the distributed energy resources and do not consider the emissions from the large-scale power plants within the main grid. This implies that these problems will minimise the emissions by minimising the usage of certain distributed energy resources, which requires an MG to purchase additional energy from the main grid to satisfy the electrical demand. This strategy will decrease the emissions from the distributed energy resources; however, it could increase the overall emissions because the large-scale power plants within the main grid emit more emissions compared to the distributed energy resources [4, 5, 28]. This drawback is addressed by the optimisation problem in [28], which considers the emissions from the distributed energy resources as well as the emissions from the large-scale power plants within the main grid.

The problems in [31, 32, 45] only minimise the operational cost; however, they do consider the externality cost (environment protection expenses) of the emissions. This implies that these problems will minimise the emissions to minimise the externality cost; however, there are two drawbacks associated with these three problems. The first is that the reduction in the emissions is dependent on the magnitude of the externality cost, which implies that if the externality cost is inexpensive, then these problems will not be motivated to minimise the emissions. The second is that these problems only consider the emissions from the distributed energy resources and do not consider the emissions from the large-scale power plants within the main grid, which is similar to the drawback of the problems in [27, 46].

2.7.2 MMG system

Similar to the problems developed for a single MG system, operational cost minimisation problems have also been developed for an MMG system. On the other hand, studies on reducing the emissions of MGs have been focused on single MGs as no emissions minimisation problem has been developed for an MMG system. This study addresses that research gap by proposing an OCEM problem for an MMG system that can identify an energy management strategy, which minimises the operational cost and emissions simultaneously. It should be noted that this study is focused on the development of an energy management problem for a grid-tied MMG system whereas an energy management problem for a grid-isolated MMG system is beyond the scope of this study.

2.8 CHAPTER SUMMARY

This chapter provides an overview on the previous studies that have proposed energy management problems for single MG and MMG systems. This chapter also identifies and evaluates several research gaps in the energy management field. One of these research gaps is discussed in Section 2.7, which states that studies on reducing the emissions of MGs have been focused on single MGs and no emissions minimisation problem has been developed for an MMG system. The next chapter addresses this research gap by proposing an OCEM problem that can identify an energy management strategy for an MMG system, which minimises the operational cost and emissions simultaneously.

CHAPTER 3 PROBLEM FORMULATION

3.1 CHAPTER OVERVIEW

The literature review in the previous chapter indicated that studies on reducing the emissions of MGs have been focused on single MGs and no emissions minimisation problem has been developed for an MMG system. This chapter addresses that research gap by proposing an OCEM problem that can identify an energy management strategy for an MMG system, in a centralised manner, which minimises the operational cost and emissions simultaneously. This problem considers an MMG system in which each MG includes an electrical demand, distributed energy resources, is grid-tied and can share electricity with other MGs. Details of the objective functions, decision variables, and constraints of the OCEM problem are given in Section 3.2, 3.3, and 3.4, respectively.

3.2 OBJECTIVE FUNCTIONS

3.2.1 Operational cost minimisation

The first objective of the OCEM problem is to minimise the operational costs of an MMG system. It is captured by the following objective function, which was developed in [40].

$$F_{MMG} = \sum_{i=1}^{O} F_{MGi}, \tag{3.1}$$

where

$$\begin{aligned} F_{MGi} = \sum_{k=1}^{K} \Big[& C_{MGi-Grid}(k) + I_{MGi-Grid}(k) + \sum_{z=1}^{D_i} \omega_{MGi,z}(k) \\ & + \sum_{\substack{j=1 \\ j \neq i}}^{O} \left[C_{MGi-MGj}(k) + I_{MGi-MGj}(k) \right] \Big], \end{aligned} \tag{3.2}$$

where F_{MMG} and F_{MGi} are the operational costs (\$) of the MMG system and the i-th MG over the time period $[0, K\Delta t]$ with Δt being the sampling interval in hours, respectively. O is the number of MGs within the MMG system, D_i is the number of distributed energy resources within the i-th MG, and $\omega_{MGi,z}(k)$ is the operational cost of the z-th distributed energy resource within the i-th MG during time interval k. The k-th time interval refers to the duration of $[(k-1)\Delta t, k\Delta t)$. $C_{MGi-MGj}(k)$ and $C_{MGi-Grid}(k)$ are the costs (\$) associated with the i-th MG for purchasing electricity from the j-th MG and main grid, respectively. $I_{MGi-MGj}(k)$ and $I_{MGi-Grid}(k)$ are the incomes (\$) received by the i-th MG for selling electricity to the j-th MG and main grid during time interval k, respectively.

In (3.2),

$$C_{MGi-MGj}(k) = \max(P_{MGi-MGj}(k), 0) \times W_{Pur}^{MG}(k) \times \Delta t, \tag{3.3}$$

where $W_{Pur}^{MG}(k)$ is the electricity price (\$/kWh) for purchasing electricity from another MG during time interval k, and $P_{MGi-MGj}(k)$ is the amount of power (kW) flowing between the i-th and j-th MGs during time interval k. If $P_{MGi-MGj}(k) > 0$, then the i-th MG is purchasing electricity from the j-th MG whereas if $P_{MGi-MGj}(k) < 0$, then the i-th MG is selling electricity to the j-th MG.

$$C_{MGi-Grid}(k) = \max(P_{MGi-Grid}(k), 0) \times W_{Pur}^{Grid}(k) \times \Delta t, \tag{3.4}$$

where $W_{Pur}^{Grid}(k)$ is the electricity price (\$/kWh) for purchasing electricity from the main grid during time interval k, and $P_{MGi-Grid}(k)$ is the amount of power (kW) flowing between the i-th MG and main grid during time interval k. If $P_{MGi-Grid}(k) > 0$, then the i-th MG is purchasing electricity from the main grid whereas if $P_{MGi-Grid}(k) < 0$, then the i-th MG is selling electricity to the main grid.

$$I_{MGi-MGj}(k) = \min(P_{MGi-MGj}(k), 0) \times W_{Sell}^{MG}(k) \times \Delta t, \tag{3.5}$$

where $W_{Sell}^{MG}(k)$ is the electricity price (\$/kWh) for selling electricity to another MG during time interval k.

$$I_{MGi-Grid}(k) = \min(P_{MGi-Grid}(k), 0) \times W_{Sell}^{Grid}(k) \times \Delta t, \tag{3.6}$$

where $W_{Sell}^{Grid}(k)$ is the electricity price (\$/kWh) for selling electricity to the main grid during time interval k.

$$\omega_{MGi,z}(k) = B_{MGi,z}(k) + Y_{MGi,z}(k) + X_{MGi,z}(k) + Q_{MGi,z}(k), \tag{3.7}$$

is developed in [40] and the terms on the right-hand side represent the fuel cost, shut-down cost, start-up cost, and maintenance cost of the z-th distributed energy resource within the i-th MG during time interval k, respectively. The start-up and shutdown costs are defined in [6] and given by (3.8) and

(3.9), respectively.

$$X_{MGi,z}(k) = C_{SU,MGi,z} \times U_{MGi,z}(k)\left[1 - U_{MGi,z}(k-1)\right], \tag{3.8}$$

$$Y_{MGi,z}(k) = C_{SD,MGi,z} \times U_{MGi,z}(k-1)\left[1 - U_{MGi,z}(k)\right], \tag{3.9}$$

where $C_{SU,MGi,z}$ is the start-up cost coefficient (\$/start-up) of the z-th distributed energy resource within the i-th MG, $C_{SD,MGi,z}$ is the shutdown cost coefficient (\$/shutdown) of the z-th distributed energy resource within the i-th MG, and $U_{MGi,z}(k)$ is a binary decision variable that determines the operational status of the z-th distributed energy resource within the i-th MG during time interval k. If $U_{MGi,z}(k)$ = 1, then the unit is on whereas if $U_{MGi,z}(k)$ = 0, then the unit is off.

If the z-th distributed energy resource within the i-th MG is a gas-fired micro-turbine, then its fuel cost is determined by [9]

$$B_{MGi,z}(k) = \left[C_{FC1,MT} \times P_{MT}(k) + C_{FC2,MT}\right]\Delta t, \tag{3.10}$$

where $C_{FC1,MT}$ and $C_{FC2,MT}$ are the fuel cost coefficients (\$/kWh and \$/h, respectively) of an micro-turbine, and $P_{MT}(k)$ is the output power (kW) of an micro-turbine during time interval k.

The maintenance cost of all distributed energy resources; except, ESSs, is calculated by [41]

$$Q_{MGi,z}(k) = C_{MC,MGi,z} \times P_{MGi,z}(k) \times \Delta t, \tag{3.11}$$

where $P_{MGi,z}(k)$ is the output power (kW) of the z-th distributed energy resource within the i-th MG during time interval k, and $C_{MC,MGi,z}$ is the maintenance cost coefficient (\$/kWh) of the z-th distributed energy resource within the i-th MG.

For an ESS, its maintenance cost is determined by [35]

$$Q_{MGi,z}(k) = C_{MC,MGi,z} \times |P_{MGi,z}(k)| \times \Delta t. \tag{3.12}$$

3.2.2 Emissions minimisation

The second objective of the OCEM problem is to minimise the emissions of an MMG system, which is captured by the following objective function

$$E_{MMG} = \sum_{i=1}^{O} E_{MGi}, \tag{3.13}$$

where

$$E_{MGi} = \sum_{k=1}^{K} \sum_{s=1}^{\Lambda} \left[E_{MGi-Grid,s}(k) + \sum_{z=1}^{D_i} E_{MGi,z,s}(k) \right], \tag{3.14}$$

where E_{MMG} and E_{MGi} are the mass (kg) of the emissions produced by the MMG system and i-th MG over time period $[0, K\Delta t]$, respectively. Λ is the number of different emissions, $E_{MGi,z,s}(k)$ is the mass (kg) of the s-th emission from the z-th distributed energy resource within the i-th MG during time interval k, and $E_{MGi-Grid,s}(k)$ is the mass (kg) of the s-th emission from the large-scale power plants within the main grid during time interval k. s is the index of different types of emissions considered such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), etc. Λ is the total number of different emissions considered.

In (3.14),

$$E_{MGi,z,s}(k) = H_{MGi,z,s} \times P_{MGi,z}(k) \times \Delta t, \tag{3.15}$$

where $H_{MGi,z,s}$ is the emission coefficient (kg/kWh) of the s-th emission of the z-th distributed energy resource within the i-th MG.

$$E_{MGi-Grid,s}(k) = H_{Grid,s} \times P_{MGi-Grid}(k) \times \Delta t, \tag{3.16}$$

where $H_{Grid,s}$ is the emission coefficient (kg/kWh) of the s-th emission of the large-scale power plants within the main grid. Note that emissions are produced when an MG imports electricity from the main grid; however, when an MG exports electricity to the main grid, it contributes to emission reduction. In other words, only the absolute amount of electricity imported from the main grid generates emissions.

3.3 DECISION VARIABLES

The OCEM problem proposed in this study optimises the power flows within an MMG system and that between the MMG system and the main grid as listed in the following:

1. The output power (kW) of the z-th distributed energy resource within the i-th MG during time interval k: $P_{MGi,z}(k)$.
2. The operational status of the z-th distributed energy resource within the i-th MG during time interval k: $U_{MGi,z}(k)$.
3. The amount of power (kW) flowing between the i-th and j-th MGs during time interval k: $P_{MGi-MGj}(k)$.

4. The amount of power (kW) flowing between the i-th MG and main grid during time interval k: $P_{MGi-Grid}(k)$.

3.4 CONSTRAINTS

The physical and operational limits that must be respected by the optimisation problem are discussed in this section.

3.4.1 Power supply and demand balance

The constraint that ensures that the loads within the i-th MG are satisfied for all the MGs $i = 1,2,...,O$ and at all time $k = 1,2,...,K$ is given by [40]

$$\sum_{\substack{j=1 \\ j\neq i}}^{O} P_{MGi-MGj}(k) + \sum_{z=1}^{D_i} P_{MGi,z}(k) + P_{MGi-Grid}(k) = L_{MGi}(k), \tag{3.17}$$

where $L_{MGi}(k)$ is the electrical demand (kW) within the i-th MG during time interval k.

3.4.2 Limits on distributed energy resources

The output power of the z-th distributed energy resource should not exceed the maximum and minimum limits during each time interval k, and is defined by [40]

$$P_{MGi,z}^{Min} \leq P_{MGi,z}(k) \leq P_{MGi,z}^{Max}, \tag{3.18}$$

where $P_{MGi,z}^{Min}$ and $P_{MGi,z}^{Max}$ are the minimum and maximum output powers (kW) of the z-th distributed energy resource within the i-th MG, respectively.

3.4.3 Limits on ESSs

The amount of energy stored within an ESS should not exceed the maximum and minimum limits during each time interval k, and is defined by [40]

$$S_{ESS}^{Min} \leq S_{ESS}(k) \leq S_{ESS}^{Max}, \tag{3.19}$$

where $S_{ESS}(k)$ is defined by [11]

$$S_{ESS}(k+1) = S_{ESS}(k) + \left[\frac{P_{ESS}(k) \times \Delta t}{R_{ESS}} \times 100\% \right], \tag{3.20}$$

where R_{ESS} is the capacity (kWh) of an ESS, $P_{ESS}(k)$ is the amount of power (kW) flowing to or from an ESS during the time interval k, and $S_{ESS}(k)$ is the state-of-energy, which refers to the amount of energy stored within an ESS during time interval k and is measured as a percentage (%) of R_{ESS}. S_{ESS}^{Min} and S_{ESS}^{Max} are the minimum and maximum amount (%) of energy that can be stored within an ESS, respectively.

In addition to (3.19), an additional constraint (3.21) from [40] is added to ensure that the initial and final state-of-energy of an ESS are the same, which ensures that the solution of the energy management optimisation problem can be implemented repeatedly as the ESS can provide long-term support to an MG [35].

$$S_{ESS}(1) = S_{ESS}(K), \tag{3.21}$$

where $S_{ESS}(1)$ and $S_{ESS}(K)$ are the initial and final state-of-energy of an ESS, respectively.

3.4.4 Power flow limits

The power flowing between the i-th and j-th MGs should not exceed the maximum and minimum limits during each time interval k, and is defined by [18]

$$-P_{MGi-MGj}^{Max} \leq P_{MGi-MGj}(k) \leq P_{MGi-MGj}^{Max}, \tag{3.22}$$

where $P_{MGi-MGj}^{Max}$ is the maximum amount of power (kW) that can flow between the i-th and j-th MGs.

The power flowing between the i-th MG and main grid should not exceed the maximum and minimum limits during each time interval k, and is defined by [18]

$$-P_{MGi-Grid}^{Max} \leq P_{MGi-Grid}(k) \leq P_{MGi-Grid}^{Max}, \tag{3.23}$$

where $P_{MGi-Grid}^{Max}$ is the maximum amount of power (kW) that can flow between the i-th MG and main grid.

3.5 CHAPTER SUMMARY

This chapter addresses a research gap that has been identified in the literature review by proposing an OCEM problem that can identify an energy management strategy for an MMG system, in a centralised manner, which minimises the operational cost and emissions simultaneously. The performance of the OCEM problem is evaluated in the next chapter where it is used to solve the energy management problem of a grid-tied MMG system and its results are compared to those of an OCM problem.

CHAPTER 4 CASE STUDY

4.1 CHAPTER OVERVIEW

The previous chapter proposes an OCEM problem that can identify an energy management strategy for an MMG system, in a centralised manner, which minimises the operational cost and emissions simultaneously. This chapter assesses the effectiveness of the proposed OCEM problem by using it to solve the energy management problem of a grid-tied MMG system and by comparing its results to those of an OCM problem in [40], which was identified as the state-of-the-art energy management problem for an MMG system during the literature review. The OCM problem in [40] is similar to the OCEM problem, except, it only minimises the operational cost and does not include the emissions minimisation objective, which is given by (3.13).

This chapter consists of several sections, namely Section 4.2 introduces the characteristics and configuration of the MMG system, Section 4.3 introduces the optimisation algorithm used to solve this optimisation problem, and Section 4.4 provides an analyses and comparison of the results.

4.2 CONFIGURATION OF THE MMG SYSTEM

The grid-tied MMG system considered in the study is similar to the MMG system presented in [40], which consists of two MGs. However, the MMG system presented in this study includes three MGs as shown by Figure 4.1 and the configuration of each MG within this MMG system is shown by Figure 4.2. In this study, it is assumed that each MG has the same owner as the energy management problem of this MMG system is solved in a centralised manner. It is important to note that the OCEM problem is a generic framework, it can be used to solve any MMG energy management problem, and it is not limited to the case study in this dissertation.

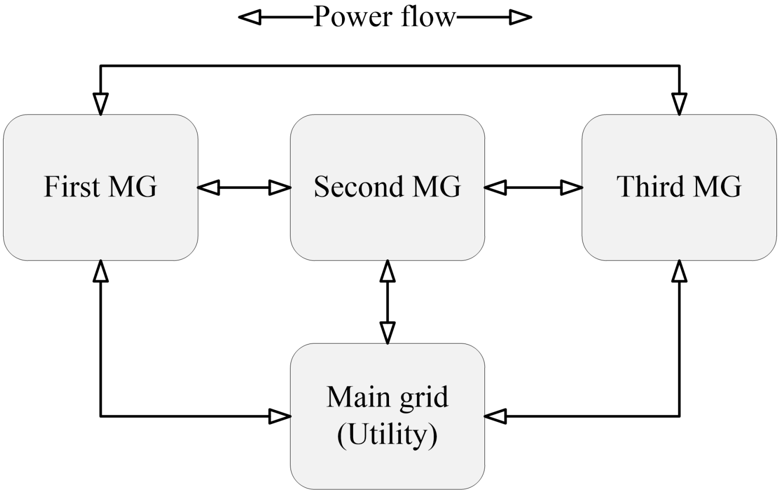


Figure 4.1. Configuration of the MMG system.

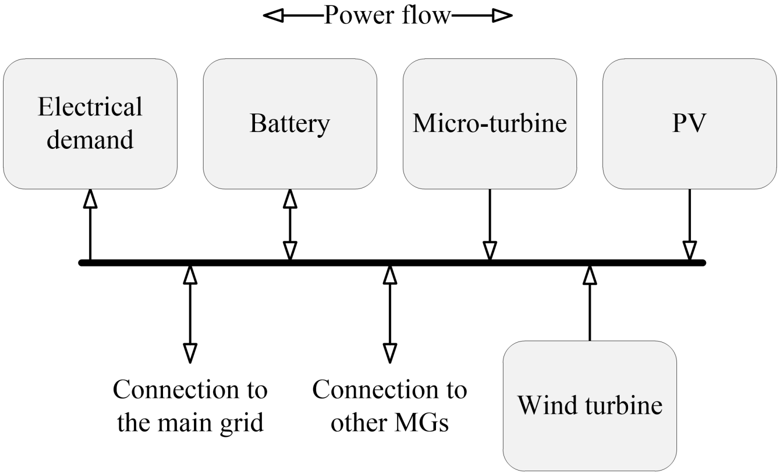


Figure 4.2. Configuration of a single MG system.

4.2.1 Overview of the distributed energy resources within the MGs

This subsection provides the models and specifications of each distributed energy resource within each MG. It should be noted that the aim of this study is to identify the optimal energy management strategy of an MMG system. The process of identifying the optimal size/capacity of each distributed energy resource within an MG, as was done in [9, 57–60], is beyond the scope of this study.

4.2.1.1 Micro-turbine

An micro-turbine is a combustion turbine, which can be powered by various clean fuel types such as natural gas, hydrogen, diesel, biogas, propane, etc. [9]. It produces few emissions as it operates with a lean air-to-fuel ratio, low turbine temperatures and utilises sophisticated combustion systems [61]. Thanks to its simple mechanical design, an micro-turbine only has a few moving parts, which improves its reliability and hence reduces its operation and maintenance costs [31, 61]. Detailed specifications of the natural gas-fired micro-turbines within each MG are provided in Table 4.1.

Table 4.1. Specifications of the micro-turbines [40]

Generating unit	Minimum output power (kW)	Maximum output power (kW)
Micro-turbine in MG1	3	40
Micro-turbine in MG2	5	50
Micro-turbine in MG3	3	35

4.2.1.2 PV system

A PV module consists of an array of PV cells, which are constructed from semiconducting materials [9]. These PV cells generate DC electricity when they are struck by sunlight, as a result of the transference of the solar radiation energy from the sun to the electrons within the PV cells, which is known as the PV effect [62]. The advantages of a PV module is that it does not produce emissions, operates silently and has no fuel cost associated with it as its fuel (solar irradiance) is provided by the sun [3, 31]. On the other hand, the disadvantages are that its operational efficiency is quite low and its output power is intermittent as it is dependent on environmental conditions such as the ambient temperature, solar irradiance, etc. [3, 8].

The output power of a PV system (W), which includes multiple PV modules is modelled in [63] and is given by

$$P_{PV} = \eta_{PV} \times N_{PV} \times A_{PV} \times I_r, \tag{4.1}$$

where N_{PV} is the number of PV modules within the PV system, A_{PV} is the surface area of one PV module (m^2), I_r is the solar irradiance (W/m^2), and the conversion efficiency is modelled in [63] and is given by

$$\eta_{PV} = \eta_{module} \times \eta_{MPPT} \times \left[1 - K_{PV}\left(T_{cell} - T_{STC}\right)\right], \tag{4.2}$$

where η_{MPPT} is the efficiency of the maximum power point tracking (95% [64]), η_{module} is the efficiency of the PV module (%), K_{PV} is the temperature coefficient of the PV module (%/°C), T_{STC} is the temperature (°C) of the PV cells under the standard test conditions (STC), namely 25°C PV cell temperature, air mass coefficient of 1.5, and 1000 W/m^2 solar irradiance [65]. T_{cell} is the temperature of the PV cells (°C), it is modelled in [63], and is given by

$$T_{cell} = T_{amb} + \left[\frac{\zeta - 20°C}{800\,{}^{W}\!/_{m^2}}\right] \times I_r, \tag{4.3}$$

where ζ is the normal operating cell temperature (NOCT), and T_{amb} is the ambient temperature (°C).

The Sharp NU-R250J5 is the PV module used in this case study, and its characteristics are provided in Table 4.2. MGs 1-3 include 240, 120 and 180 of these PV modules, respectively, which implies that under STC the maximum power outputs of the PV systems within MGs 1-3 are 60 kW, 30 kW and 45 kW, respectively [40].

Table 4.2. Specifications of the NU-R250J5 PV module [65]

Specification	Value
Maximum output power under STC	250 W
Module efficiency (η_{module})	15.2%
NOCT	47.5°C
Temperature coefficient (K_{PV})	-0.463%/°C
Surface area (A_{PV})	1.64 m^2

The solar irradiance and ambient temperature within each MG are obtained from the South African power utility, Eskom [66] and are shown by Figure 4.3-4.4.

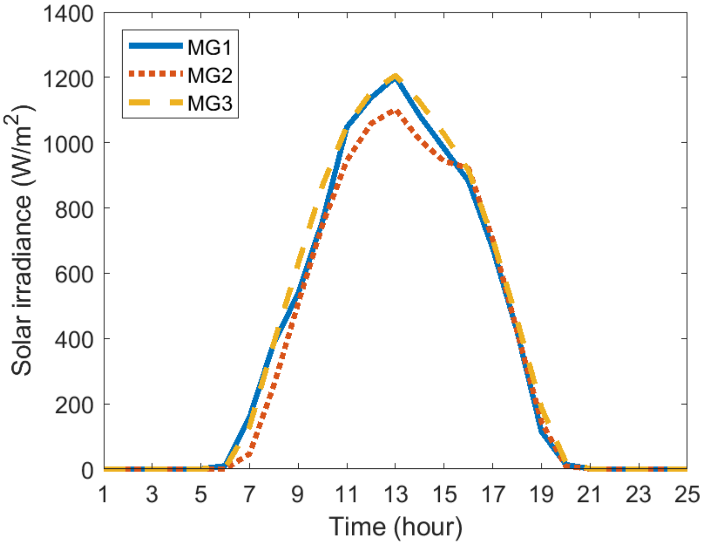


Figure 4.3. Solar irradiance within each MG [66].

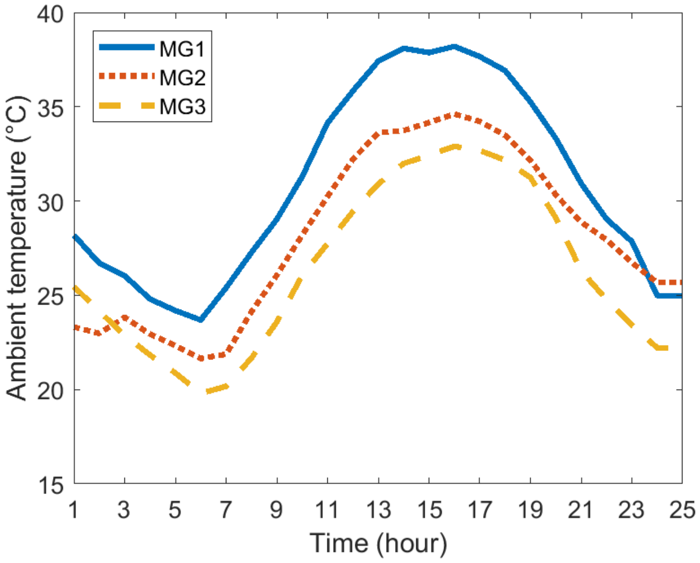


Figure 4.4. Ambient temperature within each MG [66].

4.2.1.3 Wind turbine

A horizontal axis wind turbine consists of a nacelle, tower and rotor blades [3]. The rotor blades rotate when wind pushes against them and thus capture the kinetic energy of the wind [3]. The wind power is then mechanically transferred to a gearbox and generator located within the nacelle, which convert the wind power into electrical power [3]. The rotor blades and nacelle are usually mounted on top of a tower high above ground obstacles or obstructions [9, 62] to capture the potential wind power from various directions. The advantages of a wind turbine is that it does not produce emissions, has no fuel cost associated with it as its fuel (wind) is provided by nature and it has a higher energy conversion efficiency, higher power density and is less expensive in comparison to a PV module [3, 31, 62, 67]. On the other hand, the disadvantages of a wind turbine is that it can injure or kill bats and birds, it produces aerodynamic and mechanical noise, the rotor blades could cast a flickering shadow on nearby buildings and its output power is intermittent as it is dependent on environmental conditions such as wind speed, etc. [8, 68–70].

In this case study, the wind turbines in MGs 1-3 are the GP Yonval 40-16 [71], FX EVO 21-75 [72] and FX EVO 21-50 [73], respectively. The data-sheets of these wind turbines do not provide models of the wind turbines but rather provide several data points, which indicate the power output for certain wind speeds. As a result, regression analysis is perfromed on these data points through the use of the polyfit function [74] in MATLAB in order to identify polynomial functions that provide the best fit for these data points. The MATLAB used in this study is version 9.3.0.713579 in the R2017b release. These polynomial functions represent the power output characteristics of these wind turbines, have a coefficient of determination (R^2) of 0.99, allow a user to identify the power output for any wind speed and are given by

$$P_{MG1}^{WT}(V) = \begin{cases} 0, & \text{if } V < 3.5 \text{ m/s or } V \geq 24 \text{ m/s.} \\ \big[-0.0105V^4 + 0.2046V^3 - 0.8246V^2 & \text{if } V \geq 3.5 \text{ m/s and } V < 11 \text{ m/s.} \\ +2.2007V - 2.4737\big], & \\ 40, & \text{if } V \geq 11 \text{ m/s and } V < 24 \text{ m/s.} \end{cases} \tag{4.4}$$

$$P_{MG2}^{WT}(V) = \begin{cases} 0, & \text{if } V < 2.5 \text{ m/s or } V \geq 25 \text{ m/s.} \\ \big[-0.0304V^4 + 0.6475V^3 - 3.6865V^2 & \text{if } V \geq 2.5 \text{ m/s and } V < 11 \text{ m/s.} \\ +10.3784V - 10.6971\big], & \\ 75, & \text{if } V \geq 11 \text{ m/s and } V < 25 \text{ m/s.} \end{cases} \tag{4.5}$$

$$P_{MG3}^{WT}(V) = \begin{cases} 0, & \text{if } V < 2.5 \text{ m/s or } V \geq 25 \text{ m/s.} \\ \big[-0.0207V^5 + 0.4910V^4 - 4.3396V^3 & \text{if } V \geq 2.5 \text{ m/s and } V < 8.5 \text{ m/s.} \\ +18.8547V^2 - 37.4327V + 27.1745\big], & \\ 50, & \text{if } V \geq 8.5 \text{ m/s and } V < 25 \text{ m/s.} \end{cases} \tag{4.6}$$

where $P_{MG1}^{WT}(V)$, $P_{MG2}^{WT}(V)$ and $P_{MG3}^{WT}(V)$ are the power outputs (kW) of the wind turbines within MGs 1-3, respectively, and V is the wind speed (m/s).

The wind speed within each MG is also obtained from Eskom [66]; however, the wind speed was measured at a height of 9 m while the hub height of the wind turbines is 30 m. Figure 4.5 shows the Eskom wind speed, which is adjusted according to the height of the wind turbines through the use of an approach in [75], which is

$$V = V_0 \times \left[\frac{H}{H_0}\right]^{\alpha}, \tag{4.7}$$

where V and V_0 are the wind speed (m/s) at a height (m) of H and H_0, respectively, and α is the ground surface friction coefficient. The value of α varies according to the ambient temperature, time of day, wind speed, elevation, nature of the terrain, season, etc. [75]. However, in this case study α takes the recommended value of 1/7 [75].

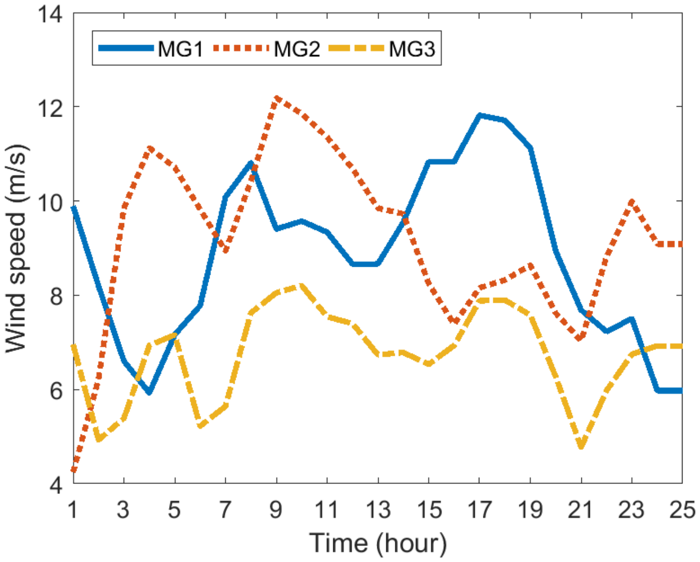


Figure 4.5. Wind speed within each MG at a height of 30 m [66].

4.2.1.4 ESS

One of the disadvantages of a wind turbine and PV system is that their output power is intermittent; however, this problem can be solved with an ESS, which can compensate for the fluctuations in the output power of a renewable generating unit by storing all of the surplus energy and supplying that energy when the renewable generating unit is unable to satisfy the demand [8]. Similarly, an ESS can also be used to compensate for the fluctuations in the output power of slow-acting generating units such as a diesel generator when it is accelerating, decelerating or performing a start-up [12]. There are several types of ESSs such as [8, 76]:

1. battery energy storage system (BESS),
2. flywheel energy storage system (FESS),
3. supercapacitor/electric double layer capacitor (EDLC), etc.

A Lead-acid battery is a popular ESS in renewable energy applications because of its low cost and rugged design [8, 76]; however, its cycle life drastically decreases with a deep depth of discharge [77]. If its recommended depth of discharge of 30% to 50% is exceeded, then it needs to be replaced regularly, which generally results in an impractical capital cost [8, 75]. On the other hand, a Lithium-ion battery is more expensive in comparison to a Lead-acid battery [8]; however, it has no memory effect, and has a high cycle life even at a deep depth of discharge, which implies that most of the capacity of the battery can be utilised without damaging the battery [76, 78]. As a result of these advantages, the ESS in each MG is a Lithium-ion battery and the characteristics of this BESS are provided in Table 4.3. In this case study, the BESS in each MG has an initial state-of-energy ($S_{ESS}(1)$) of 70%. This 70% is selected because it allows the optimisation problems to identify the optimal energy management strategies by providing them with the freedom to charge or discharge the BESS during the first time interval. If $S_{ESS}(1)$ is 100%, then the BESS will not be able to charge during the first time interval and if it is 10%, then it will not be able to discharge during the first time interval.

Table 4.3. Specifications of the Lithium-ion BESS [9, 40]

Specification	Value
Capacity (kWh)	1400
Minimum state-of-energy (%)	10
Maximum state-of-energy (%)	100
Maximum charging power (kW)	30
Maximum discharging power (kW)	30

4.2.2 Operation costs of the MMG system

The time-of-use tariff of the electricity flowing between an MG and the main grid, as well as the electricity flowing between two MGs are provided by (4.8), (4.9) and (4.10) [40]. The maximum amount of power that can flow between an MG and the main grid is 250 kW whereas the maximum amount of power that can flow between two MGs is 100 kW.

$$W_{Pur}^{Grid}(k) = \begin{cases} \$0.0266/\text{kWh}, & \text{during the off-peak period: } k \in [1,6] \cup [21,24]. \\ \$0.0766/\text{kWh}, & \text{during the standard period: } k \in [7,9] \cup [15,17]. \\ \$0.1297/\text{kWh}, & \text{during the peak period: } k \in [10,14] \cup [18,20]. \end{cases} \tag{4.8}$$

$$W_{Sell}^{Grid}(k) = \begin{cases} \$0.0203/\text{kWh}, & \text{during the off-peak period: } k \in [1,6] \cup [21,24]. \\ \$0.0594/\text{kWh}, & \text{during the standard period: } k \in [7,9] \cup [15,17]. \\ \$0.1016/\text{kWh}, & \text{during the peak period: } k \in [10,14] \cup [18,20]. \end{cases} \tag{4.9}$$

$$W_{Pur}^{MG}(k) = W_{Sell}^{MG}(k) = \$0.0781/\text{kWh} \quad \forall\, k \in \{1,2,3,...,24\} \tag{4.10}$$

The operation costs of the various distributed energy resources within each MG are provided in Table 4.4-4.5. Table 4.4 does not include the PV systems, wind turbines and BESSs because these distributed energy resources are not associated with shutdown, start-up and fuel costs [40].

Table 4.4. Shutdown, start-up and fuel costs of the micro-turbines [40]

Generating unit	$C_{FC1,MT}$ ($/kWh)	$C_{FC2,MT}$ ($/h)	$C_{SU,MGi,z}$ and $C_{SD,MGi,z}$ ($)
Micro-turbine in MG1	0.047	0.953	0.109
Micro-turbine in MG2	0.041	1.094	0.141
Micro-turbine in MG3	0.047	0.953	0.109

Table 4.5. Maintenance costs of the distributed energy resources [40]

Generating/storage unit	$Q_{MGi,z}$ (\$/kWh)
Micro-turbine in MG1	0.00781
Micro-turbine in MG2	0.00625
Micro-turbine in MG3	0.00781
ESS in each MG	0.01313
Wind turbine in each MG	0.00938
PV in each MG	0.00469

4.2.3 Emissions of the MMG system

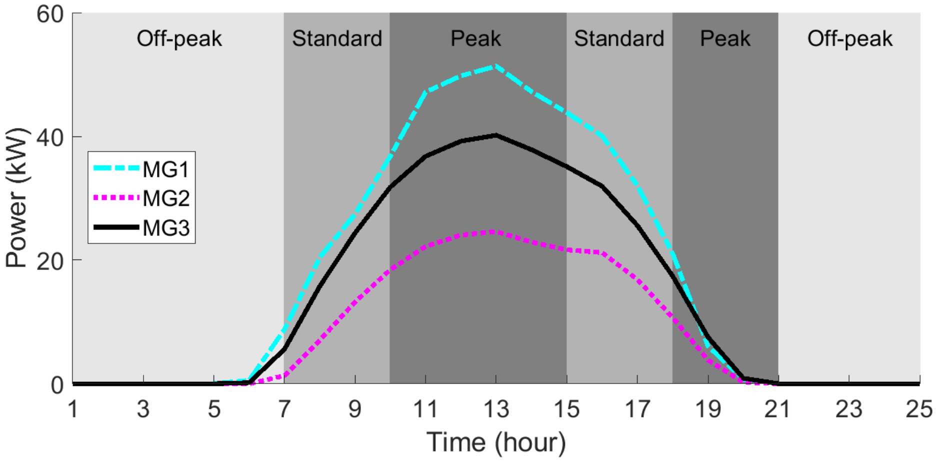
Renewable generating units such as wind turbines and PV systems do not generate emissions [3] but micro-turbines and coal-fired power plants within the main grid do. The emission rates of an micro-turbine and large-scale coal power plant in terms of SO_2, NO_x and CO_2 are provided in Table 4.6.

Table 4.6. Emission rates of generating units [4, 5]

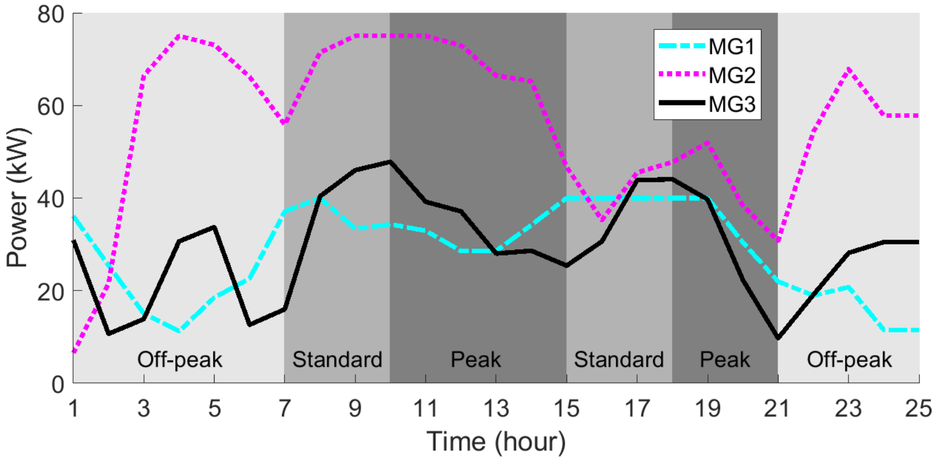
Generation unit	NO_x (g/kWh)	SO_2 (g/kWh)	CO_2 (g/kWh)
Micro-turbine	0.62	0.0009	184.08
Coal-fired power plant	1.23	1.87	845.62

4.2.4 Renewable power generation and electrical demand in each MG

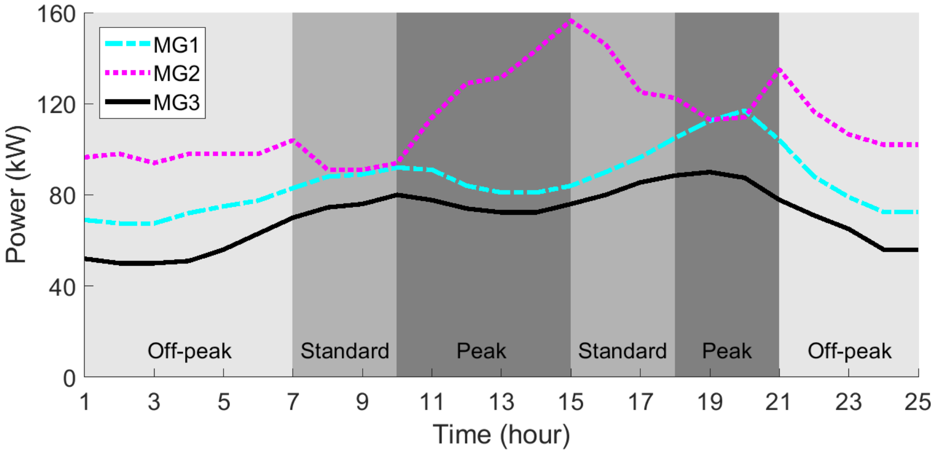
The power outputs of the PV system and wind turbine, as well as the electrical demand profile within each MG, are shown by Figure 4.6(a)-4.6(c). The electrical demand profiles in MG1 and MG2 were obtained in [40] whereas the electrical demand profile in MG3 was obtained in [54].



(**a**) Power output of the PV system within each MG.



(**b**) Power output of the wind turbine within each MG.



(**c**) Electrical demand within each MG [40, 54].

Figure 4.6. Power outputs of the PV system and wind turbine, as well as the electrical demand profile within each MG.

4.3 OPTIMISATION ALGORITHMS

The OCEM problem formulated and the OCM problem used as a baseline problem are complex nonlinear programming problems, which can be solved through the use of the following two methods [48]. The first are known as conventional or analytical methods such as nonlinear programming (NLP), mixed integer nonlinear programming (MINLP), etc. whereas the second are known as artificial intelligent or heuristic methods such as the genetic algorithm (GA), particle swarm optimisation (PSO), etc. [48]. Analytical methods are simpler in comparison to heuristic methods; however, heuristic methods can handle and generally identify better solutions for complex optimisation problems [48]. This study does not only use one of these methods but rather uses both in a hybrid approach. The heuristic method, which is used in this study is the genetic algorithm because it is a popular algorithm [79] and it is one of the few algorithms in MATLAB (version 9.3.0.713579 in the R2017b release) that can solve single and multi-objective problems, which is essential because the OCEM and OCM programming problems need to be solved by the same algorithm to ensure a fair comparison. Biological evolution was the inspiration for the genetic algorithm, which was introduced in 1975 by John Henry Holland [79]. A genetic algorithm identifies the optimal solution of a problem by continuously adapting a population of solutions through the use of a process, which includes selection, crossover, mutation and inheritance [79, 80]. During each iteration, the genetic algorithm creates a new population of solutions, known as children, through the use of parent solutions, which are randomly selected from the previous population [80]. A genetic algorithm is able to quickly identify the region in which the global minimum of an optimization problem is located; however, it can take a long time to accurately identify the global minimum because the genetic algorithm requires a lot of function evaluations to converge towards the global minimum [79, 81]. This problem can be solved through the use of a hybrid approach in which the genetic algorithm is executed for a short period in order to identify the region in which the global minimum is located [81]. The solution provided by the genetic algorithm is taken as the initial guess for a second algorithm, which has a fast converging feature that allows it to solve the problem as quickly and accurately as possible [81]. For multi-objective optimisation, MATLAB only has one routine available with which the genetic algorithm can be combined to form a hybrid approach. This routine is known as fgoalattain and the algorithm, which it uses to solve an optimisation problem is known as sequential quadratic programming. Sequential quadratic programming is a nonlinear programming method and is regarded as a state-of-the-art analytical method [82]. For single objective optimisation, MATLAB has several routines available with which the genetic algorithm can be combined to form a hybrid approach. However, fmincon is the only routine, which can solve a constrained problem through the use of the sequential quadratic programming algorithm. For the OCM, MATLAB's genetic algorithm and fmincon routines are used while genetic algorithm and fgoalattain are used to solve the OCEM problem because of its multi-objective setup. It is noted that both the fmincon and fgoalattain are set to use sequential quadratic programming to ensure a fair comparison between the results obtained. In this study, the OCM and OCEM optimisation problems are solved by a hybrid approach, which is implemented in MATLAB's optimisation toolbox (version 8.0 in the R2017b release) [83]. Detailed settings of the optimisation algorithms are provided by Table 4.7-4.8.

Table 4.7. Genetic algorithm settings.

Setting	Genetic algorithm: OCM	Genetic algorithm: OCEM
Creation function	gacreationuniform	gacreationuniform
Crossover function	crossoverscattered	crossoverintermediate
Crossover fraction	0.8	0.8
Mutation function	mutationgaussian	mutationadaptfeasible
Selection function	selectionstochunif	selectiontournament
Maximum generations	150 000	150 000
Population size	500	500
Pareto fraction	n/a	0.3

Table 4.8. fmincon and fgoalattain settings.

Setting	fmincon: OCM	fgoalattain: OCEM
Algorithm	Sequential quadratic program	Sequential quadratic program
Maximum function evaluations	1 000 000	1 000 000
Maximum iterations	800 000	800 000

4.4 RESULTS AND DISCUSSION

This section presents the results provided by the OCM and OCEM problems after they solved the energy management problem of the MMG system in Section 4.2 over a time period of 24 hours and with a sampling interval of 1 hour.

4.4.1 Evaluation of the OCEM problem results

Due to the characteristics of the genetic algorithm, the same results are not guaranteed after each run. Therefore, the OCEM problem was solved 30 times and the statistics of these solutions are analysed. After each run, the hybrid algorithm between the genetic algorithm and fgoalattain provides a frontier of non-dominated solutions, which according to Table 4.7 can include between 1 to 150 solutions ($500 \times 0.3 = 150$). This implies that 30 runs will provide 30 frontiers, which have been merged to form the Pareto frontier and is shown in Figure 4.7. All the solutions in the Pareto frontier are referred to as non-dominated solutions, which implies that none of the solutions dominate one another. As an example, a solution U_2 is dominated by solution U_1 if both of the following two criteria are true [84]. Firstly, the fitness values of U_1 for all objectives must be smaller or equal to those of U_2 as given by

$$G_j(U_1) \leq G_j(U_2) \quad \forall j \in \{1,2,3,...,J\}, \tag{4.11}$$

where $G_j(U_1)$ and $G_j(U_2)$ are the fitness values of solutions U_1 and U_2 for the j-th objective, respectively, and J is the number of objectives. Secondly, there exists an objective where the fitness value of U_1 is smaller than that of U_2 as given by

$$G_j(U_1) < G_j(U_2) \quad \exists j \in \{1,2,3,...,J\}, \tag{4.12}$$

If a solution was located close to point D in Figure 4.7, then according to these two criteria that solution would be dominated by the solutions located close to point B. On the other hand, a solution located close to point D would not be dominated by the solutions located close to points A and C.

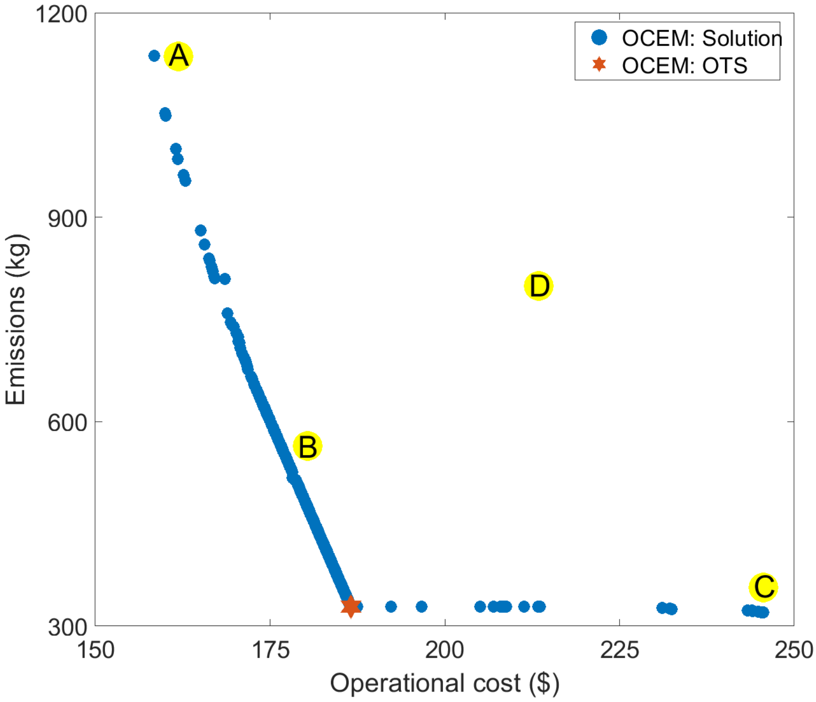


Figure 4.7. OCEM problem solutions.

The shape of the Pareto frontier in Figure 4.7 indicates that the operational cost and emissions are competing objectives. This implies that if one selects a solution that improves the one objective, then that solution will also degrade the other objective. Therefore, a trade-off between them must be made in practical applications by a decision maker. There should exist a solution on the Pareto frontier, which simultaneously minimises the operational cost and emissions as much as possible and which effectively provides the optimal trade-off between the competing objectives. In this study, the solution on the Pareto frontier that provides the optimal trade-off between the operational cost and emissions is identified through a fuzzy set-based approach [85] that is given by

$$\mu_{M_i}(x) = \begin{cases} 1, & \text{if } M_i(x) \leq M_i^{min}. \\ \dfrac{M_i^{max} - M_i(x)}{M_i^{max} - M_i^{min}} & \text{if } M_i^{min} < M_i(x) < M_i^{max}. \\ 0, & \text{if } M_i(x) \geq M_i^{max}. \end{cases} \tag{4.13}$$

where $\mu_{M_i}(x)$ is the x-th non-dominated solution's degree of membership in the i-th objective function. This implies that $\mu_{M_i}(x)$ indicates the extent (with a value from 0 to 1) to which the i-th objective has been satisfied by the x-th non-dominated solution. $M_i(x)$ is the x-th non-dominated solution's fitness value for the i-th objective function, and M_i^{max} and M_i^{min} are the maximum and minimum fitness values amongst all the non-dominated solutions for the i-th objective function, respectively.

The x-th non-dominated solution's degree of membership for each objective can be added together to calculate its accomplishment of satisfying all the objectives. This accomplishment can then be normalised in order to rate the accomplishment of the x-th non-dominated solution according to the accomplishments of all of the non-dominated solutions as given by [85]

$$\beta(x) = \frac{\sum_{i=1}^{\psi} \mu_{M\,i}(x)}{\sum_{x=1}^{\xi} \sum_{i=1}^{\psi} \mu_{M\,i}(x)}, \tag{4.14}$$

where $\beta(x)$ is the normalised accomplishment of the x-th non-dominated solution, ξ is the number of non-dominated solutions, and ψ is the number of objectives.

The non-dominated solution that has the highest normalised accomplishment can be regarded as the optimal trade-off solution (OTS) on the Pareto frontier.

4.4.2 Comparing the results of the OCM and OCEM problems

In this subsection, the results provided by the OCEM problem are compared to those of the OCM problem. To ensure a fair comparison between the OCM and OCEM problems, the OCM problem was also solved 30 times. The OCM problem provides one solution after each run of the hybrid algorithm between the genetic algorithm and fmincon, which implies that 30 runs will provide 30 unique solutions. The 30 solutions provided by the OCM problem are compared to the Pareto frontier provided the OCEM problem in Figure 4.8.

The best, minimum and maximum solutions of the OCM problem are compared to the optimal trade-off, minimum and maximum solutions of the OCEM problem in Figure 4.9-4.10. In Figure 4.9, the minimum and maximum solutions refer to the solutions, which have the lowest and highest operational costs, respectively. Similarly, in Figure 4.10, the minimum and maximum solutions refer to the solutions, which have the lowest and highest emissions, respectively. The OTS of the OCEM problem is identified through fuzzy decision making on the Pareto frontier whereas the best solution of the OCM problem refers to the solution, which has the lowest operational cost amongst the 30 OCM solutions. Figure 4.9-4.10 indicate that the emissions of the MMG system are reduced by 73.07% by the OTS provided by the OCEM problem in comparison to the best solution provided by the OCM problem. This is; however, at a cost of a 18.86% increase in the operational cost of the MMG system. As discussed in subsection 4.4.1, a trade-off is necessary between the operational cost and emissions as they are competing objectives, which implies that it is expected that the OTS provided by the OCEM problem will increase the operational cost if it decreases the emissions. This answers the first research question in Section 1.2.

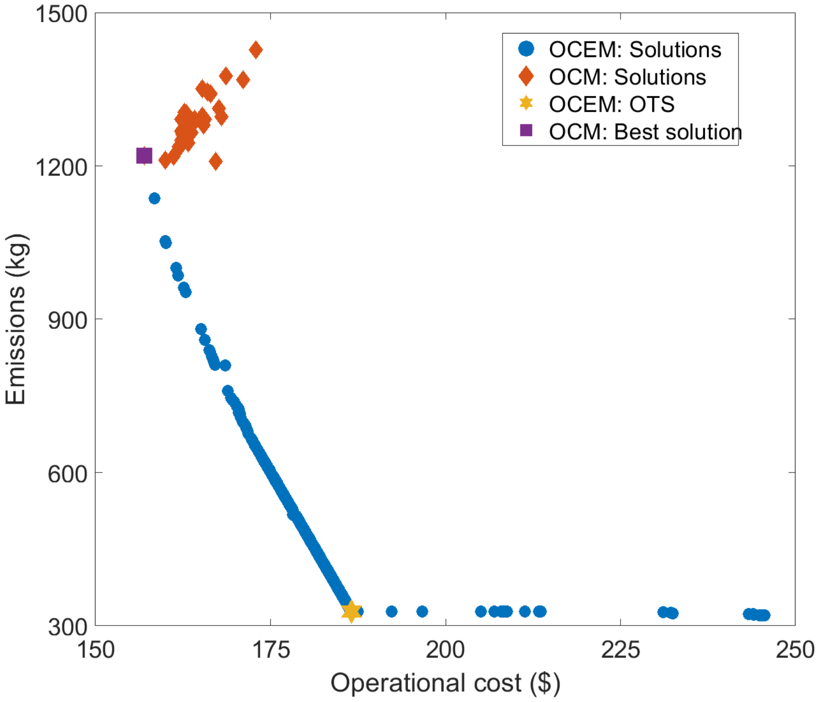


Figure 4.8. OCM and OCEM problem solutions.

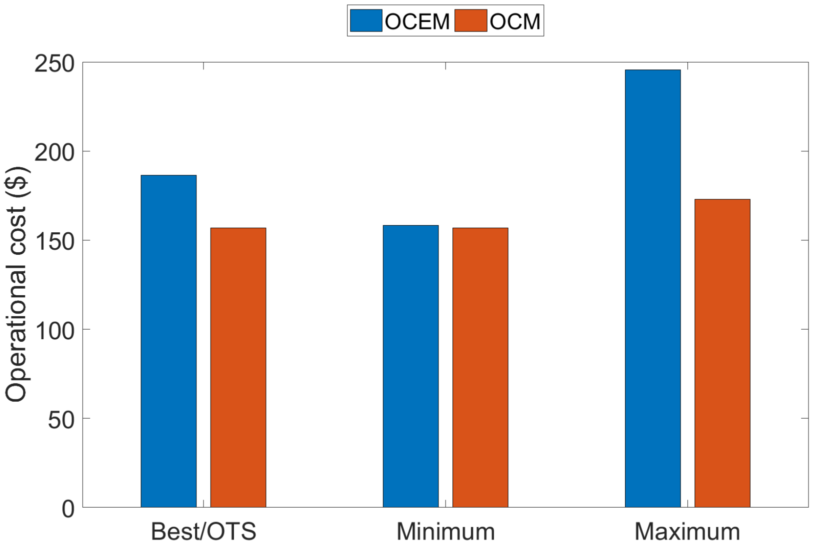


Figure 4.9. Comparison between the operational cost of the OCM and OCEM problem solutions.

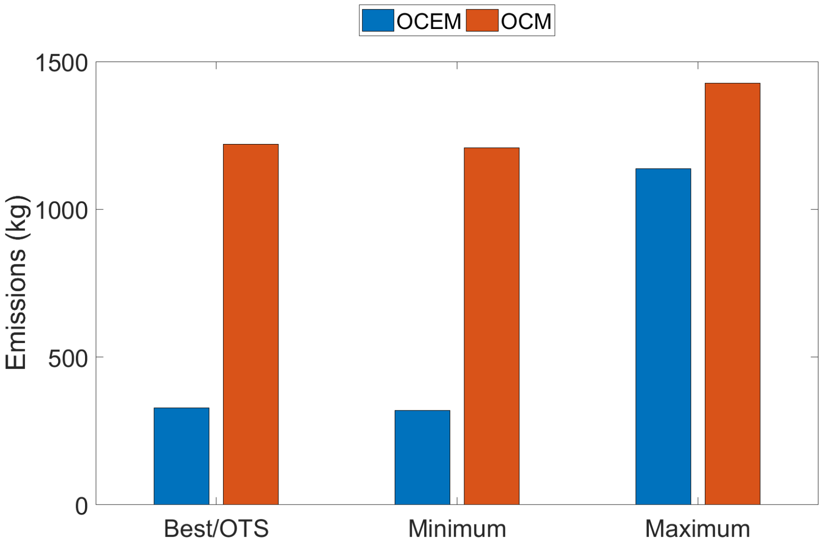


Figure 4.10. Comparison between the emissions of the OCM and OCEM problem solutions.

To analyse the contributions of the OCEM problem, Table 4.9 provides a comparison between the OTS provided by the OCEM problem and the best solution provided by the OCM problem. From Table 4.9, the following observations are clear:

- Distributed energy resource penetration: the solution provided by the OCEM problem increased the utilisation of the distributed energy resources in particular, the energy generated by the micro-turbines increased from 1657.66 kWh to 2999.44 kWh per day (80.94% increase). As a result, the energy purchased from and sold to the main grid decreased by 52.52% and increased by 7.64%, respectively. In comparison to the solution provided by the OCM problem that imports a net 1076.22 kWh energy from the main grid, the OCEM problem achieves a net 265.71 kWh energy export to the main grid per day, which contributes towards increased renewable penetration, emission reduction and demonstrates that the MMG system is actually supporting the main grid in terms of energy generation. This answers the second and third research questions in Section 1.2.
- Demand management: under the main grid's time-of-use tariff programme, the OCEM and OCM problems both tried to reduce the MMG system's operating cost by importing power from the main grid during the off-peak demand periods and exporting power to support the main grid's operation during the peak demand periods. To this end, the OCM and OCEM problems managed to export 1010.74 kWh to the main grid during the peak demand periods. Additionally,

the maximum power flow from the main grid to the MMG system reduced from 340.05 kW by the OCM problem to 230.18 kW by the OCEM problem (32.31% decrease).

- ESS utilisation: both the OCM and OCEM problems utilised the ESSs to their full capacities for load shifting and as energy buffers.

The above observations are demonstrated in Figure 4.11-4.13, which illustrate the reduction in the maximum demand, increased utilisation of the distributed energy resources, decrease in the energy imported from and increase in the energy exported to the main grid.

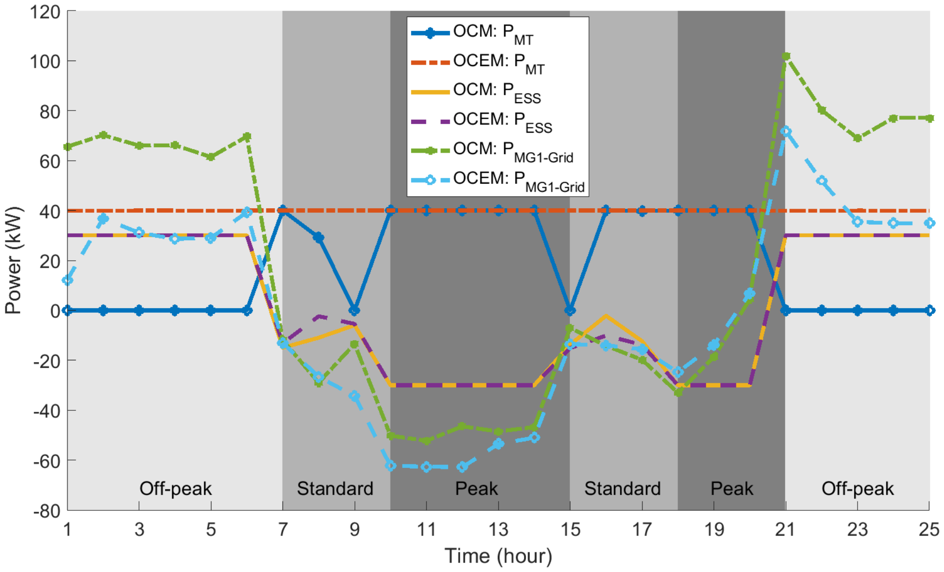


Figure 4.11. OTS of the OCEM problem versus best solution of the OCM problem for MG1.

Further analysis of Figure 4.11-4.13 indicates that the OTS provided by the OCEM problem and best solution provided by the OCM problem are similar during the standard and peak load periods; however, during the off-peak load periods, there is a significant difference between the two solutions. During the off-peak load periods, the OCEM problem decreases the energy imported from the main grid from 2356.77 kWh to 1113.50 kWh (decreased by 52.75%) and rather utilises the distributed energy resources by increasing the energy produced by the micro-turbines from 0 kWh to 1249.44 kWh in comparison to the OCM problem. According to Table 4.6, the solution provided by the OCEM problem will decrease the emissions of the MMG system as it increases the utilisation of the distributed energy resources and decreases the utilisation of the large-scale coal power plants. However, according to (4.8) and Table 4.4, this solution will also increase the operational cost of the MMG system as the fuel costs of the micro-turbines are higher in comparison to the cost of importing energy from the main grid during the off-peak demand periods. This explains why the OTS provided by the OCEM problem decreases the emissions by 73.07% but increases the operational cost by 18.86%, it is because the OCEM problem had to make a trade-off during the off-peak load periods between utilising the distributed energy resources to minimise the emissions and importing energy from the main grid to minimise the operational cost.

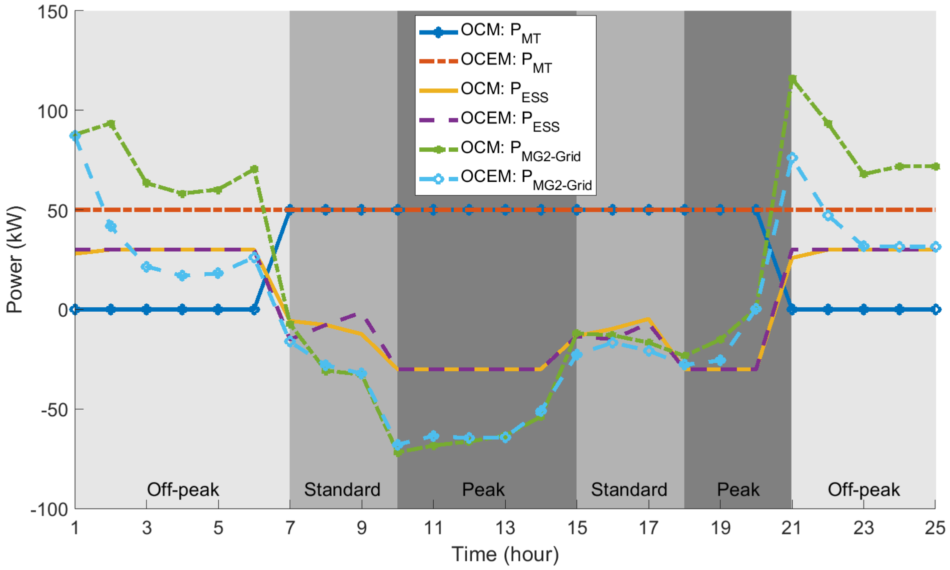


Figure 4.12. OTS of the OCEM problem versus best solution of the OCM problem for MG2.

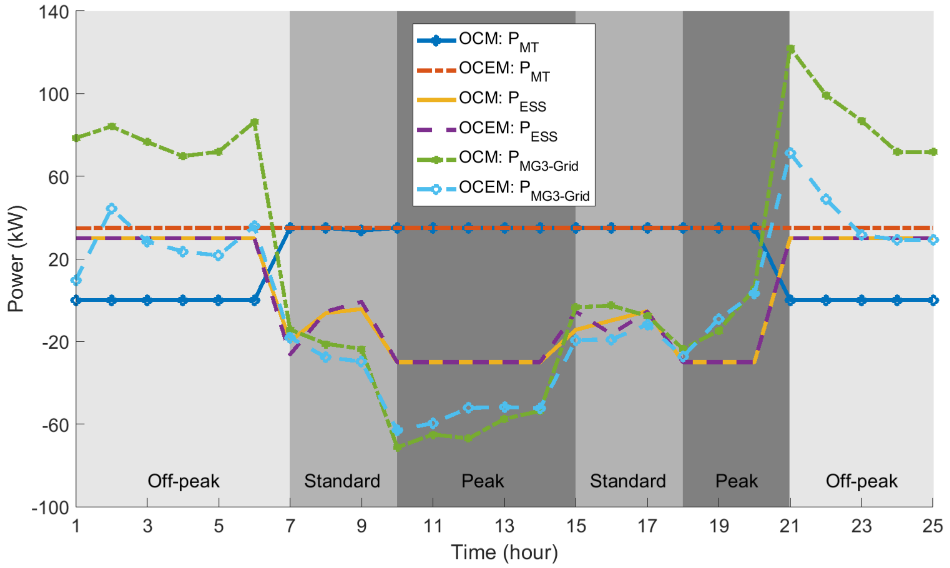


Figure 4.13. OTS of the OCEM problem versus best solution of the OCM problem for MG3.

Table 4.9. OTS provided by the OCEM problem versus best solution provided by the OCM problem.

	OCM				OCEM				OCEM versus OCM
	MG1	MG2	MG3	Total	MG1	MG2	MG3	Total	Difference
Energy supplied by the PV (kWh)	433.75	208.63	350.52	992.91	433.75	208.63	350.52	992.91	0%
Energy supplied by the wind turbine (kWh)	701.70	1341.97	709.14	2752.82	701.70	1341.97	709.14	2752.82	0%
Energy supplied by the micro-turbine (kWh)	469.02	700	488.65	1657.66	959.67	1200	839.77	2999.44	↑ 80.94%
Energy imported from the main grid (kWh)	731.60	783.22	852.47	2367.30	377.94	398.41	347.67	1124.03	↓ 52.52%
Energy exported to the main grid (kWh)	391.19	474.75	425.14	1291.08	447.90	501.14	440.70	1389.74	↑ 7.64%
Maximum power from the main grid (kW)	101.94	115.99	122.13	340.05	71.87	87.07	71.24	230.18	↓ 32.31%
Maximum power to the main grid (kW)	52.24	71.81	71.24	195.29	62.61	67.92	63.08	193.61	↓ 0.86%
Energy flow to the ESS (kWh)	300	293.83	300	893.83	300	300	300	900	↑ 0.69%
Energy flow from the ESS (kWh)	300	293.83	300	893.83	300	300	300	900	↑ 0.69%
Operational cost ($)	59.32	70.37	27.24	156.93	65.22	74.85	46.45	186.53	↑ 18.86%
Emissions (kg)	375.54	391.09	452.94	1219.58	117.88	134.45	76.16	328.49	↓ 73.07%

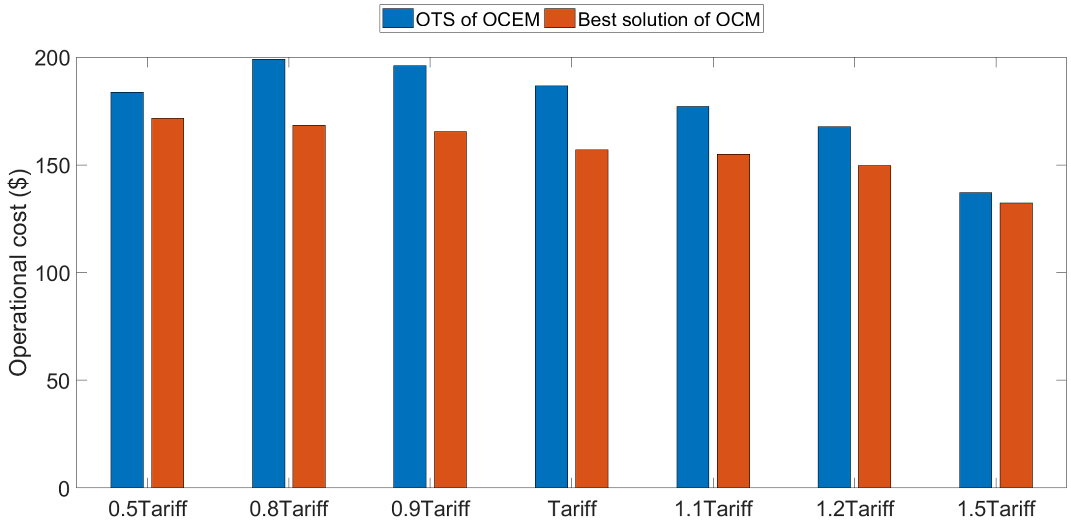
4.4.3 Sensitivity analysis

This subsection evaluates the performance of the OCEM problem in comparison to the OCM problem when there are variations in the time-of-use tariff, electrical demands, and fuel costs.

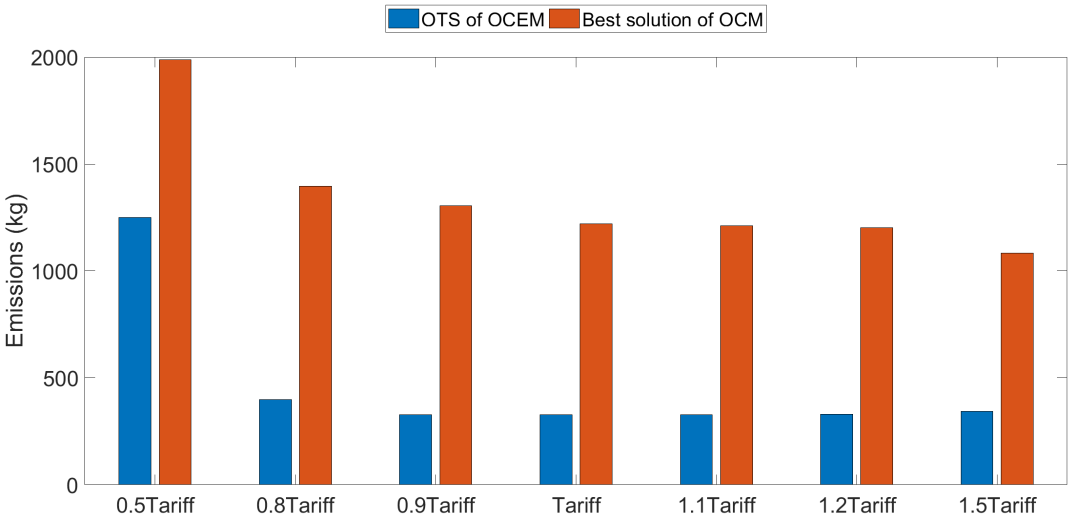
4.4.3.1 Time-of-use tariff

The time-of-use tariff given by (4.8), (4.9) and (4.10) is multiplied by scaling factors to obtain a set of several scaled tariffs. The operational cost and emissions of the best solution provided by the OCM problem and OTS provided by the OCEM problem for these various tariffs are shown in Figure 4.14 whereas a detailed overview of these solutions is provided by Table 4.10. This scaling approach is similar to the way in which Eskom changes the tariff because Eskom does not change the ratios between the tariffs in the off-peak, standard and peak periods but rather increases or decreases the tariff by a certain percentage [86].

According to Table 4.10, the solutions provided by the OCEM problem from 0.8Tariff to 1.5Tariff are all similar in terms of energy supplied by the micro-turbines, energy exported to the main grid and energy imported from the main grid. This implies that it can be expected that the emissions of these solutions will also be similar and is confirmed by Figure 4.14. On the other hand, all of these OCEM solutions are similar to the OCEM solution shown in Figure 4.11-4.13 as they also export energy to the main grid during the standard and peak periods and import energy from the main grid during the off-peak periods. However, when the standard tariff is increased by 50% (1.5Tariff), then the off-peak purchasing price increases by \$0.013/kWh whereas the standard and peak selling prices increase by \$0.029/kWh and \$0.152/kWh, respectively. This implies that the increase in the income received from the main grid will be significantly greater in comparison to the increase in the main grid expenses, which implies that the operational cost of the OCEM solutions will decrease as the time-of-use tariff increases and is confirmed by Figure 4.14. However, the OCEM solution at 0.5Tariff is an exception as it has a lower operational cost in comparison to the OCEM solution at 0.8Tariff. This is because from 0.8Tariff to 1.5Tariff the operational costs of the micro-turbines are less expensive than the electricity import price of the main grid during the standard and peak periods; however, at 0.5Tariff the operational costs of the micro-turbines are only less expensive during the peak periods. As a result, the OCEM problem identified an alternative solution at 0.5Tariff, which in comparison to the OCEM solution at 0.8Tariff decreases the utilisation of the micro-turbines by 19.17% and increases the energy imported from the main grid from 0 kWh to 68.61 kWh during the standard periods. Similarly, the solution at 0.5Tariff also decreases the utilisation of the micro-turbines by 89.63% and increases the energy imported from the main grid by 100.92% during the off-peak periods. This increase in the utilisation of the energy from the main grid suggests that the solution at 0.5Tariff will emit significantly more emissions in comparison to the solution at 0.8Tariff; however, at the same time the solution at 0.5Tariff has a lower operational cost.



(a) Operational cost.



(b) Emissions.

Figure 4.14. Best solution of OCM problem versus OTS of OCEM problem for various time-of-use tariffs.

Table 4.10. Best solution of the OCM problem versus OTS of the OCEM problem for various time-of-use tariffs.

	0.5Tariff	0.8Tariff	0.9Tariff	Tariff	1.1Tariff	1.2Tariff	1.5Tariff
OCM: Energy supplied by the micro-turbines (kWh)	502.29	1390.80	1529.65	1657.66	1670	1683.24	1861.13
OCM: Energy imported from the main grid (kWh)	2744.62	2338.90	2271.88	2367.30	2371.79	2360.23	2182.34
OCM: Energy exported to the main grid (kWh)	513.03	995.80	1067.66	1291.08	1309.42	1309.59	1309.59
OCM: Maximum power flow from the main grid (kW)	330.19	335.93	311.27	340.05	342.68	330.96	308.22
OCM: Energy flow to and from the ESS (kWh)	1560.77	1707.37	1656.24	1787.65	1799.66	1800.00	1800.00
OCM: Energy shared amongst the MGs (kWh)	588.28	596.04	634.06	652.08	628.08	733.30	656.39
OCEM: Energy supplied by the micro-turbines (kWh)	1650.62	2819.67	2999.95	2999.44	2999.65	2999.13	2916.20
OCEM: Energy imported from the main grid (kWh)	2181.12	1056.55	1123.53	1124.03	1123.82	1124.35	1139.12
OCEM: Energy exported to the main grid (kWh)	1061.88	1200.04	1389.59	1389.74	1389.59	1389.59	1369.51
OCEM: Maximum power flow from the main grid (kW)	278.94	203.33	219.20	230.18	219.20	219.28	213.15
OCEM: Energy flow to and from the ESS (kWh)	1452.50	1512.01	1800	1800	1800	1800	1715.39
OCM: Energy shared amongst the MGs (kWh)	519.57	481.79	1028.94	484.13	511.17	506.85	425.96

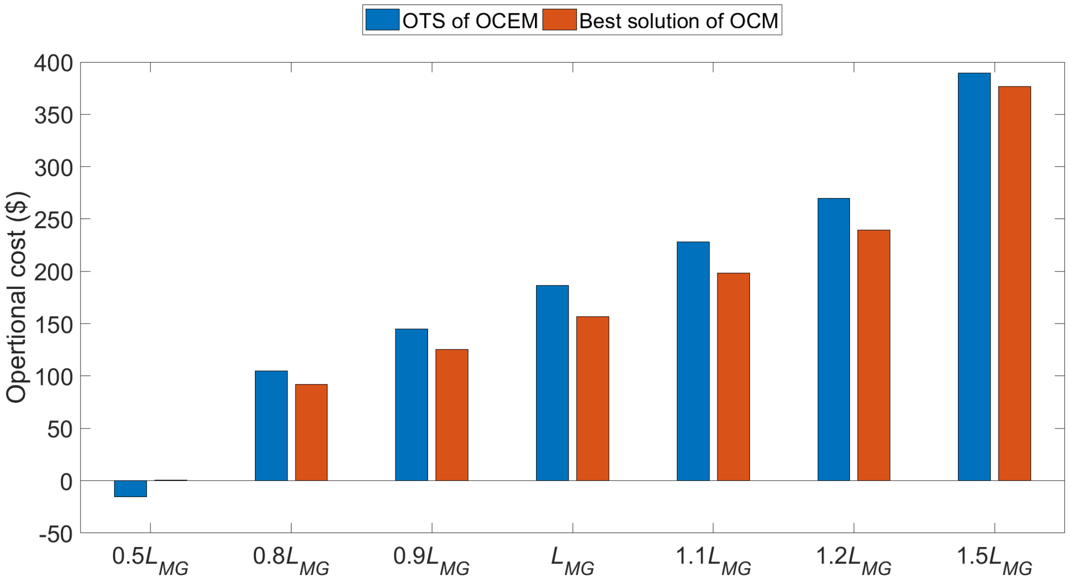
According to Table 4.10, when there is an increase in the time-of-use tariff, then the OCM problem will provide a solution that decreases the energy imported from the main grid and increases the utilisation of the micro-turbines, which will decrease the emissions. The emissions are decreased even further as there is also an increase in the energy exported to the main grid, which contributes to emissions reduction. This implies that it can be expected that the emissions of the OCM solutions will decrease when there is an increase in the time-of-use tariff and is confirmed by Figure 4.14.

In conclusion, when compared to the best solution provided by the OCM problem, the benefits of the OTS provided by the OCEM problem for various tariffs are similar to the benefits outlined in subsection 4.4.2. These benefits can be observed in Table 4.10, namely, reduction in the maximum demand from the main grid, decrease in the energy imported from the main grid, increase in the energy exported to the main grid, and increase in the utilisation of the distributed energy resources (micro-turbines in particular).

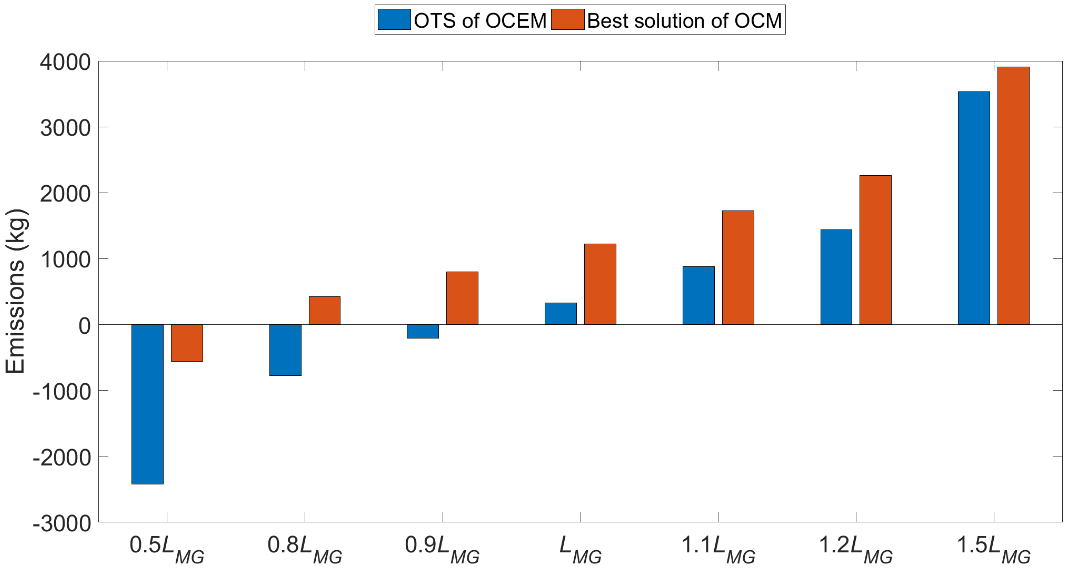
4.4.3.2 Electrical demand

The electrical demands in Figure 4.6(c) are multiplied by scaling factors to obtain a set of several electrical demands. The operational cost and emissions of the best solution provided by the OCM problem and OTS provided by the OCEM problem for these various electrical demands are shown in Figure 4.15 whereas a detailed overview of these solutions is provided by Table 4.12. This scaling approach does not change the ratios between the demands in the off-peak, standard, and peak periods. This implies that the aim of this sensitivity analysis is to evaluate the performance of the OCM and OCEM problems if there is an increase or decrease in the demand and not to evaluate the behavioral characteristics of the demand.

According to Table 4.12, if there is an increase in the electrical demand, then the OCM and OCEM problems will ensure that the electrical demand is satisfied by increasing the energy imported from the main grid, decreasing the energy exported to the main grid and in the case of the OCM problem it also increases the energy supplied by the micro-turbines. However, this implies that if there is an increase in the electrical demand, then there will also be an increase in the operational costs as there is an increase in main grid expenses, decrease in the income received from the main grid and in the case of the OCM problem there is an increase in the operational costs of the micro-turbines. This is confirmed by Figure 4.15(a). Similarly, if there is an increase in the electrical demand, then there will also be an increase in the emissions as there is an increase in the utilisation of the coal power plants and in the case of the OCM problem there is also an increase in the utilisation of the micro-turbines. This is confirmed by Figure 4.15(b).



(a) Operational cost.



(b) Emissions.

Figure 4.15. Best solution of the OCM problem versus OTS of the OCEM problem for various electrical demands.

Table 4.11. Best solution of the OCM problem versus OTS of the OCEM problem for various electrical demands.

	$0.5L_{MG}$	$0.8L_{MG}$	$0.9L_{MG}$	L_{MG}	$1.1L_{MG}$	$1.2L_{MG}$	$1.5L_{MG}$
OCM: Energy supplied by the micro-turbines (kWh)	200	1205	1466.17	1657.66	1716.54	1750	1750
OCM: Energy imported from the main grid (kWh)	1159.79	1881.68	2122.31	2367.30	2616.54	2948.36	4393.65
OCM: Energy exported to the main grid (kWh)	1865.72	1648.73	1502.57	1291.08	951.23	668.56	173.52
OCM: Maximum power flow from the main grid (kW)	185.80	280.84	312.52	340.05	370.86	407.56	501.36
OCM: Energy flow to and from the ESS (kWh)	1800.00	1800.00	1800.00	1787.65	1787.82	1800.00	1798.46
OCM: Energy shared amongst the MGs (kWh)	342.71	502.68	591.49	652.08	740.30	814.09	1124.42
OCEM: Energy supplied by the micro-turbines (kWh)	3000	2999.81	2975.64	2999.44	2999.31	2988.98	2326.96
OCEM: Energy imported from the main grid (kWh)	85.56	631.88	896.68	1124.03	1396.64	1709.38	3826.01
OCEM: Energy exported to the main grid (kWh)	3591.49	2193.73	1786.40	1389.74	1014.11	668.56	173.73
OCEM: Maximum power flow from the main grid (kW)	60.14	155.87	188.27	230.18	251.18	282.61	409.82
OCEM: Energy flow to and from the ESS (kWh)	1798.54	1800	1800	1800	1800	1800	1800
OCEM: Energy shared amongst the MGs (kWh)	410.38	420.47	427.67	484.13	483.66	567.28	689.93

Figure 4.15 indicates that the emissions of the OCM solution at $0.5L_{MG}$ as well as the emissions of the OCEM solutions at $0.5L_{MG}$, $0.8L_{MG}$ and $0.9L_{MG}$ are negative. This is because these emissions, which are calculated through (3.13), represent the net emissions of an MMG system, which refers to the emissions that are emitted subtracted by the emissions that are avoided. Emissions are avoided when electricity is exported to the main grid because that electricity can supply an electrical demand that is beyond the MMG system, which decreases the utilisation of large-scale coal-fired power plants. This implies that if the net emission is positive, then more emissions have been emitted than have been avoided whereas if the net emission is negative, then fewer emissions have been emitted than have been avoided.

In conclusion, when compared to the best solution provided by the OCM problem, the benefits of the OTS provided by the OCEM problem for various electrical demands are similar to the benefits outlined in subsection 4.4.2. These benefits can be observed in Table 4.12, namely: reduction in the maximum demand from the main grid, decrease in the energy imported from the main grid, increase in the energy exported to the main grid, and increase in the utilisation of the distributed energy resources (micro-turbines in particular).

4.4.3.3 Fuel cost

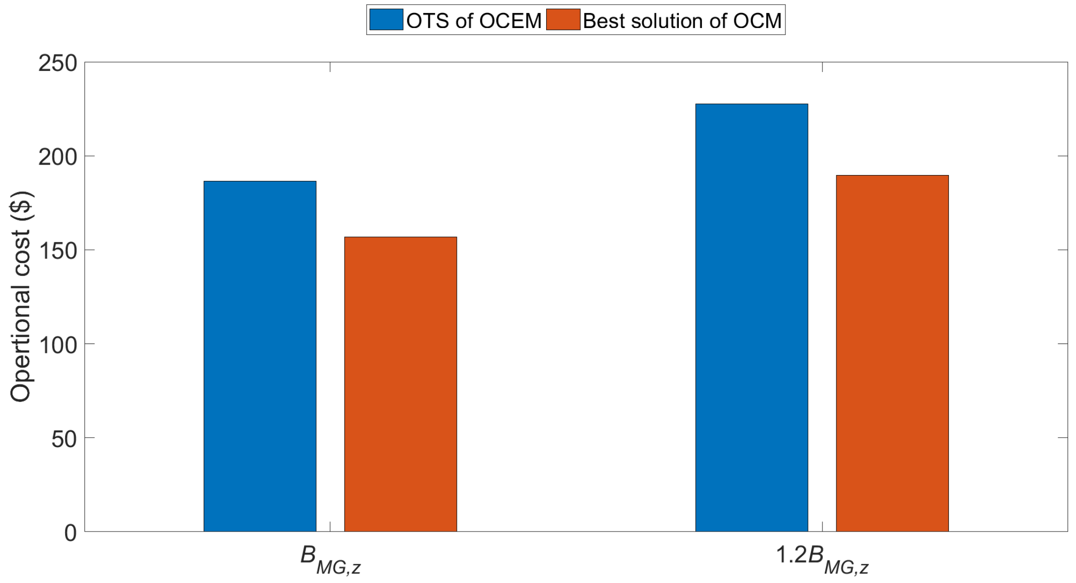
The fuel costs in Table 4.4 are multiplied by a scaling factor to obtain a new set of fuel costs. The operational cost and emissions of the best solution provided by the OCM problem and OTS provided by the OCEM problem for these fuel costs are shown in Figure 4.16 whereas a detailed overview of these solutions is provided by Table 4.12.

According to Table 4.12, if there is an increase in the fuel cost of 20%, then there is no significant change in the utilisation of the micro-turbines, energy imported from and exported to the main grid for the OCEM problem. As a result, there is no significant change in the cost of purchasing energy from the main grid as well as the income received for selling energy to the main grid; however, the operational cost of the micro-turbines increased by 18.08% (\$227.32 to \$268.42) because of the increase in the fuel cost. This implies that it can be expected that the operational cost of the MMG system will increase and is confirmed by Figure 4.16(a). On the other hand, it can be expected that there is no significant change in the emissions of the OCEM solution because there is no significant change in the utilisation of the micro-turbines, energy imported from and exported to the main grid. This is confirmed by Figure 4.16(b), which indicates that the emissions increased from 328.49 kg to 329.21 kg when there is an increase in the fuel cost of 20%.

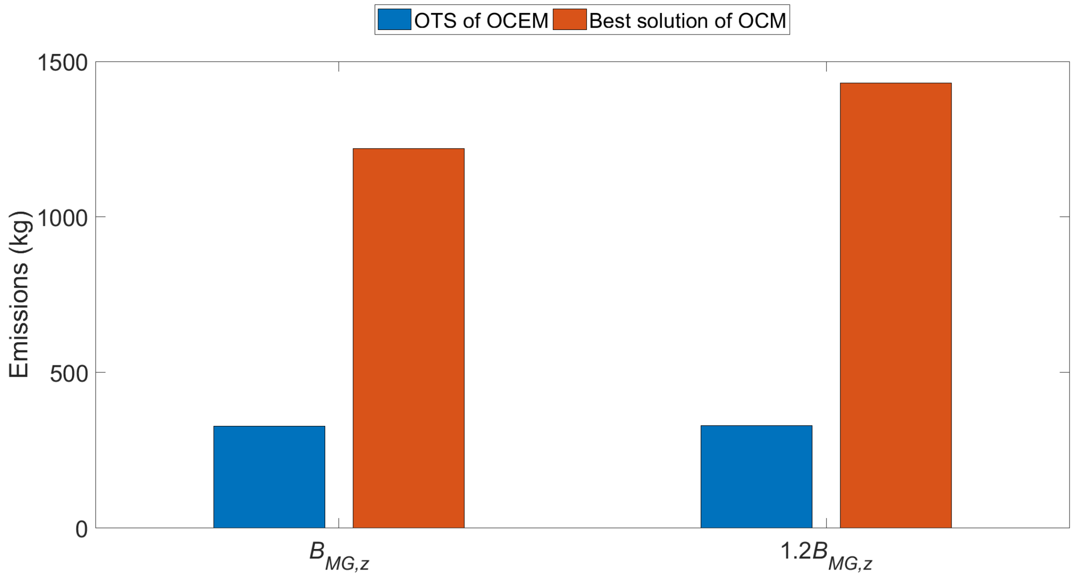
Table 4.12. Best solution of the OCM problem versus OTS of the OCEM problem for various fuel costs.

	$B_{MG,z}$	$1.2B_{MG,z}$
OCM: Energy supplied by the micro-turbines (kWh)	1657.66	1341.79
OCM: Energy imported from the main grid (kWh)	2367.30	2370.51
OCM: Energy exported to the main grid (kWh)	1291.08	978.42
OCM: Maximum power flow from the main grid (kW)	340.05	341.75
OCM: Energy flow to and from the ESS (kWh)	1787.65	1794.07
OCM: Energy shared amongst the MGs (kWh)	652.08	625.58
OCEM: Energy supplied by the micro-turbines (kWh)	2999.44	2998.54
OCEM: Energy imported from the main grid (kWh)	1124.03	1124.93
OCEM: Energy exported to the main grid (kWh)	1389.74	1389.59
OCEM: Maximum power flow from the main grid (kW)	230.18	219.22
OCEM: Energy flow to and from the ESS (kWh)	1800.00	1800.00
OCEM: Energy shared amongst the MGs (kWh)	484.13	531.37

According to Table 4.12, if there is an increase in the fuel cost of 20%, then the OCM problem will decrease the utilisation of the micro-turbines by 19.06%, which decreases the emissions by 58.34 kg; however, the OCM problem also decreases the energy exported to the main grid by 24.22%, which means that 265.36 kg of emissions that have been previously avoided are no longer being avoided. This implies that if there is an increase in the fuel cost of 20%, then the net emissions of the OCM solution will increase and is confirmed by Figure 4.16(b). On the other hand, Figure 4.16(a) indicates that there is an increase in the operational cost of the MMG system when there is an increase in the fuel cost by 20%. This is because the OCM problem decreased the energy exported to the main grid by 24.22%, which decreases the financial income of the MMG system by 19.80% (\$119.30 to \$95.67) and the operational cost of the micro-turbines increased by 5.71% (\$157.56 to \$166.56) even though their utilisation was decreased by 19.06%.



(a) Operational cost.



(b) Emissions.

Figure 4.16. Best solution of the OCM problem versus OTS of the OCEM problem for various fuel costs.

In conclusion, when compared to the best solution provided by the OCM problem, the benefits of the OTS provided by the OCEM problem for various fuel costs are similar to the benefits outlined in subsection 4.4.2. These benefits can be observed in Table 4.12, namely: reduction in the maximum demand from the main grid, decrease in the energy imported from the main grid, increase in the energy exported to the main grid, and increase in the utilisation of the distributed energy resources (micro-turbines in particular).

4.5 CHAPTER SUMMARY

This chapter assesses the effectiveness of the proposed OCEM problem by using it to solve the energy management problem of a grid-tied MMG system and by comparing its results to those of an OCM problem in [40], which was identified as the state-of-the-art energy management problem for an MMG system during the literature review. According to subsection 4.4.2, when compared to the best solution provided by the OCM problem, the OTS provided by the OCEM problem decreases the emissions by 73.07% with a 18.86% increase in the operational cost. Furthermore, in comparison to the OCM problem, the OCEM problem reduces the maximum demand from the main grid, increases utilisation of the distributed energy resources, decreases the energy imported from and increases the energy exported to the main grid. According to subsection 4.4.3, the OCEM problem provided similar benefits even if there are variations in the time-of-use tariff, electrical demands, and fuel costs. The MMG case study demonstrates the capability of the OCEM problem in designing an energy management strategy, which is cost-effective and minimises the emissions. The next chapter provides an overview of this dissertation and summarizes the benefits of the OCEM problem.

CHAPTER 5 CONCLUSION

5.1 SUMMARY

Existing energy management problems for an MMG system only minimise the operational cost. This study proposes a multi-objective OCEM problem that identifies an energy management strategy for a grid-tied MMG system, which minimises the operational cost and emissions simultaneously. This energy management strategy takes into account the power sharing among all the MGs as well as a price-based demand response programme. The benefits of the OCEM problem are demonstrated by comparing its results with those of a single-objective OCM problem reported in the literature. These results are obtained by applying both problems to the same MMG case study, which consists of three interconnected MGs and solving these two optimisation problems with a hybrid optimisation algorithm between the genetic algorithm and sequential quadratic programming in MATLAB. When compared to the best solution provided by the OCM problem, the OTS provided by the OCEM problem decreases the emissions by 73.07% with a 18.86% increase in the operational cost. The OCEM problem does provide a decision maker with the flexibility to choose the best solution according to the trade-off between the emissions and operational costs, which are competing objectives.

The OTS provided by the OCEM problem has several advantages in comparison to the best solution provided by the OCM problem, namely:

1. Increase in the utilisation of the distributed energy resources in particular, the energy generated by the micro-turbines increased by 80.94%.
2. The energy imported from and exported to the main grid decreased by 52.52% and increased by 7.64%, respectively. As a result, the net energy imported from the main grid is negative, which contributes towards emission reduction and main grid support in terms of energy generation.

3. Reduction in the maximum demand of the MMG system from the main grid as the maximum power flow from the main grid to the MMG system decreased by 32.31%.

The MMG case study demonstrates the capability of the OCEM problem in designing an energy management strategy, which is cost-effective and minimises the emissions.

5.2 FUTURE RESEARCH AND RECOMMENDATIONS

The OCEM problem identifies an energy management strategy in a centralised manner as it minimises the overall emissions and operational costs of an MMG system. This implies that the problem could identify a strategy, which minimises the overall operational cost but also increases the operational cost of certain MGs in comparison to when those MGs operate on their own. This is not a drawback as all of the MGs within the MMG system considered in this study have the same owner. However, in the case of an MMG system in which each MG has a different owner with different objectives, it is recommended that an MMG problem should be developed that minimises the operational cost and emissions in a decentralised manner. This problem will not necessarily be able to identify the optimal costs and emissions minimisation strategies, which can be identified by the OCEM problem but it can ensure that the unique objectives of each MG are satisfied.

The OCEM problem uses a day-ahead predication of the demand profiles and renewable resources to identify an energy management strategy for an MMG system. However, the identified strategy might no longer be optimal when there are unexpected fluctuations in the predictions [11]. As a result, a dispatching controller, which is beyond the scope of this study, can be employed to adjust the strategy in real-time according to the latest future predictions and current state of the system. Alternatively, the OCEM problem can be improved by ensuring that it considers the uncertainties in the predictions whilst it identifies an energy management strategy.

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