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RENEWABLE ENERGY AUTONOMOUS POLYGENERATION SMARTGRIDS OPTIMIZED WITH SOFT COMPUTING TECHNIQUES

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Ph.D. Thesis

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To all those who strive to make earth a better place to live in…

Abstract

The novel concept of autonomous polygeneration smartgrids was proposed, investigated and validated in this thesis. A microgrid topology is chosen, since it can allow distributed generation in a larger geographical area. The products of this smartgrid include power, potable water through desalination, hydrogen as fuel for transportation and space heating and cooling. Renewable energy technologies such as photovoltaics and wind turbines are the primary power producers. A reverse osmosis desalination unit equipped with energy recovery produces potable water. Hydrogen is mainly used as fuel for transportation. High efficiency heat pumps are considered for space heating and cooling. Available hardware for such systems already exists in the market and can be interconnected in such a way that allows the formation of the polygeneration microgrid. A simulation platform was created using the software packages TRNSYS, GenOpt, Matlab and TRNOPT. New routines for the simulation of the various components of the microgrid were written. For the sizing of the microgrid for specific needs and geographical location an approach based on particle swarm optimization was used. Three different Energy Management Systems (EMS) were developed and compared. The first is a simple EMS that turns on or off the fuel cell, the electrolyzer and the desalination unit. In order to allow part load operation soft computing approaches were implemented. The second EMS was based on Fuzzy Logic and the third on a combined Petri Net – Fuzzy Cognitive Maps approach. A methodology was created in order to be able to optimize at the same time the operational parameters of the EMS and the sizes of the various devices when designing a microgrid. Part load operation proved to be essential since it can decrease the sizes of the various components of the microgrid considerably. A Demand Side Management (DMS) system based on a multi-agent system was developed and validated through simulation. The DMS gives the intelligence to the microgrid to operate in occasions beyond the loads limits that were used when designing it. Without DSM the various devices would operate outside of specifications and in the end the microgrid would collapse. The DSM can protect the system in such occasions, minimize the power deficit and at the same time guaranty the maximum utilization of the available devices. Finally the

Autonomous Polygeneration Smartgrid topology was investigated economically and proved to be a profitable investment even with current prices.

Extended Abstract

At the dawn of the 21st century there are many areas of the world that are still not connected to any major electrical grid. This is not only observed in regions of developing countries but also in rural areas of countries like Canada and Russia. In these areas this is often addressed through the use of hybrid systems that usually include a combination of renewable energy technologies (like photovoltaic panels and wind turbines), a diesel generator and a battery bank. The use of such a topology has many shortcomings like the limited area that can be covered by the system, the centralized energy producers and the use of fossil fuel generators, which adds to the environmental problems of our time, while at the same time increase considerably the operation and maintenance cost of these systems. Microgrids based on distributed power generation by renewables emerge as one of the most advanced and sustainable solutions for these areas.

At the same time many regions globally face problems with the supply of potable water. In many cases, even if there is water is available, it might not be potable because of its brackishness or because of the presence of biological contaminants. Desalination systems have emerged as a solution to such situations. Reverse osmosis desalination units coupled with renewables can provide high quality water in a sustainable and environmentally friendly manner. The on-site production of fuel for transportation is a novel idea that can add to the autonomy of remote rural areas. Finally, in our days, electric appliances that present very low energy consumption are available in the market. Energy efficient fridges and freezers as well as induction cookers and LED lamps can lower considerably the energy consumption in households. Space heating and cooling needs can be covered by efficient heat pumps. Market available heat pumps have now exceeded a COP rating of 5.

The concept behind this thesis is to be able to supply a remote area with all the perquisites for survival and prosperity in a sustainable, environmentally friendly and autonomous manner. Apart from food, which can only be addressed through agriculture, the rest of the needs can be categorized under needs that can be covered by electrical appliances, availability of potable water, availability of fuel for

transportation and space heating and cooling. Renewable energy technologies are chosen as the primary energy producers in a microgrid topology that allows distributed generation over a larger geographical area. Water desalination through the use of reverse osmosis coupled with energy recovery devices is chosen as the potable water producer. Hydrogen is chosen as the transportation fuel, since it can be produced on-site with water and electricity. Finally space heating and cooling is decided to take place through high efficiency heat pumps. This microgrid has to be autonomous and has to produce multiple products.

After the concept had been formed, the technical feasibility question was addressed through a pilot autonomous polygeneration microgrid that was installed at the grounds of the Agricultural University of Athens. The market available microgrid topology "Sunny Island©" based on inverters offered by SMA was chosen as the basis of the polygeneration microgrid.

In order to make the topology operational an automatic intelligent supervisory management system ought to be designed. Also since the concept is versatile a design tool should be developed, because the needs and the renewable energy potential vary in different locations globally. A simulation platform was designed and implemented so in one hand it could be used as the development platform of the intelligent supervisory management system and in the other hand to be used as a sizing tool. The software packages TRNSYS, Matlab, GenOpt and TRNOPT were coupled together. New routines were written in order to simulate all the new components that were not available in the existing libraries. There are many approaches in how to write code that simulates a device (eg. empirical, semi-empirical, using theoretical equations etc.). Since the platform will serve as a design and sizing tool in the future, it was decided that the code should ask the minimum needed data from device manufacturers, so that locally available components can be used. The newly written routines use manufacturer available data, such as efficiency curves, in order to simulate the various components. Particle Swarm Optimization (PSO) is used in order to optimally size the various components. This was decided mainly because of the complexity of the system. It features three energy buffers (power in the battery, potable water in the potable water tank and hydrogen in the metal hydride tank) and various devices whose sizes are interrelated with each other.

The first Energy Management System (EMS) that was designed was very simple and in essence it turned on or off the electrolyzer, desalination unit and fuel cell. Part load operation of these devices was the next step to be investigated. Fuzzy Logic was used and a new EMS was designed. The parameters of the Fuzzy Logic controller were optimized intuitively. An automatic optimization of these parameters can theoretically take place, but simultaneous optimization of 150 variables proves very complex. Finally an EMS based on a combined Petri Net – Fuzzy Cognitive Maps was developed. Since the parameters of this EMS were much less (in the magnitude of 10) it was decided to further optimize them using PSO. Since the operation of the EMS and the sizing of the microgrid are affecting each other a new methodology was proposed that can at the same time optimize the parameters of the EMS and the sizes of the various components of the microgrid. The three EMSs were compared through a case study. The most important outcome of this comparison is that part load operation of the devices is very important and can decrease considerably the sizes of the various devices. The combined Petri Net – Fuzzy Cognitive Maps EMS proved to be the best of the three.

Afterwards, a Demand Side Management (DSM) system was designed. Experience has shown that most of the times, after some time, the needs change, but the people do not have the needed capital in order to expand their energy systems. In such situations the systems usually collapse often and their out of specification operation minimizes the operational life time of the devices. A DSM can protect the system in such occasions, and at the same time guaranty the maximum use of the available devices. A multi-agent approach is used for the designed DSM. The intelligent agents control the various power lines of each house. This approach can be implemented easily using low cost electronics. Its operation was investigated through simulation and the results validated it. The DSM can be used also for new systems, where there is limited capital available, and as a result the best system for the available money can be designed.

Finally an economic evaluation of the proposed topology took place. The investment in such a smartgrid was investigated both deterministically and stochastically. The deterministic investigation included the calculation of the Net Present Value and Payback Period of the system. The stochastic investigation was based on Monte Carlo Simulation method. The results showed that the investment in an autonomous polygeneration smartgrid is profitable even today, whereas it is expected that it will become even more profitable in the short future.

Summarizing, the novel topology of autonomous smart polygeneration microgrids was investigated and validated. First it was proved that the available hardware for such systems exists and can be interconnected in such a way that allows the formation of the polygeneration microgrid. Afterwards, different approaches using soft computing tools like fuzzy logic, fuzzy cognitive maps and particle swarm optimization were used in order to design an Energy Management System for the polygeneration microgrid, as well as a design and sizing tool. Then, a Demand Side Management approach was designed and validated through simulation for such systems. Finally the Autonomous Polygeneration Smartgrid topology was investigated economically and proved to be a profitable investment even with current prices.

Abstract in Greek

Στην αυγή του 21ου αιώνα υπάρχουν ακόμη πολλές περιοχές στον κόσμο χωρίς πρόσβαση σε δίκτυο ηλεκτροδότησης. Αυτό δεν παρατηρείται μόνο σε περιοχές του αναπτυσσόμενου κόσμου, αλλά και σε περιοχές της υπαίθρου χωρών όπως ο Καναδάς και η Ρωσία. Σε αυτές τις περιοχές το πρόβλημα της ηλεκτροδότησης αντιμετωπίζεται με τη χρήση υβριδικών ενεργειακών συστημάτων που συνήθως περιλαμβάνουν ένα συνδυασμό τεχνολογιών ανανεώσιμων πηγών ενέργειας (όπως φωτοβολταϊκά και ανεμογεννήτριες), ηλεκτρογεννήτριες πετρελαίου και συσσωρευτές. Η χρήση αυτής της τοπολογίας έχει πολλά μειονεκτήματα όπως η περιορισμένη περιοχή που μπορεί να καλύψει το σύστημα, η κεντρική χωροθέτηση των παραγωγών ενέργειας και η χρήση ηλεκτρογεννητριών που χρησιμοποιούν ορυκτά καύσιμα, επιβαρύνοντας το περιβάλλον και την ίδια στιγμή αυξάνουν σημαντικά το κόστος λειτουργίας και συντήρησης αυτών των συστημάτων. Τα μικροδίκτυα που βασίζονται σε κατανεμημένη παραγωγή ισχύος με τη χρήση τεχνολογιών ανανεώσιμων πηγών αναδεικνύονται στην πιο εξελιγμένη τεχνολογικά και βιώσιμη λύση για τις περιοχές αυτές.

Την ίδια στιγμή πολλές περιοχές παγκόσμια αντιμετωπίζουν πρόβλημα διαθεσιμότητας πόσιμου νερού. Σε πολλές περιπτώσεις ακόμη και όταν υπάρχει διαθέσιμο νερό, μπορεί να μην είναι πόσιμο λόγω αλατότητας ή παρουσίας βιολογικών ρυπαντών. Συστήματα αφαλάτωσης έχουν αναδειχθεί σαν ένας τρόπος αντιμετώπισης αυτού του προβλήματος. Η αφαλάτωση με τη χρήση τεχνολογίας αντίστροφης ώσμωσης συνδυασμένη με ανανεώσιμες μπορεί να παράξει νερό υψηλής ποιότητας με βιώσιμο και περιβαλλοντικά φιλικό τρόπο. Η επί τόπου παραγωγή καυσίμου για μετακινήσεις είναι μια καινοτόμος ιδέα που μπορεί να αυξήσει την ενεργειακή αυτονομία απομονωμένων περιοχών της υπαίθρου. Τέλος, στις ημέρες μας, υπάρχουν διαθέσιμες στην αγορά ηλεκτρικές συσκευές πολύ χαμηλής ηλεκτρικής κατανάλωσης. Μεγάλης ενεργειακής αποδοτικότητας ψυγεία και καταψύκτες και λαμπτήρες τεχνολογίας LED μπορούν να μειώσουν σημαντικά την ενεργειακή κατανάλωση των κατοικιών. Η ψύξη και θέρμανση χώρου μπορεί να καλυφθεί αποδοτικά με τη χρήση αντλιών θερμότητας αέρα-αέρα. Συσκευές που είναι σήμερα εμπορικά διαθέσιμες παρουσιάζουν COP μεγαλύτερο του 5.

Η γενική ιδέα αυτής της διδακτορικής διατριβής είναι η κάλυψη σε απομακρυσμένες περιοχές της υπαίθρου όλων των απαραίτητων προϋποθέσεων για διαβίωση και ευημερία με ένα βιώσιμο, φιλικό προς το περιβάλλον και αυτόνομο τρόπο. Εκτός από την τροφή που μπορεί να παραχθεί αποκλειστικά από τη γεωργία, όλες οι υπόλοιπες ανάγκες μπορούν να κατηγοριοποιηθούν σε ανάγκες που καλύπτονται μέσω ηλεκτρικών συσκευών, σε διαθεσιμότητα πόσιμου νερού, σε διαθεσιμότητα καυσίμου για μεταφορές και σε ψύξη και θέρμανση των κατοικιών. Τεχνολογίες ανανεώσιμων πηγών ενέργειας επιλέγονται σαν τους βασικούς παραγωγούς ηλεκτρικής ισχύος σε μια τοπολογία μικροδικτύου που επιτρέπει την κατανεμημένη παραγωγή σε μια μεγάλη γεωγραφικά έκταση. Η αφαλάτωση νερού μέσω αντίστροφης ώσμωσης συνδυασμένη με διατάξεις ανάκτησης ενέργειας επιλέγεται ως ο παραγωγός πόσιμου νερού. Το υδρογόνο επιλέγεται ως καύσιμο για τις μεταφορές μιας και μπορεί να παραχθεί επί τόπου με τη χρήση ηλεκτρικής ισχύος και νερού. Τέλος η θέρμανση και η ψύξη των κατοικιών αποφασίστηκε να καλυφθεί με τη χρήση υψηλής ενεργειακής αποδοτικότητας αντλιών θερμότητας αέρα-αέρα. Αυτό το μικροδίκτυο πρέπει να είναι αυτόνομο και να παράγει πολλαπλά προϊόντα.

Μετά την μορφοποίηση της ιδέας διερευνήθηκε η δυνατότητα υλοποίησης από τεχνική σκοπιά μέσω ενός πιλοτικού αυτόνομου μικροδίκτυο που εγκαταστάθηκε στους χώρους του Γεωπονικού Πανεπιστημίου Αθηνών. Η εμπορικά διαθέσιμη τοπολογία "Sunny Island©" που βασίζεται σε αναστροφείς της εταιρίας SMA επιλέχθηκε σαν την βάση του πιλοτικού μικροδικτύου.

Για να μπορέσει αυτή η τοπολογία να γίνει λειτουργική έγινε κατανοητό πως έπρεπε να αναπτυχθεί ευφυής εποπτικός διαχειριστής. Επίσης λόγω της ευελιξίας και της διαμόρφωσης με συναρτησιακά στοιχεία του μικροδικτύου έπρεπε να αναπτυχθεί ένα εργαλείο σχεδιασμού και διαστασιολόγησης, γιατί οι ανάγκες και το δυναμικό των ανανεώσιμων πηγών ενέργειας μεταβάλλεται σε διάφορες περιοχές της γης σημαντικά. Μια πλατφόρμα προσομοίωσης σχεδιάστηκε και υλοποιήθηκε με διπλή στόχευση· από τη μία να αποτελέσει την πλατφόρμα ανάπτυξης του συστήματος ευφυούς εποπτικής διαχείρισης και από την άλλη να χρησιμοποιηθεί ως εργαλείο διαστασιολόγησης των συσκευών που απαρτίζουν το μικροδίκτυο. Τα εμπορικά λογισμικά πακέτα TRNSYS, Matlab, GenOpt και TRNOPT συνδυάστηκαν σε μια ενιαία πλατφόρμα. Νέες ρουτίνες γράφηκαν με σκοπό την προσομοίωση όλων των νέων συσκευών που δεν υπήρχαν διαθέσιμες στις βιβλιοθήκες των λογισμικών πακέτων. Υπάρχουν πολλές προσεγγίσεις στο πώς να γράψεις κώδικα που προσομοιώνει μια συσκευή (πχ. χρησιμοποιώντας εμπειρικές ή ημιεμπειρικές σχέσεις, χρησιμοποιώντας θεωρητικές εξισώσεις και ισοζύγια κλπ.). Μιας και αυτή η πλατφόρμα θα αποτελέσει στο μέλλον το εργαλείο σχεδιασμού και διαστασιολόγησης τέτοιων μικροδικτύων, αποφασίστηκε ότι ο κώδικας έπρεπε να απαιτεί τα ελάχιστα δυνατά δεδομένα από τους κατασκευαστές των συσκευών, με σκοπό την εύκολη ενσωμάτωση συσκευών διαθέσιμων σε κάθε περιοχή του κόσμου. Οι καινούργιες ρουτίνες χρησιμοποιούν δεδομένα των κατασκευαστών όπως καμπύλες βαθμού απόδοσης με στόχο την προσομοίωση της λειτουργίας των διάφορων συσκευών. Η βελτιστοποίηση βασισμένη στη θεωρία σμηνών (Particle Swarm Optimization) χρησιμοποιήθηκε για την διαστασιολόγηση των διαφόρων συσκευών. Αυτή η προσέγγιση αποφασίστηκε κυρίως λόγω της μεγάλης πολυπλοκότητας του συστήματος, το οποίο περιλαμβάνει τρεις διατάξεις αποθήκευσης ενέργειας (ηλεκτρική ισχύ στο συσσωρευτή, πόσιμο νερό στη δεξαμενή αποθήκευσης του πόσιμου νερού και υδρογόνο στο δοχείο των μεταλλικών υδριδίων) και η διαστασιολόγηση της κάθε συσκευής συσχετίζεται άμεσα με τα μεγέθη των υπολοίπων.

Το πρώτο σύστημα διαχείρισης της ενέργειας που σχεδιάστηκε ήταν πολύ απλό και στην πράξη ενεργοποιούσε ή απενεργοποιούσε τη μονάδα ηλεκτρόλυσης, τη μονάδα αφαλάτωσης και την κυψέλη καυσίμου, που όλες λειτουργούσαν στο σημείο ονομαστικής λειτουργίας. Το επόμενο βήμα περιλάμβανε τη μελέτη λειτουργίας των συσκευών σε μερικό φορτίο. Χρησιμοποιήθηκε η Ασαφής Λογική (Fuzzy Logic) και ένα νέο σύστημα διαχείρισης σχεδιάστηκε. Οι παράμετροι του διαχειριστή βασισμένου στην ασαφή λογική βελτιστοποιήθηκαν διαισθητικά βάση της εμπειρίας που είχε συσσωρευτεί πάνω στην τοπολογία. Μια αυτοματοποιημένη βελτιστοποίηση των παραμέτρων αυτών μπορεί θεωρητικά να επιτευχθεί, αλλά η ταυτόχρονη βελτιστοποίηση 150 μεταβλητών είναι πολύ περίπλοκη. Τελικά σχεδιάστηκε ένα σύστημα διαχείρισης της ενέργειας βασισμένο σε μια συνδυαστική προσέγγιση δικτύων Petri και ασαφών γνωσιακών χαρτών (fuzzy cognitive maps). Μιας και οι παράμετροι λειτουργίας αυτού του συστήματος διαχείρισης ήταν σημαντικά λιγότεροι (της τάξης των 10) αποφασίστηκε να γίνει βελτιστοποίηση αυτών με τη χρήση της θεωρίας σμηνών. Επειδή όμως η λειτουργία του συστήματος διαχείρισης της ενέργειας και η διαστασιολόγηση των επί μέρους συσκευών αλληλοεπηρεάζονται μια νέα μεθοδολογία προτάθηκε και υλοποιήθηκε, που μπορεί την ίδια στιγμή να βελτιστοποιεί τις παραμέτρους λειτουργίας του συστήματος ελέγχου και να διαστασιολογεί τις διάφορες συσκευές του μικροδικτύου. Τα τρία διαφορετικά συστήματα διαχείρισης της ενέργειας συγκρίθηκαν μεταξύ τους μέσω μιας μελέτης περίπτωσης. Το σημαντικότερο αποτέλεσμα αυτής της σύγκρισης είναι ότι η λειτουργία σε μερικό φορτίο των συσκευών είναι πολύ σημαντική και μπορεί να μειώσει σημαντικά τα μεγέθη των συσκευών. Η συνδυαστική προσέγγιση των δικτύων Petri και των ασαφών γνωσιακών χαρτών αποδείχθηκε ότι είναι η βέλτιστη των τριών.

Στη συνέχεια αναπτύχθηκε ένα έξυπνο σύστημα διαχείρισης της ισχύος από την πλευρά της κατανάλωσης. Η εμπειρία έχει δείξει ότι, τις περισσότερες φορές, μετά από κάποιο χρονικό διάστημα, οι ανάγκες αλλάζουν, αλλά οι άνθρωποι δεν έχουν το απαραίτητο κεφάλαιο για να αυξήσουν την εγκατεστημένη ισχύ του ενεργειακού συστήματος. Σε αυτές τις περιπτώσεις τα συστήματα συνήθως καταρρέουν συχνά και η λειτουργία των συσκευών εκτός προδιαγραφών μειώνει σημαντικά τον λειτουργικό χρόνο ζωής τους. Ένα σύστημα διαχείρισης της ισχύος από την πλευρά της κατανάλωσης μπορεί να προστατεύσει το σύστημα σε περιπτώσεις σαν την ανωτέρω και την ίδια στιγμή να διασφαλίσει τη μέγιστη τεχνικά αποδεκτή χρήση των διαθέσιμων συσκευών. Μια πολυπρακτορική (Multi-agent) προσέγγιση χρησιμοποιήθηκε για το σχεδιασμό του συστήματος διαχείρισης ισχύος από την πλευρά της κατανάλωσης. Οι ευφυείς πράκτορες ελέγχουν τις διάφορες γραμμές ισχύος της κάθε κατοικίας και μπορούν να τις απενεργοποιούν προοδευτικά. Αυτή η προσέγγιση μπορεί να υλοποιηθεί εύκολα χρησιμοποιώντας ηλεκτρονικά μικρού κόστους. Η λειτουργία του διερευνήθηκε μέσω προσομοίωσης και τα αποτελέσματα επικύρωσαν το σχεδιασμό του. Το σύστημα διαχείρισης της ενέργειας από την πλευρά του φορτίου μπορεί να χρησιμοποιηθεί και κατά τον σχεδιασμό νέων αυτόνομων μικροδικτύων πολυπαραγωγής, όταν υπάρχει περιορισμός στο διαθέσιμο κεφάλαιο και σαν αποτέλεσμα μπορεί να σχεδιασθεί το βέλτιστο σύστημα για το διαθέσιμο αυτό κεφάλαιο.

Τέλος πραγματοποιήθηκε οικονομική αξιολόγηση της τοπολογίας. Η επένδυση σε ένα τέτοιο αυτόνομο έξυπνο μικροδίκτυο πολυπαραγωγής διερευνήθηκε τόσο ντετερμινιστικά όσο και στοχαστικά. Η ντετερμινιστική διερεύνηση περιλάμβανε τον υπολογισμό της καθαρής παρούσας αξίας και του χρόνου αποπληρωμής του συστήματος. Η στοχαστική διερεύνηση βασίστηκε στην μέθοδο προσομοίωσης Monte Carlo. Τα αποτελέσματα έδειξαν ότι η επένδυση σε ένα αυτόνομο έξυπνο μικροδίκτυο πολυπαραγωγής είναι κερδοφόρος ακόμη και σήμερα, ενώ αναμένεται να αποτελέσει μια ακόμη πιο κερδοφόρο επένδυση στο βραχυπρόθεσμο μέλλον.

Συνοψίζοντας η καινοτόμος τοπολογία των αυτόνομων έξυπνων μικροδικτύων πολυπαραγωγής διερευνήθηκε και επικυρώθηκε. Πρώτα αποδείχθηκε ότι υπάρχουν οι απαραίτητες συσκευές εμπορικά διαθέσιμες και η διασύνδεση μεταξύ τους είναι τεχνικά εφικτή. Μετά διερευνήθηκαν διαφορετικές προσεγγίσεις με τη χρήση εργαλείων υπολογιστικής νοημοσύνης όπως η ασαφής λογική, οι ασαφείς γνωσιακοί χάρτες και η βελτιστοποίηση με θεωρία σμηνών με στόχο τον σχεδιασμό ενός συστήματος διαχείρισης της ενέργειας και ενός εργαλείου σχεδιασμού και διαστασιολόγησης. Ύστερα αναπτύχθηκε ένα σύστημα διαχείρισης της ισχύος από την πλευρά της κατανάλωσης το οποίο διερευνήθηκε μέσω προσομοίωσης. Τέλος η τοπολογία αυτόνομων έξυπνων μικροδικτύων πολυπαραγωγής διερευνήθηκε οικονομικά και αποδείχθηκε ότι αποτελεί κερδοφόρο επένδυση ακόμη και με σημερινά κόστη.

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Publications

The below papers were published throughout the preparation of this PhD thesis.

Journal Publications

1. Kyriakarakos, G., A. I. Dounis, K. G. Arvanitis, , S. Rozakis, G. Papadakis (2011). "Polygeneration microgrids: A viable solution in remote areas for supplying power, potable water and hydrogen as transportation fuel." Applied Energy Volume 88, Issue 12, December 2011, Pages 4517-4526.
2. Kyriakarakos, G., A. I. Dounis, K. G. Arvanitis, G. Papadakis (2011). "A Fuzzy Logic Energy Management System for Polygeneration Microgrids." Renewable Energy Volume 41, May 2012, Pages 315-327.
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International Conference Publications

1. G. Kyriakarakos, A.I. Dounis, K.G. Arvanitis, G. Papadakis, "Comparison of three approaches for energy management in polygeneration microgrids", 6th European PV-Hybrid and Mini-Grid Conference, 2012, France *(Poster Presentation)*
2. G. Kyriakarakos, E. Mohamed, G. Papadakis, "Polygeneration Smartgrids: A Solution for the Supply of Electricity, potable Water and Hydrogen as Fuel for Transportation in Remote Areas", 5th European PV-Hybrid and Mini-Grid Conference, 2010, Spain *(Oral Presentation)*
3. G. Kyriakarakos, E. Mohamed, G. Papadakis, "A pilot polygeneration microgrid for covering the needs of remote regions in electricity, potable

water and fuel", Smartgrids & Mobility Conference, 2009, Germany *(Poster Presentation)*

4. G. Kyriakarakos, E. Mohamed, G. Papadakis, "A Pilot Microgrid that Uses Potable Water and Hydrogen Both as End-User Products and Medium to Long Term Energy Storage" 6th MedPower Conference, 2008, Greece *(Oral Presentation)*
5. G. Kyriakarakos, E. Mohamed, G. Papadakis, "Experimental operation and evaluation of a hybrid renewable energy polygeneration microgrid", RE 2008, 2008, Korea *(Oral Presentation)*
6. G. Kyriakarakos, E. Mohamed, G. Papadakis, "Experimental Operation of a hybrid renewable energy polygeneration system", AgEng2008, 2008, Greece *(Oral Presentation)*
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9. G. Kyriakarakos, E. Mohamed, G. Papadakis, "Creation Of A Software Design Model And Realization Of A Hybrid Renewable Energy Polygeneration System", Renewable Energy 2006 conference, 2006, Japan *(Oral Presentation)*
10. G. Kyriakarakos, E. Mohamed, G. Papadakis, "Renewable Energy Polygeneration Systems: A Viable Solution For The Desert Regions", Global Conference on Renewable Energy Approaches for Desert Regions, 2006, Jordan *(Oral Presentation)*

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Nomenclature

A	Slope of the linear equation of the efficiency.	-
a_g	The development coefficient of grey algorithm	-
a_i	Acknowledge signal	-
A_i	Value of FCM Concept	-
B	The Y axis intercept of the linear equation of the efficiency.	-
c	Steepness Parameter	-
CF	Cost Function	€
C_i	Concept of FCM	-
$CONS_{high}$	Consumptions high SOC set point	%
$CONS_{low}$	Consumptions low SOC set point	%
EFF_{EL}	Efficiency of the electrolyzer unit for the given time step	-
EFF_{FC}	Efficiency of the fuel cell for the given time step	-
F	Frequency of the microgrid	Hz
F	Frequency of the microgrid	Hz
FC_{high}	Fuel Cell high SOC set point	%
FC_{low}	Fuel Cell low SOC set point	%
FF	Fuzzified Frequency	-
FM	Flow Matrix of PN	-
FSOC	Fuzzified SOC	-
H_2^{MIN}	Minimum quantity of hydrogen in the metal hydride tank throughout the year	Nm^3
H_2^{TANK}	Volume of the metal hydride tank	Nm^3
H_{CONS}	Hydrogen consumed by the fuel cell	Nm^3
H_{PROD}	Hydrogen produced by the electrolyzer unit	Nm^3
lbest	Local best of the Swarm	-
LHV_{H2}	Lower Heating Value of Hydrogen	Wh/Nm^3
M	marking of the PN	-
n_p	number of particles in each generation for PSO	-
OP_{DS}	Fractional operation point of the desalination unit given by FLEMS	%
OP_{DS}	Fractional operation point of the desalination unit given by FLEMS	%
OP_{EL}	Fractional operation point of the electrolyzer unit given by FLEMS	%
OP_{FC}	Fractional operation point of the Fuel Cell given by FLEMS	%
P	Finite set of places in PN	-
P_b	Battery Penalty	€
P_{DS}	Power consumed by the desalination unit	W
$P_{DSnominal}$	Nominal power of the electrolyzer unit	W
P_{EL}	Power consumed by the electrolyzer unit	W
$P_{ELnominal}$	Nominal power of the electrolyzer unit	W
P_{FC}	Power produced by the Fuel Cell	W
$P_{FCnominal}$	Nominal power of the fuel cell	W
P_{H2}	Hydrogen Penalty	€
p_i	Place in the PN	-

P_S	Tanks Penalty	€
P_w	Water Penalty	€
SEC_{DS}	Specific Energy Consumption for the given time step	Wh/m³
SOC	State of Charge	%
SOCL	set point of SOC from which and below the fuel cell should be turned on	%
SOCM	set point of SOC from which and above one or both the consumptions should be turned on	%
T	Finite set of Transitions in PN	-
T_c	Indoor comfort temperature	^{0} C
t_i	Transition of the PN	-
T_o	Outside Temperature	^{0} C
TS	A parameter for calculating energy from power for a given time period	hours
u_g	Grey input	-
u_k	control vector of PN	-
$w_{(p,t)}$	Weight of PN	-
Water	Water in the potable water tank	m^3
w_i	Activation signal	-
W_{ij}	Weight of FCM Concept	-
W^{MIN}	Minimum quantity of water in the potable water tank throughout the year	m^3
W_{PROD}	Potable water produced by the electrolyzer unit	m^3
W^{TANK}	volume of the potable water tank	m^3

Abbreviations

AGO	Accumulated Generating Operations
ANN	Artificial Neural Networks
APS	Autonomous Polygeneration Smartgrids
CA	Control Agent
DAI	Distributed Artificial Intelligence
DSM	Demand Side Management
EMS	Energy Management System
FCM	Fuzzy Cognitive Maps
FLEMS	Fuzzy Logic Energy Management System
FLS	Fuzzy Logic System
FPEMS	Fuzzy Cognitive Maps - Petri Nets Energy Management System
GDE	Grey Differential Equation
GP	Grey Predictor
IAGO	Inverse Accumulated Generating Operations
IDSEMS	Intelligent Demand Side Energy Management System
MAS	Multi Agent System
MCS	Monte Carlo Simulation
NCF	Net Cash Flows
NPV	Net Present Value
OM	Operation and Maintenance costs
PAGE	Percepts, Actions, Goals, Environment
PEM	Proton Exchange Membrane
PMV	Predicted Mean Vote
PN	Petri Net
PSO	Particle Swarm Optimization
PV	Photovoltaics
RES	Renewable Energy Sources
SEMS	Simple Energy Management System
SOC	State Of Charge
TLFLS	Top Level management Fuzzy Logic System

1 Introduction

1.1 Preface

At the dawn of the 21st century our world faces many challenges in the continued evolution of the human species. The 20th century historically presented probably the biggest advances in all fields of science and technology. The technological revolution changed the everyday lives of humanity as nothing had before. The major aspects of this revolution are the always accelerating pace of new scientific discoveries, the vast number of inventions and the growing industrial production of the manufactured goods coupled with declining costs.

Unfortunately this process was and still is not uniform globally. It presents two axis of inequality. The first is between economically advanced countries and the developing world ones and the second between the urban and rural areas. Two centuries ago food and water were the main needs that ought to be covered in an area in order to be able to support a human community. In our days the main needs have expanded to include power, heating, cooling, fuel for transportation and communication provisions, which, finally, are all dependent on power. Fossil fuels, mainly oil and coal, were the original and still are the main energy drivers for all the above needs.

Fossil fuels and mainly oil were presented as the only viable solution for mankind's energy needs throughout the last century. When addressed critically, they present some major disadvantages. Probably the most important is their increasing cost due to the decrease in the available quantities. World renowned journals like Oil and Gas Journal and World Oil state that new oil deposits are discovered every year, when, at the same time, the deposits that can be reclaimed are increasing due to technological breakthroughs (Rifkin, 2002). This approach usually leaves the reader with the notion that there is and there will be no problem in the oil supply. It is interesting to mention here the theory that was presented by geophysicist M. Hubbert in 1956 (Hubbert, 1956). He developed a model that could theoretically predict the decline in the oil production of the USA. This point was set according to this model between 1965 and 1970. He became the ridicule of the oil world and was marginalized scientifically because of his model. History, though, proved him right since in 1970 the USA's oil production reached its peak, decrease signs were evident, USA ceased to be the first oil producing country in the world and the first oil crisis followed.

What Hubbert's theory says is that oil production begins from zero, increases and reaches its peak when half of the finally reclaimable deposits have been used. Following this point there is a constant decline following a normal distribution curve. This theory does not say that after the peak the oil is ending soon, but what it emphatically says is that it will certainly become more expensive, because of its scarcity. In addition to that many the available oil deposits (tar sands, oil sands, heavy crude oil, oil shale, oil present in big depths and oil in the Polar Regions) present higher extraction cost. According to some researchers the peak in the global oil production has already occurred in 2010, while others expect it to take place around 2040. In any case during the past years the price of a barrel of crude oil has reached its record high price of 145.91 US $ in July 2008, and is about 110 $ in November 2011.

Natural gas is also another fossil fuel of high importance. It is the most environmentally friendly fossil fuel. Still, though, it follows the same trend as oil as far as pricing is concerned. Shell oil company in some of its studies has acknowledged the possibility of natural gas shortages even as close as 2025 (Rifkin, 2002).

Apart from the increasing price, oil and generally fossil fuel usage adds to the greenhouse effect and also their deposits present a non-uniform distribution around the world. Other power production technologies include nuclear energy and renewable energy sources. The fission technology that has been around since the Second World War has proved to be unpredictable as far as accidents are concerned. Chernobyl in the 1980s and Fukusima in the 2010s are major examples of what happens if something goes wrong. On top of that, fission reactors produce toxic radioactive waste which has to be stored somewhere; a nice legacy for the generations to come. Nuclear fusion is researched in our days and presents one of humanities hopes as far as abundant and clean energy is concerned. Unfortunately many breakthroughs are needed in order to reach the point of having a nuclear fusion reactor and this is not expected to take place at least for some decades more.

Renewable Energy Sources (RES) is a group of energy sources that directly or indirectly harvest the energy of the sun. As long as the sun is shining, all these forms will continue to exist and they will be at mankind's hands for usage. RES includes:

- Solar Energy. Through Photovoltaic panels (PV) power can be produced. Through solar thermal panels, heat can be produced.

- Wind Energy. Windmills and wind turbines can harvest the power of the wind and produce mechanical work or electrical power.

- Geothermal Energy. The earth's heat can be used as is or converted to electricity.

- Biomass. Plant or animal tissues and excrements can be used for the production of heat, or the production of fuels.

- Hydro Energy. Water flow, along with waterfalls can be used in order to produce mechanical work, which can be used as is or converted to electricity.

- Sea current energy. Underwater currents can power turbines which can produce mechanical work or electricity.

- Wave Energy. The movement of waves can be harvested and mechanical work or electricity can be produced.

RES are coupled with mature technologies that can provide energy in a sustainable and environmentally friendly way.

The first power stations were centralized around big cities of the economically developed world. Through the expansion of distribution grids, the rural areas of these countries also got access to energy in all forms. Even in the developed countries of the world today there are still some remote rural areas away from the main electricity grid (e.g. Canada, Russia). In the developing world most of the population still lives in rural areas. According to the International Energy Agency's World Energy Outlook 2010 about 1.44 billion people still do not currently have access to electricity and almost all of them live in developing countries (IEA, 2010). In those countries access is limited even in urban areas.

1.2 Current Situation in rural areas

Renewable energy systems consisting of photovoltaics, wind turbines and batteries have been used extensively in remote areas for the last few decades in order to cover electricity needs (Buran, Butler et al., 2003). These systems are modular, they can be custom made to cover specific needs and require only minimal maintenance. A general problem of renewable energy systems is that there isn't always a concurrence between supply and demand. Since long term electricity storage is usually expensive - batteries are expensive, have life spans of about 5 years, and are also delicate to handle afterwards because they contain toxic elements - such systems have high energy losses in a yearly basis (Manolakos, Papadakis et al., 2004; Kaldellis, Zafirakis et al., 2010) . It has also been proposed that the use of a backup power source can increase the cost effectiveness of such systems (Zoulias, Glockner et al., 2006).

Potable water shortages are frequent in many areas of the world as well. Usually places that have scarce potable water sources also face energy supply difficulties. This happens especially on islands and remote areas. Reverse Osmosis (RO) desalination systems which are powered by photovoltaics and wind turbines have been considered in order to provide potable water. The main advantages of RO are low energy consumption and modest maintenance requirements. This approach can also be used in cases of brackish water as well (Kaldellis, Kavadias et al., 2004; Mohamed and Papadakis, 2004).

Hydrogen's applications are expanding constantly nowadays. This energy carrier can be used as a fuel for transportation (Ally and Pryor, 2007), as well as a medium to long term energy storage (Bielmann, U.F.Vogt et al., 2011). Hydrogen subsystems are also being coupled with renewable energy sources systems in recent years (Zoulias and Lymberopoulos, 2007). The typical components of a hydrogen subsystem usually include a water electrolyzer, hydrogen storage, refueling system and a fuel cell. An electrolyzer is a unit which produces hydrogen by means of electrolysis. The most common approaches in hydrogen storage for renewable energy systems include gas tanks and metal hydride tanks. The cost of the metal hydride tanks is bigger, but the advantages include the higher security against accidents (Botzung, Chaudourne et al., 2008), which is very important for autonomous systems installed in remote areas. A refueling system is present if hydrogen is going to be used as fuel for transportation as well. A fuel cell is the device which produces electricity from the stored hydrogen. With the use of a hydrogen subsystem, significant advantages arise in comparison with big battery banks in terms of energy density and long-term storage (Conte, Prosini et al., 2004). Hydrogen subsystems present considerable advantages such as low noise level, potential for high energy density storage, seasonal energy storage without energy loss over time, ability to handle power fluctuations and therefore ideal for integration with RES, potential for low and predictable O&M costs and reduced environmental impact compared to conventional energy sources (Zoulias, Glockner et al., 2006).

Microgrids are small scale power supply networks. They can work either autonomously or interconnected with a larger grid (Llaria, Curea et al., 2011; Manfren, Caputo et al., 2011). In microgrids different energy sources and energy storage devices can be distributed at any location covered by the grid. They offer higher reliability than compact systems since they can operate at lower power levels if there is a failure of one power source instead of shutting down completely. Microgrids, especially when they are used autonomously, demand intelligent management and efficient design in order to be able to meet the needs of the area they cover (Markvart, 2006). Since most of the rural areas are not expected to be interconnected with any major grid in the following years and the option to just wait for this is not a viable alternative, microgrids based on distributed power generation by renewables emerge as one of the most advanced and sustainable solutions for these areas (Thiam, 2010). These microgrids can autonomously cover the needs of these areas for the following years and when the actual interconnection with a major electricity grid occurs, they will be able to complement it for higher power quality and efficiency (Markvart, 2006; Llaria, Curea et al., 2011).

Refrigeration in most cases is addressed through the use of energy efficient electrical refrigerators that are usually powered by PVs. This approach has been used extensively for the storage of medical supplies and vaccines.

Space heating and cooling are most of the times ignored in remote rural areas, since poverty is high and they are considered to be a luxury. For heating purposes biomass is usually used. Wood and animal excrements are most often used in fire places and stoves. In most remote places of the developed world diesel burners have been used for space heating. Electricity based heating in the past had high power ratings, which led to very expensive power systems in order to support it. Nowadays though there are split type air conditioner units available in the market based on heat pumps that have a COP rating of above 5. These units are also equipped with inverters, which makes part load operation of the compressor feasible. This fact, along with the dropping prices of photovoltaic panels (prices below 0.70 €/Wp were recorded in 2011(Neidlein H-C and J., 2011)) has made it a viable alternative that should be investigated. Air conditioning units can offer both space heating and cooling.

In most cases separate systems that produce electricity (Nema, Nema et al., 2009), and separate ones for water production are used today (Mohamed and Papadakis, 2004). Cogeneration and trigeneration systems have been proposed mainly for covering the electrical power, heating and cooling needs (Chicco and Mancarella, 2009; Zhao, Akbarzadeh et al., 2009). Producing onsite fuel for transportation is a novel concept (Degiorgis, Santarelli et al., 2007) when, currently, in most cases diesel or gasoline is used for such purposes. An integrated approach in covering more needs of a remote area (power, potable water, fuel for transportation, heating and cooling) can be preferable since it offers advantages in terms of reliability and high efficiencies (Kyriakarakos, Mohamed et al., 2010).

1.3 Autonomous Polygeneration Smartgrids

This thesis presents a novel concept, autonomous polygeneration smartgrids (APS), which aims at covering the needs of a remote area in a holistic, environmentally friendly and sustainable way, along with a technical in depth investigation of its realization and application.

First of all this concept presents the autonomous aspect. No outside inputs are needed except for renewable energy sources. Through RES power can be produced locally. Then there is the microgrid aspect. This islanded low voltage AC grid can expand to cover all buildings in a remote area. The power producers can physically be located anywhere on this grid. Distributed generation is the generation of electricity from many small energy sources and offers more freedom degrees for such systems. A wind turbine can be located on top of a hill, whereas PV panels can be installed at multiple locations facing south and with no shading from trees or other structures. This microgrid is considered to be a smartgrid when it attempts to predict and intelligently respond to the behavior and actions of all producers and consumers both on the production and demand sides (Chebbo, 2007). Polygeneration is the final aspect that characterizes this concept. This topology generates multiple products. These products include power, potable water through desalination, onsite fuel production for transportation in the form of hydrogen, heating, cooling and refrigeration.

2 Microgrid Topology

2.1 Introduction

The basis of the polygeneration smartgrid is the electrical part of it upon which all other parts are built. Different approaches have been presented in literature on how to form an autonomous AC microgrid. It was decided that a market available topology should be used since that would allow focusing on the polygeneration aspect of it. The topology chosen is the Sunny Island topology patented by "SMA Solar Technology AG" (Engler, Meinhardt et al., 2004). This approach allows distributed generation on the AC bus of various technologies like PV panels, wind turbines, fuel cells, diesel gensets etc. Another important aspect of it is that other companies like "Studer Innotec SA" and "Steca" are producing inverters which can form a comparable microgrid or can even be coupled in this microgrid topology (Moix Pierre-Olivier and Claude, 2010). This topology is modular and can be expanded to a 3-phase autonomous network in excess of 500 kW, without the need for a diesel genset. It can allow distributed generation and because of its modularity, it can be expanded easily in the future, without having to discard equipment.

This topology is based on frequency control - the frequency of the microgrid is used for the control of all the connected inverters when in islanded mode. If the central inverter sees that the battery bank is getting fully charged it starts to increase the frequency of the microgrid from 50 Hz up to 52 Hz so as in the end to protect the battery from overcharging. When the inverters connected to the energy producers (pv, wind, etc.) detect a frequency higher than 50 Hz they start to decrease the power they supply the microgrid and they cut it completely when the frequency reaches 52 Hz. When there is an energy deficit in the microgrid the frequency is decreased gradually down to 49 Hz (SMA America, 2011). This way frequency in the islanded mode is an indicator of the power balance in it.

It is decided that all energy producers should give their power on the AC bus and all consumers to take their power from there as well. The DC bus is only used for the batteries of the system. This topology is presented in detail in Figure 2.1.

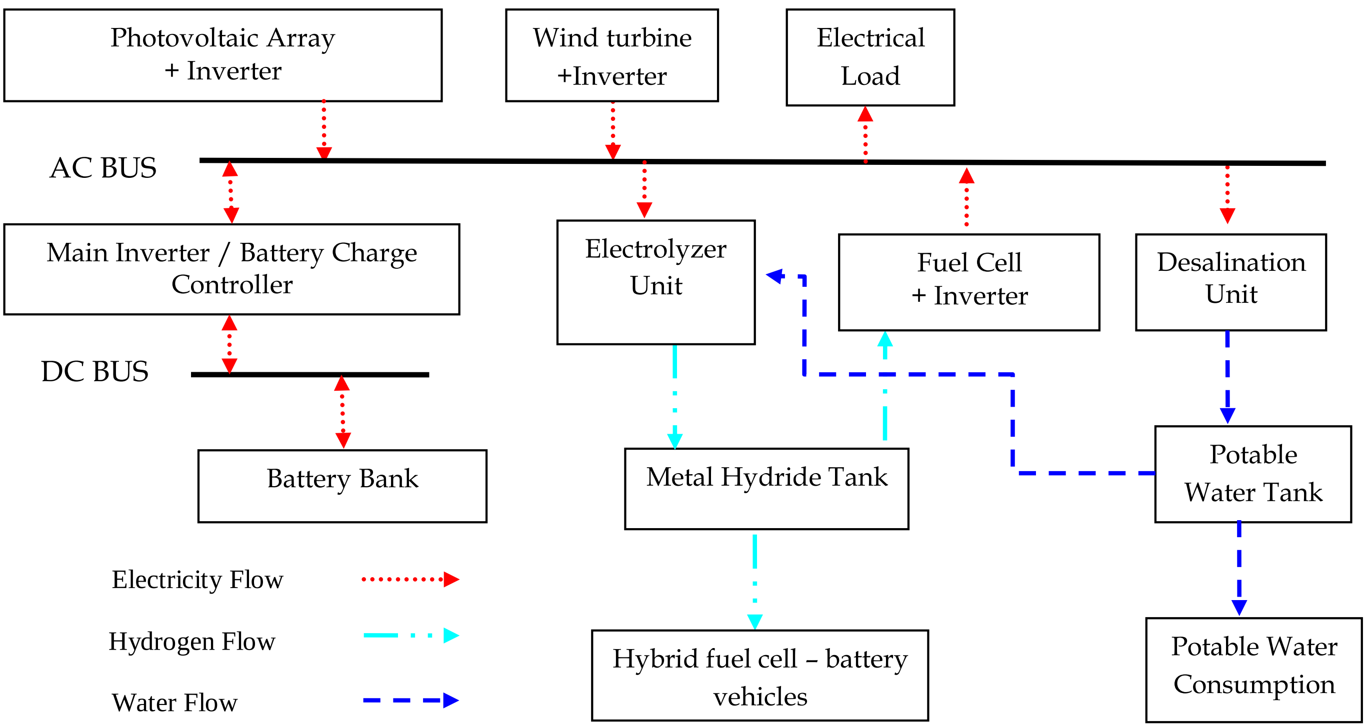


Figure 2.1 Schematic Presentation of the polygeneration microrgrid

A pilot microgrid was erected at the grounds of the Agricultural University of Athens based on the above mentioned topology. The components included:

- Photovoltaic arrays
- Wind turbine
- Desalination Unit
- Electrolyzer
- Metal Hydride Hydrogen storage tank
- Hydrogen vehicle
- Central Inverter
- Battery Bank
- Electronic Load
- Data Logging system

2.2 Experience Accumulation

Experiments were carried out and were presented in various conferences. (Kyriakarakos G. , Mohamed E. et al., 2006; Kyriakarakos G. , Mohamed E. et al., 2008; Kyriakarakos G. , Mohamed E. et al., 2008; Kyriakarakos G. , Mohamed E. et al., 2008; Kyriakarakos G. , Mohamed E. et al., 2008; Kyriakarakos G. , Mohamed E.

et al., 2009). Through them experience was accumulated concerning the operation of all the microgrid subsystems and especially for the frequency shift power control of the chosen topology.

The microgrid is based on the SMA Sunny Island topology. In this topology the frequency of the microgrid is used for the control of all the connected inverters. If the central inverter sees that the battery bank is getting fully charged it starts to increase the frequency of the microgrid from 50 Hz up to 52 Hz so as to protect the battery from overcharging (see Figure 2.2.). When the inverters connected to the energy producers (pv, wind, etc.) detect a higher frequency they start to decrease the power they give to the microgrid and they cut the supply completely when the frequency reaches 52 Hz. When there is an energy deficit in the microgrid the frequency is decreased gradually down to 49 Hz (SMA America, 2011). This is presented schematically in Figure 2.2.

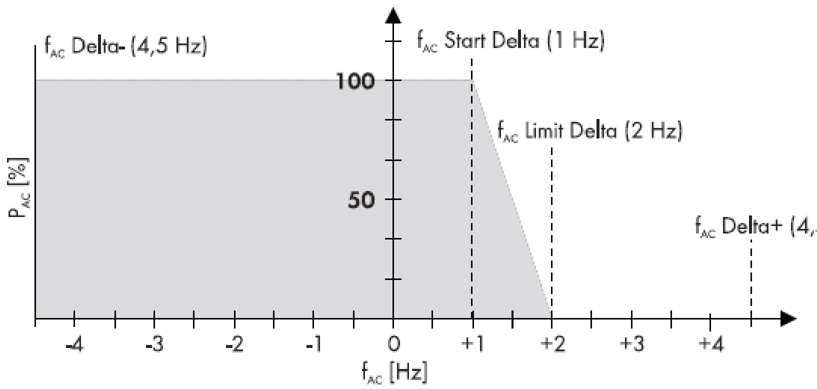


Figure 2.2 Frequency Shift Power Control (SMA America, 2011)

2.3 The need for Intelligent Supervisory Management

After all subsystems had been investigated experimentally it was time to interconnect them in order to form the polygeneration microgrid. The PV array, wind turbine and battery bank operated flawlessly since the topology used is a market available solution. The electrolyzer and desalination unit are AC powered and they can be connected to the microgrid by just plugging them to a power socket. The fuel cell interconnection to the microgrid had also been worked out. What remained to be done in order for the APM to become operational was to design and implement an intelligent supervisory management system which would activate and deactivate the various devices.

There are two aspects that need to be addressed for thoroughly investigating the autonomous polygeneration microgrid topology. A third aspect arises when the sustainability of the topology is considered when operating outside of the design specifications. In detail:

1. An automatic intelligent supervisory management system should be designed.
2. An approach to size such microgrids according to the needs of that area (electrical load, space cooling and heating load, potable water needs, hydrogen fuel needs) and the meteorological conditions throughout the year.
3. An intelligent demand side management control of the loads. Even if a system is designed optimally, it is only so for the given demand specifications. It is usual, though, that in just a couple of years for the demands to have changed, without the people owning the installation to be willing to invest to an extension of the system.

In order to theoretically investigate the microgrid and be able to design and test virtually various supervisory management approaches simulation of the system must take place. Based on the simulations a software platform ought to be developed for the optimal sizing of the various system components.

3 Simulation tools

3.1 Introduction to TRNSYS

In order to design the supervisory manager of the system a simulation approach was opted. The system would be simulated in the computer where different approaches can be implemented and tested in less time and with more detail. The main simulation software suite chosen is TRNSYS (Laboratory', 2011).

TRNSYS is a dynamic modular simulation software package for energy systems. Based on its modular structure it can solve big groups of equations that are described by the various subroutines written in FORTRAN. Each FORTRAN subroutine contains a model for a specific part of the complete system. For example Subroutine 180 includes a model that can simulate a PV array. Each subroutine has inputs, outputs and parameters. It can also include reference to a file stored on the computer that can include parameters for the ease of the end user. For example the subroutine that simulates the PV arrays has as parameters the technical data of the panels (e.g. open circuit voltage, short circuit current etc.), as inputs the meteorological data (e.g. temperature, solar irradiation etc.) and as outputs the produced power. In the input file the user connects the various subroutines which as a whole represent the system to be simulated. The TRNSYS calculations engine calls each subroutine that is referenced in the input file and tries to find a solution for each time step. The big number of possible interconnections of the subroutines gives freedom to the user. Another very important aspect of this software package is that the user is able to write his own subroutines and include them in the software package. This way since 1975 when version 1 was released many subroutines have been written that allow the simulation of thermal systems, buildings and renewable energy technologies systems.

Version 16 of TRNSYS was used. This version includes a graphical user interface for the creation of the input file. This studio application can visualize the different interconnections and simplify the input file creation process.

Subroutines present in the software package like the PV array and the batteries were used for the simulations. Apart from the available routines that were used, routines had to be developed for the hydrogen and desalination subsystems. As far as the hydrogen subsystem is concerned TRNSYS includes some types for their simulation, but these types need very detailed data that manufacturers do not give. Possession of the device in order to be tested is needed and finally these parameters are fed to the model. Since the simulation tool that is going to be developed should be able to design any polygeneration microgrid in any part of the world the use of the readily available routines was abandoned. New power based models of the various devices based on efficiency curves were written. This way it is easy to see what kind of devices are available in any part of the world and using the efficiency curves that are supplied by the manufacturer to model them. The FORTAN code of all these routines is presented in Annex I of this thesis.

3.2 Available TRNSYS subroutines used in the simulation

3.2.1 TYPE 89: Standard Weather Files - Trnsys TMY - Simulation Start is first line

This subroutine can read meteorological data in time steps that are determined by the user in the input file. It can then process the data, convert the units if needed and finally feed them to the rest subroutines. It can read TMY and TMY2 and EnergyPlus type of meteorological files. The above mentioned file types include meteorological data in a specific form. Even user formatted files can be input in this subroutine. Type 89b that reads TRNSYS TMY data is used. The outputs and parameters that are used are presented in Table 3.1.

Table 3.1 TYPE 89

Number of Parameter		Description
1	Mode	Number of rows to skip
2	L_{unit}	Number of logical unit for the external file that holds the meteorological data

Number of Output		Περιγραφή
3	I_{dn}	Direct solar radiation on horizontal surface [kJ/m²hr]
4	I	Total solar radiation irradiation on horizontal surface [kJ/m²hr]
5	T_{db}	Dry bulb temperature [° C]

6	RH	Relative Humidity
7	U_w	Wind Speed [m/s]
99	t_{d1}	Time of last data read [hr]
100	t_{d2}	Time of next data read [hr]

3.2.2 TYPE 16: RADIATION PROCESSOR

The solar irradiation data are usually read in time steps of 1 hour. This routine is responsible for the interpolation of solar irradiation data if the simulation time step is less than 1 hour. It can also calculate the solar irradiation on multiple surfaces (up to 8). Type 16g is used (the total solar irradiation and direct solar irradiation are known and the Isotropic sky model is used). Also this type is responsible for the calculation of the solar irradiation when the PV array is installed on trackers. The inputs, parameters and outputs are presented in Table 3.2.

Table 3.2 TYPE 16

Number of Parameter		**Description**
1		Model for the calculation of horizontal radiation
2		Surface tracking mode
3		Tilted surface mode
4	n	Starting day of the simulation
5	φ	Latitude [degrees]
6	S_c	Solar constant [kJ/hr.m^2
7	SHFT	Shift parameter for solar time
9	IE	Solar time switch

Number of Input		**Description**
1	I_{dn}	Total solar radiation irradiation on horizontal surface [kJ/m^{2}hr]
2	I	Direct solar radiation on horizontal surface [kJ/m^{2}hr]
3	t_{d1}	Time of last data read [hr]
4	t_{d2}	Time of next data read [hr]
5	ρ_g	Ground reflectance
6	β	Slope of surface [degrees]
7	γ	Azimuth of surface [degrees]

Number of Output		Description
4	I	Total solar radiation irradiation on horizontal surface [kJ/m^{2}hr]
5	I_b	Direct solar radiation on horizontal surface [kJ/m^{2}hr]
6	I_d	Diffuse radiation on horizontal surface [kJ/m^{2}hr]
7		Total solar radiation irradiation on surface 1 [kJ/m^{2}hr]
8		Direct solar radiation on surface 1 [kJ/m^{2}hr]
9		Diffuse radiation on surface 1 [kJ/m^{2}hr]
10	θ_1	Incidence angle [degrees]

3.2.3 TYPE 180: PHOTOVOLTAIC ARRAY

This component simulates a photovoltaic array. The Type 180c used in the simulations assumes that the PV array is connected to a Maximum Power Point Tracker and that the temperature of the PV-array is calculated based on an overall heat loss coefficient determined from performance at NOCT (Nominal Operating Cell Temperature). The parameters of the PV modules used are read from an external file. This approach simplifies the use of various PV modules by selecting their correspondent entry number in the external file where a big number of different modules can be saved. The inputs, parameters and outputs are presented in Table 3.3.

Table 3.3 TYPE 180

Number of Parameter		Description
1	MPPT	Maximum Power Point Tracker Activater
2	TCMODE	Cell temperature is calculated based on an overall heat loss coefficient
3	N_s	Number of PV cells in series per module
4	NS	Number of PV modules in series
5	NP	Number of PV modules in parallel
6	Area	Area of the module
7	$\tau\alpha_{norm}$	Reflectance-absorptance of PV-cover
8	ε_g	Energy band gap for silicon [eV]
9	R_s	Shunt resistance [Ω]
10	PV Type	Entry number in external file

11	L_{unit}	Number of logical unit for the external file that holds the PV module data

Number of Input		Description
1	Switch	Determines if the PV array is connected
2	G_T	The solar radiation flux on a surface [W/m^2]
3	T_a	Ambient Temperature [^{o} C]

Number of Output		Description
3	P	Produced Power [kJ/hr]

3.2.4 TYPE 90: WIND TURBINE

This subroutine simulates the operation of a wind turbine. It simulates the wind turbine through the use of power curve data supplied by the manufacturer. The inputs, parameters and outputs are presented in Table 3.4.

Table 3.4 TYPE 90

Number of Parameter		Description
1	Elev	Site elevation [m]
2	Ht_{data}	Data collection Height [m]
3	Ht_{hub}	Hub height [m]
4	Loss	Turbine power loss [%]
5	Num	Number of turbines
6	L_{unit}	Logical unit of file containing power curve data

Number of Input		Description
1	SWITCH	ON – OFF control switch
2	WS	Wind Speed [m/s]
3	T_a	Dry bulb temperature [^{o}C]
4	α	Site shear exponent
5	P	Barometric pressure [Pa]

Number of Output		Description
1	$P_{turbine}$	Power Output [W]

2	TH	Hours of operation
3	C_p	Power coefficient

3.2.5 TYPE 147: ELECTRICAL STORAGE BATTERY

This component simulates the operation of a battery bank. Type 147a that was used has the power as input and calculates the performance of the battery bank based on its efficiency. The inputs, parameters and outputs are presented in Table 3.5.

Table 3.5 TYPE 147

Number of Parameter		Description
1	MODE	Power model
2	Q_s	Cell Energy Capacity [Wh]
3	c_p	Cells in parallel
4	c_s	Cells in series
5	eff	Efficiency

Number of Input		Description
1	P	Power to or from battery

Number of Output		Description
2	FSOC	Fractional state of charge

3.2.6 TYPE 9: DATA READER

Data readers are used to read data from an external file. This data can be electrical load data, or hydrogen consumption profiles.

3.2.7 TYPE24:INTEGRATOR

This type can integrate quantities across time steps where needed.

3.2.8 EQUATIONS

The equations component can be used for various purposes in the simulation input file. They can be used for unit conversion but also for more complicated calculation based on basic if…then…else schemes. For example the wind turbine has a wind cut off speed. An equation can deactivate the wind turbine if the wind speed is below that limit.

3.2.9 TYPE 56: MULTIZONE BUILDING MODELING

This type can model a building separated in virtual zones and rooms. The modeling is very complex and a supplementary program is included in the TRNSYS package called TRNBuild in order to simplify the preparation of the needed files containing the characteristics of the building to be simulated. Libraries with typical materials and walls according to the German DIN 4108 and VDI 2078 codes are included in TRNBuild.

The needs in thermal energy for power and cooling of the building according to user profiles can be calculated. The airflow and lighting can be modeled. Profiles for the people occupying the building can be included, as well as the electrical devices that produce heat. Finally the Predicted Mean Vote (PMV) as far as thermal comfort is concerned can be calculated.

The parameters of this type are compiled in two external files. The first holds the building description (*.BLD) and the second the ASHRAE transfer function for walls (*.TRN). The inputs are the external weather conditions like dry bulb temperature and the solar radiation incident on all walls and roof of the building (there are calculated by TYPE 16). The possible outputs are many. The used ones are the power needed to heat the space, the power needed to cool the space, inside temperature and PMV. The file saved by TRNBuild has the extension (*.BUI).

3.3 The new subroutines that were developed

3.3.1 TYPE 171: FUEL CELL for steady operation

This subroutine can simulate a fuel cell operation for a given efficiency. This routine is used only when the fuel cell is operating only on one specific power point. . The inputs, parameters and outputs are presented in Table 3.6.

Table 3.6 TYPE 171

Number of Parameter	Description	
1	EFF	Efficiency [%]

2	TS	Time Step [h]
Number of Input		**Description**
1	PLOAD	Needed power from the fuel cell [W]
Number of Output		**Description**
1	HCONS	Hydrogen consumed [Nm^3]

3.3.2 TYPE 172:FUEL CELL for variable operation

This subroutine can simulate a fuel cell which is able to operate in different operation points. A typical PEM fuel cell is modeled according to experimental test results from literature or from the manufacturer. A linear efficiency curve for the fuel cell is considered. The mathematical model used is presented in EQ 1-3 and the inputs, parameters and outputs are presented in Table 3.7

$$P_{FC} = OP_{FC} \times P_{FCnominal} \quad \text{(EQ 1)}$$

$$EFF_{FC} = \left(A_{FC} \times OP_{FC}\right) + B_{FC} \quad \text{(EQ 2)}$$

$$H_{CONS} = \frac{P_{FC}}{EFF_{FC} \times LHV_{H_2}} \times TS \quad \text{(EQ 3)}$$

where:

P_{FC}:	Power produced by the Fuel Cell
OP_{FC}:	Fractional operation point of the Fuel Cell
$P_{FCnominal}$:	Nominal power of the fuel cell
EFF_{FC}:	Efficiency of the fuel cell for the given time step
A_{FC}:	Slope of the linear equation of the efficiency. This is determined by linear curve fitting to the performance data supplied by the manufacturer of the fuel cell.
B_{FC}:	The Y axis intercept of the linear equation of the efficiency. This is determined by linear curve fitting to the performance curve supplied by the manufacturer of the fuel cell.
H_{CONS}:	Hydrogen consumed by the fuel cell
LHV_{H2}:	Lower Heating Value of Hydrogen

TS: A parameter for calculating energy from power for a given time step. For an hourly simulation this parameter equals to 1.

Table 3.7 TYPE 172

Number of Parameter		Description
1	A_{FC}	Slope of the linear equation
2	B_{FC}	The Y axis intercept of the linear equation
3	P_{rated}	Rated power of the fuel cell
4	TS	Time Step [h]
Number of Input		**Description**
1	OP_{FC}	Fractional operation point of the Fuel Cell
Number of Output		**Description**
1	H_{CONS}	Hydrogen consumed [Nm^3]

3.3.3 TYPE 161: ELECTROLYZER for steady operation

This subroutine can simulate an electrolyzer operation for a given efficiency. This routine is used only when the electrolyzer is operating only on one specific power point. The inputs, parameter and output is presented in Table 3.8.

Table 3.8 TYPE 161

Number of Parameter		Description
1	EFF	Efficiency [%]
2	TS	Time Step [h]
Number of Input		**Description**
1	PLOAD	Power to be consumed by the electrolyzer [W]
Number of Output		**Description**
1	HPROD	Hydrogen produced [Nm^3]

3.3.4 TYPE 172: ELECTROLYZER for variable operation

This subroutine can simulate an electrolyzer which is able to operate in different operation points. A typical PEM electrolyzer is modeled according to experimental test results from literature or from the manufacturer. A linear efficiency curve for the electrolyzer is considered. The mathematical model used is presented in EQ 4-6 and the inputs, parameters and outputs are presented in Table 3.9.

$$P_{EL} = OP_{EL} \times P_{ELnominal} \quad \text{(EQ 4)}$$

$$EFF_{EL} = \left(A_{EL} \times OP_{EL}\right) + B_{EL} \quad \text{(EQ 5)}$$

$$H_{PROD} = \frac{P_{EL} \times EFF_{EL}}{LHV_{H_2}} \times TS \quad \text{(EQ 6)}$$

where:

P_{EL}:	Power consumed by the electrolyzer unit
OP_{EL}:	Fractional operation point of the electrolyzer unit given by FPEMS
$P_{ELnominal}$:	Nominal power of the electrolyzer unit
EFF_{EL}:	Efficiency of the electrolyzer unit for the given time step
A_{EL}:	Slope of the linear equation of the efficiency. This is determined by linear curve fitting to the performance data supplied by the manufacturer of the electrolyzer unit.
B_{EL}:	The Y axis intercept of the linear equation of the efficiency. This is determined by linear curve fitting to the performance data supplied by the manufacturer of the electrolyzer unit.
H_{PROD}:	Hydrogen produced by the electrolyzer unit
LHV_{H2}:	Lower Heating Value of Hydrogen
TS:	A parameter for calculating energy from power for a given time step. For an hourly simulation this parameter equals to 1.

Table 3.9 TYPE 172

Number of Parameter		**Description**
1	A_{EL}	Slope of the linear equation
2	B_{EL}	The Y axis intercept of the linear equation
3	P_{rated}	Rated power of the electrolyzer
4	TS	Time Step [h]

Number of Input		Description
1	OP_{EL}	Fractional operation point of the Electrolyzer
Number of Output		**Description**
1	H_{PROD}	Produced Hydrogen [Nm^3]

3.3.5 TYPE 165: HYDROGEN STORAGE WITH REFUELING STATION

This subroutine simulates a hydrogen storage tank and a refueling station for hydrogen vehicles. The inputs, parameters and outputs are presented in Table 3.10.

Table 3.10 TYPE 165

Number of Parameter		Description
1	H_2MAX	Capacity of the hydrogen storage [Nm^3]
2	H_2INIT	Initial hydrogen present in the tank in the beginning of the simulation [Nm^3]
Number of Input		**Description**
1	H_2IN	Hydrogen from the electrolyzer [Nm^3]
2	H_2FC	Hydrogen to the fuel cell [Nm^3]
3	H_2OUT	Hydrogen to the vehicles [Nm^3]
Number of Output		**Description**
1	H_2	Hydrogen stored in the tank [Nm^3]
2	H_2MIS	Hydrogen demand that was not able to be met [Nm^3]
3	H_2D	Hydrogen that was dumped because the tank was full [Nm^3]

3.3.6 TYPE 191: DESALINATION UNIT AND TANK for steady operation

This subroutine combines the simulation of a reverse osmosis desalination unit along with a water storage tank. The reverse osmosis desalination unit is considered to have constant specific energy consumption. The water tank can be coupled to any water demand profile. The inputs, outputs and parameters are presented in Table 3.11.

Table 3.11 TYPE 191

Number of Parameter		Description
1	WATMAX	Capacity of the water storage tank [m^3]
2	SPDS	Specific energy consumption

3	WATINIT	Initial water present in the tank in the beginning of the simulation [m^3]
Number of Input		**Description**
1	P_{desal}	Power to the desalination unit [W]
2	WATOUT	Water to the consumption [m^3]
Number of Output		**Description**
1	Wat	Water stored in the tank [m^3]
2	Watm	Water demand that was not met [m^3]
3	Watd	Water that was dumped because the tank was full [m^3]
4	Wprod	Water produced [m^3]

3.3.7 TYPE 192: DESALINATION UNIT AND TANK for variable operation

This subroutine can simulate a reverse osmosis desalination unit which is able to operate in different operation points. Along with a water tank. A typical desalination unit is modeled according to experimental test results from literature or from the manufacturer. A linear efficiency curve for the desalination unit is considered. The mathematical model is presented in EQ 7-9 and the inputs, outputs and parameters in Table 3.12.

$$P_{DS} = OP_{DS} \times P_{DSnominal} \quad \text{(EQ 7)}$$

$$SEC_{DS} = \left(A_{DS} \times OP_{DS}\right) + B_{DS} \quad \text{(EQ 8)}$$

$$W_{PROD} = \frac{P_{DS}}{SEC_{DS}} \times TS \quad \text{(EQ 9)}$$

where:

P_{DS}: Power consumed by the desalination unit

OP_{DS}: Fractional operation point of the desalination unit given by FPEMS

$P_{DSnominal}$: Nominal power of the electrolyzer unit

SEC_{DS}: Specific Energy Consumption for the given time step

A_{DS}: Slope of the linear equation of the specific energy consumption. This is determined by linear curve fitting to the performance data supplied by the manufacturer of the electrolyzer unit.

B_{DS}:	The Y axis intercept of the linear equation of the specific energy consumption. This is determined by linear curve fitting to the performance data supplied by the manufacturer of the electrolyzer unit.
W_{PROD}:	Potable water produced by the electrolyzer unit
TS:	A parameter for calculating energy from power for a given time step. For an hourly simulation this parameter equals to 1.

Table 3.12 TYPE 192

Number of Parameter		Description
1	A_{DS}	Capacity of the water storage tank [m^3]
2	B_{DS}	Specific energy consumption
3	P_r	Rated power of the desalination unit [W]
4	TS	Time step [h]
Number of Input		**Description**
1	OP_{DS}	Fractional operation point
Number of Output		**Description**
1	Wat	Water stored in the tank [m^3]
2	Watm	Water demand that was not met [m^3]
3	Watd	Water that was dumped because the tank was full [m^3]
4	Wprod	Water produced [m^3]
5	Pdesal	Power consumed by the desalination unit [W]
6	SEC_{DS}	Specific Power of the desalination unit [W/m^3]

3.3.8 TYPE 198: AC BUS

This subroutine simulates the ac bus of the microgrid. It simulates the microgrid as a balance between production and consumption of electrical power. It also simulates the frequency of the microgrid which is used for frequency shift power control. The inputs, parameters and outputs are presented in Table 3.13.

Table 3.13 TYPE 198

Number of Parameter		Description
1	BL	Base Load [W]
Number of Input		**Description**

1	P_{LOAD}	Fractional operation point
2	P_{PV}	Power of the PV array [W]
3	P_{WIND}	Power of the wind turbine [W]
4	P_{FC}	Power of the fuel cell [W]
5	P_{EL}	Power of the electrolyzer [W]
6	P_{DS}	Power of the desalination unit [W]
7	P_{AUX}	Power of an auxiliary power source [W]
Number of Output		**Description**
1	P_{BAT}	Power to or from the battery bank [W]

3.3.9 TYPE 169: NET PRESENT COST CALCULATION

This subroutine calculates the Net Present Cost (NPC) of the autonomous polygeneration microgrid for a period of 20 years. The inputs, parameters and output are presented in Table 3.14.

Table 3.14 TYPE 169

Number of Parameter		**Description**
1	I	Interest rate
2	C_{PV}	Cost of a single PV panel [€]
3	C_{WT}	Cost of the wind turbine [€]
4	C_{FC}	Cost of fuel cell per each W [€]
5	C_{EL}	Cost of electrolyzer per each W [€]
6	C_{HT}	Cost of hydrogen tank per Nm^3 [€]
7	C_{BT}	Cost of 2V battery per each Wh [€]
8	C_{DS}	Cost of desalination unit per each W [€]
9	C_{PWT}	Cost of potable water tank per 1 m^3 [€]
10	C_{OM}	Yearly Operation and Maintenance cost [€]
11	C_{INST}	Installation cost [€]
Number of Input		**Description**
1	MS	Number of PV modules in series
2	MP	Number of parallel PV series
3	WT	Number of wind turbines used
4	P_{FC}	Rated Power of the fuel cell [W]
5	P_{EL}	Rated Power of the electrolyzer [W]
6	V_{H2}	Volume of hydrogen tank [Nm^3]
7	QS	Energy capacity of each 2 V battery [Wh]
8	P_{DS}	Power of the desalination unit [W]
9	V_{WAT}	Volume of the water tank [m^3]

Number of Output		**Description**
1	NPC	Net Present Cost [€]

4 Soft Computing tools

4.1 Introduction to Artificial Intelligence

According to Encyclopedia Britannica Artificial Intelligence (AI) can be described as "the ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings". Soft Computing is a subset of AI. It focuses on understanding and replicating intelligence found in nature, in a computer. Through this approach, complex problems that would otherwise be very difficult or impossible to solve are addressed. Soft Computing includes Neural Networks, Fuzzy Logic Systems, Evolutionary Computation, Swarm Intelligence, and Chaos theory.

Because of the complexity of the autonomous polygeneration smartgrid concept, soft computing approaches can address the issues raised in Paragraph **Error! Reference source not found.**.

4.2 Sizing of the various components

4.2.1 Sizing through optimization

Various approaches exist in literature and are implemented in various software packages that aim to design and size renewable energy systems. One approach is the manual trial and error method. For simple systems that the variables to be optimized are 2 or 3 (eg. a system with PV panels and a battery bank) this approach can give good results. In the proposed polygeneration microgrid topology though the variables to be optimized are considerably more:

- Number of installed PV panels
- Number and rating of the Wind Turbines
- Energy capacity of the battery bank
- Rated Power of the Fuel Cell
- Rated Power of the Electrolyzer unit
- Hydrogen storage capacity
- Rated power of the desalination unit
- Potable water tank storage capacity

Since all the above parameters interact with each other a manual trial and error approach cannot be used. Another common approach used is the direct comparison through an objective function of all possible parameter combinations. The objective function usually takes the form of a monetary cost function namely the net present cost for each system. The systems that fulfill all the technical constraints are compared and the one with the minimum cost is chosen. The software package HOMER (ENERGY, 2011) is an example of this approach. TRNSYS yearly simulations when not simulating a building usually take 1-2 seconds (best case scenario). The possible parameter combinations if we decide on just 8 possible discrete values for each parameter can go up to 8^8 combinations. It is evident that the time needed would be more than half a year, which is, of course, impractical.

This optimization problem is multidimensional and non-convex and, therefore, nonlinear and multimodal. Consequently it is difficult or impossible to solve analytically or through numerical analysis. In this context, several classical approaches (e.g. Benders' Decomposition (Kaufman and Broeckx, 1978)) and computational intelligence algorithms (e.g. Particle Swarm Optimization (Eberhart and Kennedy J., 1995), Genetic Algorithms (Said, 2005)) have been developed. As far as classical approaches are concerned specific problems arise:

- Most of the classical optimization techniques need derivative information of the objective function to determine the search direction (Hazra and Sihha, 2008).
- Using the conventional methods (eg. analytical solution or numerical analysis), the whole problem is usually divided to sub-problems and various methods are utilized for solving each sub-problem. This adds further complexity.
- An improper selection of the initial condition of the algorithm may cause a convergence problem when applying conventional optimization techniques (Yorino, El-Araby et al., 2002).
- The size and non-convexity of the problem, which depend on the system parameters, are critical issues that may cause convergence problems in

classical optimization algorithms like the Bender's Decomposition algorithm (Valle, Harley et al., 2009).

When the problem is complex multi-dimensional, non-convex and non-differentiable then modern techniques based on computational intelligence such as Particle Swarm Optimization (PSO), Genetic Algorithm, Simulated Annealing, Tabu Search and Ant Colony Optimization are used to solve multidimensional optimization problems (Hazra and Sihha, 2008). The PSO is an efficient global optimizer for continuous and discrete variable problems, easily implemented, with very little parameters to fine-tune, insensitive to scaling of design variables, derivative free, very efficient global search algorithm and can accommodate constraints by using a penalty method. PSO can handle the whole problem easily and naturally and it is easy to apply to various problems compared with the conventional methods (Yamin, 2006). One main disadvantage of the computational intelligence algorithms is that they normally take extensive computing time compared with the conventional optimization methods (Yamin, 2006). Another disadvantage of PSO is the great sensitivity to parameter settings, a small change in parameters may result in a proportionally large effect on the result (Lovberg and Krink, 2002). Fortunately, different kind of settings have been tested thoroughly and the best ones can be used to overcome the above mentioned disadvantage(Papageorgiou, Parsopoulos et al., 2005).

The PSO algorithm has been investigated with good results as an optimization method for energy systems (Lee, Chen et al., 2009; Avril, Arnaud et al., 2010; Kornelakis, 2010; El-Zonkoly, 2011). Boonbumroong et al (Boonbumroong, Pratinthong et al., 2011) investigated the optimization of AC-bus coupled autonomous hybrid power systems, using different approaches and concluded that the PSO algorithm can yield the best results.

4.2.2 Software implementation of the PSO algorithm

GenOpt is an optimization program that can minimize a cost function that is evaluated by an external simulation program. It has been successfully coupled with TRNSYS. Its development has taken place for optimization problems where the cost function is computationally expensive and its derivatives are not available or may not even exist. It can optimize continuous variables, discrete variables and combinations of both discrete and continuous (California, 2011).

A PSO algorithm is included in GenOpt. PSO is a stochastic optimization technique modeled after the social behavior of members of bird flocking or fish schools and swarming in general (Eberhart and Kennedy J., 1995). PSO algorithms use a set of potential solutions for the optimization procedure. Each such solution is called particle and the set in a given iteration step is called a population. After the user has defined the search space, the initialization of the first population takes place using a random number generator in order to accomplish uniform spreading of the particles in the defined search space. If k is the generation number and n_p is the number of particles in each generation, the position ($x_i(k)$) and velocity ($u_i(k)$) of the i-th particle in the next generation is given by equations 10 and 11 (California, 2011):

$$u_i(k+1) = u_i(k) + c_1\rho_1(k)\left(p_{l,i}(k) - x_i(k)\right) + c_2\rho_2(k)(p_{g,i}(k) - x_i(k) \quad \text{(EQ 10)}$$

$$x_i(k+1) = x_i(k) + u_i(k+1) \qquad \text{(EQ 11)}$$

Where: $p_{l,i}(k)$ is the location for the i-th particle that yields the lowest cost over all generations

$p_{g,,i}(k)$ is the location of the best particle of all generations

c_1 is the cognitive acceleration constant

c_2 is the social acceleration constant

ρ_1 (k) and ρ_2(k) are uniformly distributed random numbers between 0 and 1.

The variables to be optimized in the polygeneration microgrid are discrete, due to the fact that the microgrid uses market available components which come at standardized sizes by the manufacturers. A binary version of the PSO algorithm proposed by Kennedy and Eberhard (Kennedy and Eberhart, 1997) can used for the optimization of discrete variables. In this algorithm the discrete independent variables are encoded in a string of binary numbers. For some $i \in \{1, \dots, n_d\}$ let x_i be the component of a discrete independent variable, let $\psi_i \in \{0,1\}^{m_i}$ be the binary representation of x_i obtained using Gray encoding (California, 2011), and let $\pi_{l,i}$ and

$\pi_{g,i}$ be the binary representations of $p_{l,i}$ and $p_{g,i}$. For $i \in \{1, \dots, n\}$ and $j \in \{1, \dots, m_i\}$, $\psi_i^j(0) \in \{0,1\}$ is initialized. For each generation (California, 2011):

$$\hat{u}_i^j(k+1) = u_i^j(k) + c_1\rho_1(k)\left(\pi_{l,i}^j(k) - \psi_i^j(k)\right) + c_2\rho_2(k)(\pi_{g,i}^j(k) - \psi_i^j(k))) \text{ (EQ 12)}$$

$$u_i^j(k+1) = \text{sign}\left(\hat{u}_i^j(k+1)\right)\min\{\left|\hat{u}_i^j(k+1)\right|, u_{max}\} \text{ (EQ 13)}$$

$$\psi_i^j(k+1) = \begin{cases} 0, \text{if } \rho_{i,j}(k) \geq s\left(u_i^j(k+1)\right) \\ 1, \text{otherwise} \end{cases} \text{ (EQ 14)}$$

Where: $s(u) \triangleq \frac{1}{1+e^{-u}}$

In order to couple GenOpt with TRNSYS an interface has been developed called TRNOPT (Specialists, 2011). TRNOPT streams the data from TRNSYS to GenOpt and vice versa without any interaction from the user. This structure is presented in Figure 4.1.

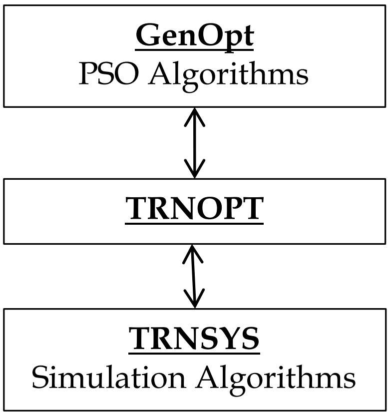


Figure 4.1 Software structure

4.3 Energy Management System design

4.3.1 Energy Management in microgrids

As was discussed in paragraph 2.3 the heart of the polygeneration microgrid lies in the Energy Management System (EMS). Without it the topology cannot operate. The first approach pursued was a simple ON/OFF EMS. Its only decisions would be to turn on or off the fuel cell, the electrolyzer and the desalination unit. Even though this simple approach could make the APM operational it is far from optimal, since it cannot allow the fuel cell, electrolyzer and desalination unit to operate in part load.

It was evident that a more sophisticated approach ought to be investigated in order for the devices to be able to operate in part load, which allows better overall management of the available energy. It is known from literature that the fuel cell (Yilanci, Dincer et al., 2008), electrolyzer (Barbir, 2005) and desalination unit (Mohamed and Papadakis, 2004) present higher efficiencies when operating in part load. Many approaches have been used in the past for the design and implementation of energy management approaches. Vosen and Keller have proposed a neural networks approach (Vosen and Keller, 1999). The main disadvantage of such an approach is the data needed for the training of the neural network. PID control has proved to be inadequate if it is not coupled with a self-tuning controller for the adjustment of its gains (Li, Song et al., 2008) or with a hybrid Fuzzy-PID controller (Paris, Eynard et al., 2011). Fuzzy logic control has been proposed and tested in the last years for renewable energy systems since linguistic rules can simplify the control of complex systems (Bilodeau and Agbossou, 2006). Fuzzy Cognitive Maps (FCMs) are able to deal with the management of systems and processes which are based on human reasoning process (Stylios and Groumpos, 1998; Beena and Ganguli, 2011) and have been proposed to be used as a supervisor in complex control systems (Stylios and Groumpos, 1998; Karlis, Kottas et al., 2007). Petri Nets (PN) are useful for the study of discrete event systems (Cassandras and Lafortune, 2008). One of the most important approaches concerns the supervisory strategy (Cassandras and Lafortune, 2008). PNs have been proposed in renewable energy systems for energy management and specifically for choosing different operating modes of the system (Lu, Fakham et al., 2010).

Based on the state of the art it was decided to pursue two different computational intelligence approaches that seem most promising. The first one is based on Fuzzy Logic and the second one is based on a combined FCM and PN approach.

4.3.2 Fuzzy Logic

Most of the books written for fuzzy logic begin with an example in order to describe the meaning of fuzziness. One of the most common ones is the example of car parallel parking. The most common description given to parallel parking in direct commands would be: Drive your car parallel to the car parked in front of the space you want to park. Drive slowly backwards and turn the steering wheel so that the end of your car starts to move towards the pavement. Before your tire reaches the pavement turn the wheel in the opposite direction and continue moving backwards until your car is parked. This description of how you park a car is a series of fuzzy operations. If crisp logic was to be used very analytical instructions would be needed when giving instructions to a robot; move your car parallel to the parked car leaving a distance of 50 cm between you and move forward for 5 meters, stop the car and put the reverse gear and so on.

In everyday life there are more examples in which crisp logic cannot address the situation. If you ask some people when the weekend starts possibly you will get a variety of answers. Others would say the weekend is Saturday and Sunday, others that the weekend starts in the afternoon of Friday. If crisp logic was to be used, the question if Friday is part of the weekend would have only two possible answers, yes or no. In reality though, the answer lies somewhere between yes and no – Friday for the most part is part of the weekend.

Even from the times of classical Greece paradoxes were put forward in order to question crisp logic. One of the most famous ones is the question of how many individual grains of sand you have to remove from a sand pile before it isn't a pile any more. In the modern world fuzzy logic was invented by Lotfi Zadeh in the 60s as a form of modeling the uncertainty of natural language. In the present day the uses of fuzzy logic have been numerous, from process control to decision making and economics.

According to McNeill and Thro (McNeill and Thro, 1994) there are five type of systems that are benefited or even need fuzziness:

- Very complex systems that their modeling is either difficult or impossible

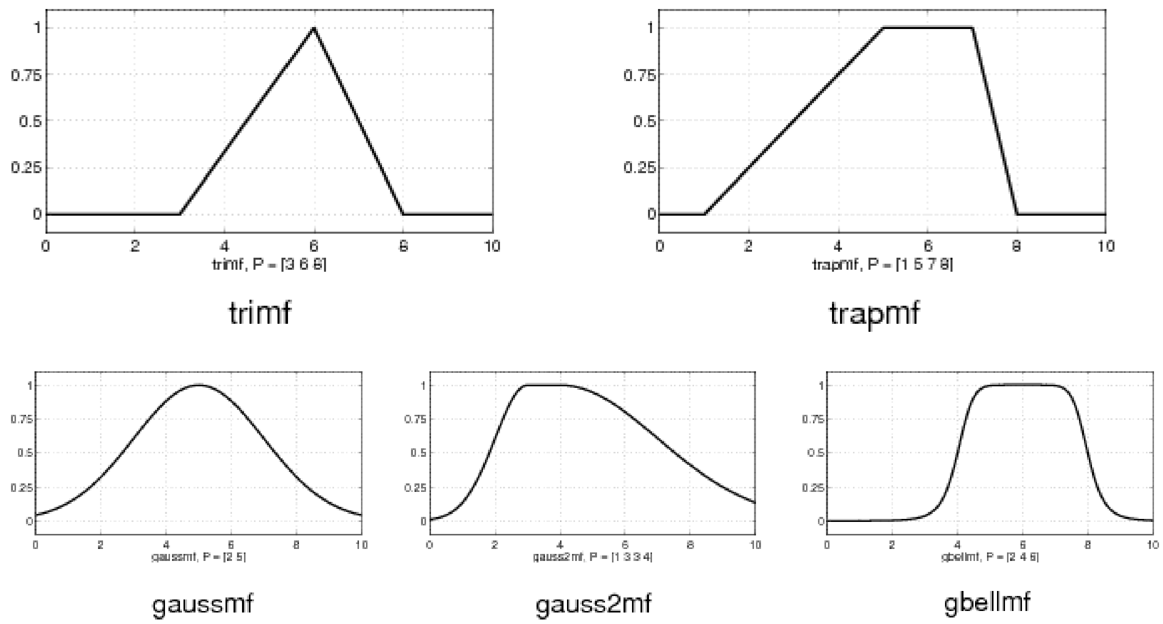
- Systems that are controlled by experts
- Systems that feature complex and continuous inputs and outputs
- Systems were human observation is treated as input or rules are based on it
- Naturally vague systems that are usually found in social sciences.

❖ Fuzzy Sets vs. Crisp Sets

A fuzzy set is a set without clearly defined boundaries, as in the previous example of what constitutes the weekend. A crisp set might be the set of “the days of the week”. Monday for example belongs to the crisp set “the days of the week”. June does not belong to the crisp set “days of the week”. For the fuzzy set “weekend” the question if Friday is a part of the weekend becomes to what degree is Friday part of the weekend.

❖ Membership Functions

The curves that define how each member is mapped to the membership value between 0 and 1 is called the membership function. The membership functions can be from simple ones, like the triangular and the trapezoid function to much complicated ones like functions built on the Gaussian distribution curve, the sigmoid curve, polynomial curves and their combinations. In Figure 4.2 all the membership functions available to be used in the fuzzy logic toolkit of Matlab software package are presented.



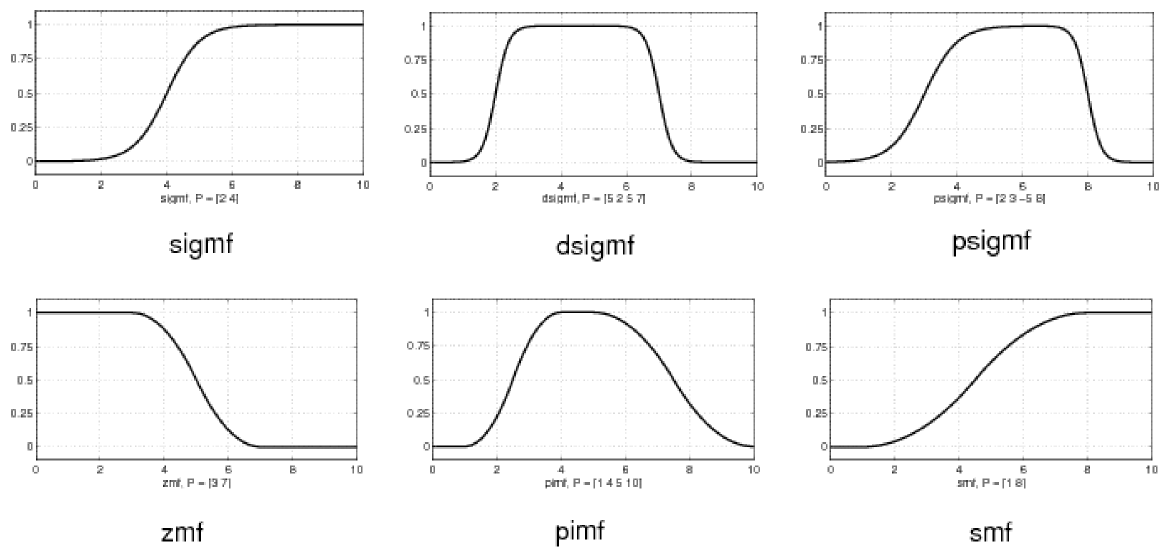


Figure 4.2 Membership functions available in Matlab (MathWorks, 2011)

❖ Logical Operations

Three fuzzy set operations exist, union (AND), intersection (OR) and implication (NOT). These logical operations are presented graphically in Figure 4.3. The figure is taken from the tutorial of the fuzzy logic toolkit of Matlab (MathWorks, 2011).

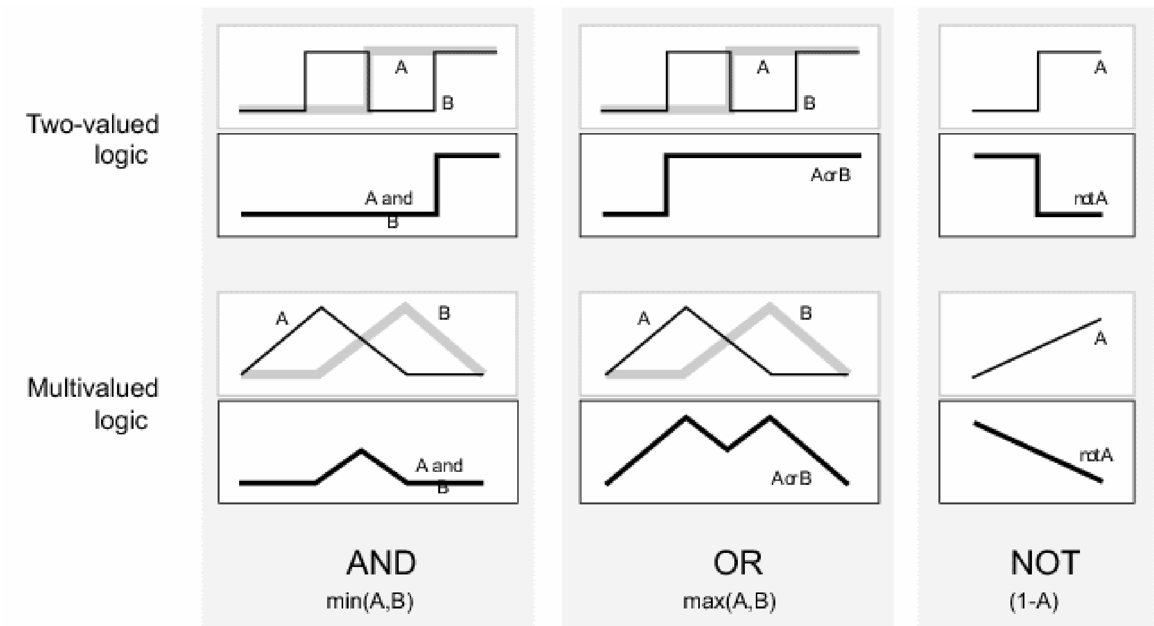


Figure 4.3 Fuzzy sets logical operations (MathWorks, 2011)

❖ Fuzzy Inference Systems

Rules of inference are rules from which you can derive truths from proven truths (McNeill and Thro, 1994). These rules are represented by if – then statements. Each such rule can have a varying weight from 0 to 1 in comparison with the rest of the rules. The most common inference process is Mamdani's fuzzy inference method. This process is based on 5 steps (MathWorks, 2011):

1. Fuzzification of the inputs
2. Application of fuzzy operators
3. Application of the if…then rules
4. Aggregation of all outputs
5. Defuzzification

The first three steps have been discussed. Aggregation of outputs can happen in various ways. The most common ones are to sum the various outputs, use the maximum output, or use a probabilistic OR operation to the output.

Defuzzification is the process by which you start from a fuzzy set and you end with a single crisp number. There are many defuzzification functions available with the most common being the centroid, the bisector, the average of the maximum value of the output set, the largest of maximum, and the smallest of maximum.

Another inference process was proposed by Takagi, Sugeno and Kang and was named after them. The main difference from the Mamdami method is that the output membership functions used are either linear or constant. The Mamdami method is intuitive, well suited to human input and already has widespread acceptance (MathWorks, 2011). On the other hand the Takagi-Sugeno-Kang can work better with linear approaches like PID control, is easier to optimize, has continuity of the output surface, it can be well suited to mathematical analysis and is computationally more efficient (MathWorks, 2011).

4.3.3 Fuzzy Cognitive Maps

FCMs are graphs which represent cause and effect relationships and are used for computational inference processing (Papageorgiou, Parsopoulos et al., 2005). Systems can be symbolically represented through FCMs. Concepts are used to present different aspects of he modeled system such as inputs, outputs, rules or intermediate states.

$$C_i,\ i=1,\ldots,N$$

where N is the total number of nodes.

The value of each concept is fuzzified in the space $[0,1]$.

$$A_i \in [0,1], i=1,\ldots,N$$

These node-concepts are interconnected with arcs which have different weights in order to express their relations. One FCM is depicted in Figure 4.4. In order to give values to the weights human knowledge and experience is used. The weights are:

$$W_{i,j} \in [-1,1],\ i=1,\ldots,N \text{ and } j=1,\ldots,N$$

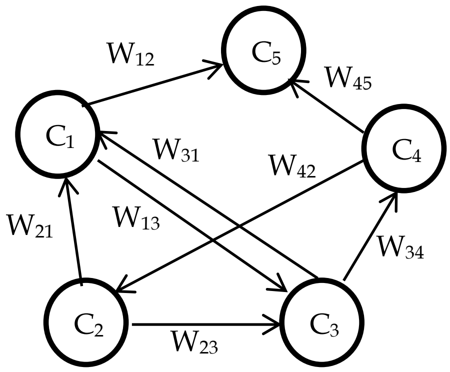


Figure 4.4 A Fuzzy Cognitive Map

When the weight expresses positive causality the weight is positive, when the weight expresses negative causality it is negative and zero declares no relation between the concepts. The weights can be presented in a matrix as below:

$$W_{i,j} = \begin{pmatrix} W_{11} & W_{12} & W_{13} & W_{14} & W_{15} \\ W_{21} & W_{22} & W_{23} & W_{24} & W_{25} \\ W_{31} & W_{32} & W_{33} & W_{34} & W_{35} \\ W_{41} & W_{42} & W_{43} & W_{44} & W_{45} \\ W_{51} & W_{52} & W_{53} & W_{54} & W_{55} \end{pmatrix}$$

This matrix can be simplified by substituting the weights of the Concepts which present no relation with zeros.

$$W_{i,j} = \begin{pmatrix} 0 & W_{12} & W_{13} & 0 & 0 \\ W_{21} & 0 & W_{23} & 0 & 0 \\ W_{31} & 0 & 0 & 0 & 0 \\ 0 & W_{42} & 0 & 0 & W_{45} \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

According to Kosko (Kosko, 1996) the values of the concepts are influenced by the rest concepts according to EQ 15. The FCM reaches a converged state after a number of iterations.

$$A_i(k+1)=f\left(A_i(k)+\sum_{\substack{j=1 \\ j\neq i}}^{n} W_{ji}A_j(k) \right) \quad \text{(EQ 15)}$$

where:

k is the iteration counter.

Function f is the activation function. Four functions have been proposed: the sigmoid function, the hyperbolic tangent function, the step function and the threshold linear function (Bueno and Salmeron, 2009).

- The sigmoid function is presented in EQ 16 where $c \in (0,+\infty)$ is a steepness parameter. For a small c value (eg. c=1) it approximates a linear function and for large values (c=10) it approximates a discrete function (Bueno and Salmeron, 2009).

$$f(x) = \frac{1}{1+e^{-cx}} \quad \text{(EQ 16)}$$

- The hyperbolic tangent function is presented in EQ 17. It maps its output in the range [-1,1] for a c value close to 5 (Bueno and Salmeron, 2009).

$$f(x) = \frac{e^{cx}-e^{-cx}}{e^{cx}+e^{-cx}} \quad \text{(EQ 17)}$$

- The step function is presented in EQ 18. In order to decrease the subjectivity of the of the step function a value of T equal to 0.5 is proposed (Bueno and Salmeron, 2009).

$$f(x) = \begin{cases} 0 & \text{if} \quad x \le T \\ 1 & \text{if} \quad x > T \end{cases} \quad \text{(EQ 18)}$$

- The threshold linear function is a derivative of the step function and is presented in EQ 19 (Bueno and Salmeron, 2009).

$$f(x) = \begin{cases} 0 & \text{if} \quad x \le T \\ (x-T) & \text{if} \quad x > T \end{cases} \quad \text{(EQ 19)}$$

According to (Bueno and Salmeron, 2009) the sigmoid function presents specific advantages than the other concepts.

In order to model a process or a controller with an FCM, expert knowledge is needed. An FCM is usually constructed by a knowledge engineer who acquires domain knowledge from systems experts and uses that knowledge to define the concepts, causal directions and linguistic variables of the edges of the graph. The domain experts identify of causal relationships among the concepts and estimate of causal link strengths with linguistic variables (Papageorgiou, 2011) .

Experts decide on the important aspects of the system which become the concepts and the weights are set according to the interrelations of the concepts (Stylios and Groumpos, 1999). Linguistic variables can be used by the experts in order to express the relations of the concepts in a simplified way. First of all negative, positive or no causality is set. After that the influence is described with variables like very weak, weak, strong, very strong etc (Papageorgiou, Parsopoulos et al., 2005).

The most important disadvantage of FCMs is the possibility to converge in an undesired steady state. This is why different FCM learning algorithms have been proposed. The first algorithms to be proposed were the Differential Hebbian Learning, the Active Hebbian Learning and the Nonlinear Hebbian Rule. The major disadvantage of the afore mentioned algorithms is the strong dependence of the final weights on the initial weights given by the experts. Other approaches include hybrid Nonlinear Hebbian Learning- Differential Evolution Algorithm, Simulated Annealing with Genetic Algorithms and Particle Swarm Optimization algorithm (Papageorgiou, 2011).

4.3.4 Petri Nets

A Petri Net (PN) is a weighted bipartite graph which is defined by four parameters P, T, A^P and w (Cassandras and Lafortune, 2008):

P: This is the finite set of places and is depicted as one type of node in the graph

T: This is the finite set of transitions and is depicted as a second type of node in the graph

A^P: $A^P \subseteq (P \times T) \cup (T \times P)$ and is the set called flow relation which includes the arcs from transitions to places and from places to transitions in the graph

w: $A^P \rightarrow \{1,2,3,...\}$ is the weight function of the arcs

It is assumed that (P,T,A,w) have no isolated places or transitions. The set of places is represented by $P = \{p_1, p_2, ..., p_n\}$ and the set of transitions by $T = \{t_1, t_2, ..., t_m\}$, $|P| = n$ and $|T| = m$. The weights of the arcs are positive integers and the arcs are represented in the form (p_i, t_j) or (t_j, p_i) (Cassandras and Lafortune, 2008).

The set of input places to a transition t_j is represented by $I(t_j)$ and the output places are presented by $O(t_j)$ (Cassandras and Lafortune, 2008).

$I(t_j) = \{p_i \in P : (p_i, t_j) \in A\}$ and $O(t_j) = \{p_i \in P : (t_j, p_i) \in A\}$

The mechanism used to indicate in a PN if a condition is met or not is the assignment of tokens to places. If a condition is satisfied, then a token is placed. A marking is defined as the way the tokens are assigned to a PN (Cassandras and Lafortune, 2008). A marking M is an m-vector, $\langle M(p_1), ..., M(p_n) \rangle$, where the number of tokens in the place p_i is denoted by $M(p_i)$. The initial marking of the PN is M_0, where $M_0 \rightarrow \{0,1,2,...\}$. All possible markings of the PN that can be reached from M_0 is the set $R(M_0)$ (Lee, Liu et al., 2003).

The movement of tokens through the PN presents the state transition function of the PN. This is called firing (Cassandras and Lafortune, 2008). A transition is enabled if there are at least w(p,t) (the weight from p to t) tokens in the inputs of place t. If a transition is enabled it might fire or it might not. If it is fired then w(p,t) tokens are removed from place t inputs and are added to the outputs according to the weight of the arc from t to p (w(t,p)).

The Flow Matrix or incidence matrix FM=[a_{ij}] of a PN with n transitions and m places is defined as an n x m matrix of integers, where its typical entry is given by (Murata, 1989):

$$a_{ij} = w(i, j) - w(j, i) \quad \text{(EQ 20)}$$

The control vector u_k is defined as an n x 1 column vector of n-1 zeros and one with its value equal to 1. The vector is given by by u=[s_1,s_2,…s_m] where $s_j \in \{0,1\}$. This position indicates that it has fired at the k-th firing. The state equation is formed as follows (Murata, 1989):

$$M_k = M_{k-1} + FM^T u_k \quad \text{(EQ 21)}$$

Where FM^T is the transpose of the Flow Matrix.

A typical petri net graph, as described above, is presented in Figure 4.5.

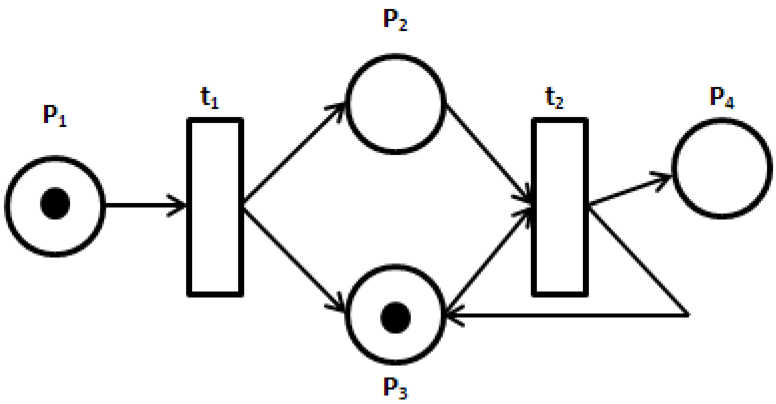


Figure 4.5 A typical petri net graph

5 Implementation of the Energy Management Systems

5.1 General Information

The Energy Management System (EMS) is the heart of the proposed topology. It is the core of making this topology operational. Since the topology is fully modular and it can expand in the future after the first commissioning it was decided that the EMS had to be able to operate using power balances instead of specific technical characteristics of the installed components. This way, if in the future, the owners of the smartgrid decide to include a new PV array, the EMS will still be operational and able to accommodate the new inclusions. In another case a full reprogramming of the EMS and re-commissioning would have to take place, increasing complexity and cost. The first approach that was developed was a simple ON-OFF approach, the second one based on Fuzzy Logic and the third based on a combined approach of Petri Nets and Fuzzy Cognitive Maps.

5.2 ON-OFF Energy Management System

For the Simple ON/OFF EMS (SEMS) three schemes run in parallel.

a. Double hysteresis control scheme

This is one of the most used schemes in PV/Wind – Hydrogen subsystem systems control (Zhou, Ferreira et al., 2008). The hysteresis (Figure 5.1) is used to prevent the devices of being turned on or off continuously at boundary operation conditions. It is used for the fuel cell and the two consumptions (electrolyzer and desalination unit).

When the State of Charge (SOC) of the battery is as low as the set SOC equal to FC_{low} then there is an ON command to the fuel cell (Figure 5.1). When the battery is charged and the SOC reaches the set SOC equal to FC_{high} then there is an OFF command to the fuel cell (Figure 5.1).

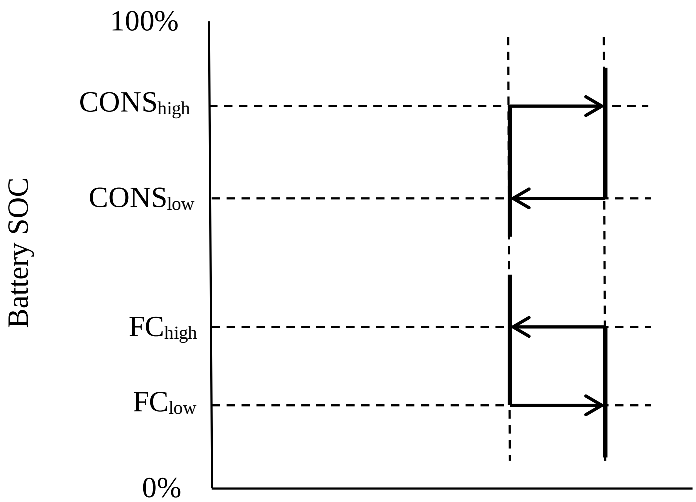


Figure 5.1 Double Hysteresis control scheme

When the SOC of the battery is as high as the set SOC equal to $CONS_{high}$ then there is a consumptions ON command to turn on one or both of the consumptions (that is decided on par with the third control scheme) (Figure 5.1). When the battery is discharged and the SOC reaches $CONS_{low}$ then both consumptions are turned off. FC_{high} was set at 45 %, FC_{low} at 25 %, $CONS_{high}$ at 85 %, and $CONS_{low}$ at 65 %, (Figure 5.1).

b. Load forecast

A simple method of load forecasting is implemented in the SEMS by determining the energy balance in the system. The electricity producers are considered positive and the electrical consumptions negative. If this function is positive then even if scheme 1 gives an ON command to the fuel cell then that command is overridden and the fuel cell is not turned on because SEMS anticipates that the SOC will become higher without the aid of the fuel cell.

This function along with the third control scheme decides if one or both of the consumptions will be turned on.

c. Hierarchy of the consumptions

Water is considered to be more important than all other products of the polygeneration microgrid. This is the reason why the controller is programmed to aim in having enough potable water to cover the needs for at least 3 days. This means that if the water in the tank is less than the water to cover the needs for 3 days then when a consumptions ON command is issued by the first control scheme then the desalination unit is turned on. After that a new energy balance of the system is calculated by subtracting the energy that will be consumed by the desalination unit for this time step. If the energy balance is still positive then the electrolyzer is also turned ON, if not it remains OFF.

If the water in the tank is sufficient for more than 3 days then when a consumptions ON command is issued by the first control scheme then the electrolyzer is turned on. After that a new energy balance of the system is calculated by subtracting the energy that will be consumed by the electrolyzer unit for that time step. If the energy balance is still positive then the desalination unit is also turned ON, if not it remains OFF.

SEMS was realized in TRNSYS, the source code is available in Annex I, and its inputs, outputs and parameters are presented in the following table.

Table 5.1 Type 190: SEMS

Number of Parameter		**Description**
1	Pfc	Rated Power of the fuel cell [W]
2	Pel	Rated Power of the Electrolyzer [W]
3	CONShigh	$CONS_{high}$
4	CONSlow	$CONS_{low}$
5	FChigh	FC_{high}
6	FClow	FC_{low}
7	TS	Time step parameter
8	Pds	Rated Power of the Desalination Unit [W]
9	FCeff	Fuel Cell efficiency
10	Water3	Emergency Water for 3 days [m^3]
Number of Input		**Description**
1	Pload	Power of the load [W]
2	Ppv	Power produced by the PV [W]
3	Pwind	Power produced by the Wind Turbine [W]
4	Paux	Auxiliary Produced Power [W]
5	$MishH_2$	Hydrogen shortage [Nm^3]
6	SOC	State of Charge
7	Water	Water in the water tank [m^3]
Number of Output		**Description**
1	Pel	Consumed Power of the Electrolyzer [W]
2	Pfc	Produced Power of the Fuel Cell [W]

3	Pds	Consumed Power of the Electrolyzer [W]
4	Es	Electrolyzer state (ON/OFF)
5	FCs	Fuel Cell state (ON/OFF)
6	DSs	Desalination Unit state (ON/OFF)
7	Pmis	Load not met [W]

5.3 Fuzzy Logic Energy Management System

The Fuzzy Logic Energy Management System (FLEMS) was the first developed EMS to allow part load operation of the fuel cell, electrolyzer and desalination unit. The water in this approach is again considered to be the most important product of the microgrid. FLEMS aims also to have potable water needed for 3 days in the water tank at all times. This way, if there is some kind of failure, there will be adequate water until a repair takes place or water can be transported from another area.

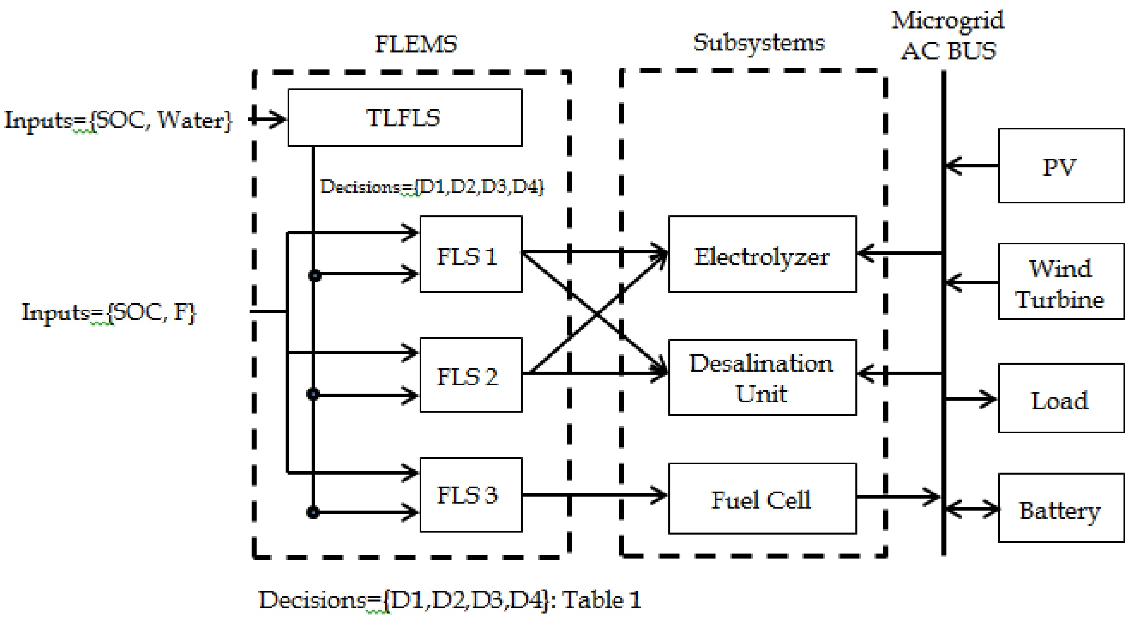


Figure 5.2 FLEMS Design

FLEMS is designed to operate in 2 levels as presented in Figure 5.2: The Top Level management Fuzzy Logic System (TLFLS) is based on Takagi-Sugeno-Kang (TSK) fuzzy inference with two inputs and four outputs and was implemented in Matlab using the Fuzzy Logic Toolkit (Jang, Sun et al., 1997). The lower level of FLEMS is comprise by three Fuzzy Logic Systems (FLS).

TLFLS is a decision-making unit based on typical fuzzy rules. Each rule represents a special situation (Dounis and Caraiscos, 2007). Considering an ndimensional decision-making problem for which N data $x \in X \subseteq R^n$, $x = (x_1, x_2, ..., x_n)$ are given for M decisions $\{d_1, d_2, ..., d_M\}$. The typical fuzzy rule of the TLFLS has the form:

$$R_i : \text{IF } x_1 \text{ is } A_{i1} \text{ and } x_2 \text{ is } A_{i2} \text{ and} \ldots x_n \text{ is } A_{in} \text{ THEN } d_i)$$

where A_{ij} denotes the antecedent fuzzy set defined for the $j = 1, ..., n$ and $i = 1, ..., M$. The TLFLS output is calculated based on the degree of activation of the rules:

$$\beta_i(\mathbf{x}) = \prod_{j=1}^{n} \mu_{A_{ij}}(x_j) \text{ (EQ 22)}$$

A crisp decision is made by taking the decision belonging to the fuzzy rule that has the highest degrees of activation (winner-take-all strategy) (Kuncheva, 2000; Dounis, Tiropanis et al., 2011; Zhang, Wu et al., 2011).

$$\mathbf{x} \in d_{i_w},\ i_w = \underset{1 \le i \le M}{\operatorname{argmax}}(\beta_i(x)) \text{ (EQ 23)}$$

The inputs are the frequency of the microgrid and a variable based on the available water. This water variable is equal to the water quantity available in the water tank minus the water needed for three days. The membership functions for the inputs of TLFLS are presented in Figure 5.3 and the linguistic variables Small, Medium and Big for the Frequency and Small and Big for the water were used. The output membership functions are constant, either ON (1) or OFF (0). The outputs are in essence the weight ranging from 0 to 1 of the following four states:

- Load FLS 1
- Load FLS 2
- Keep all devices off
- Load FLS 3

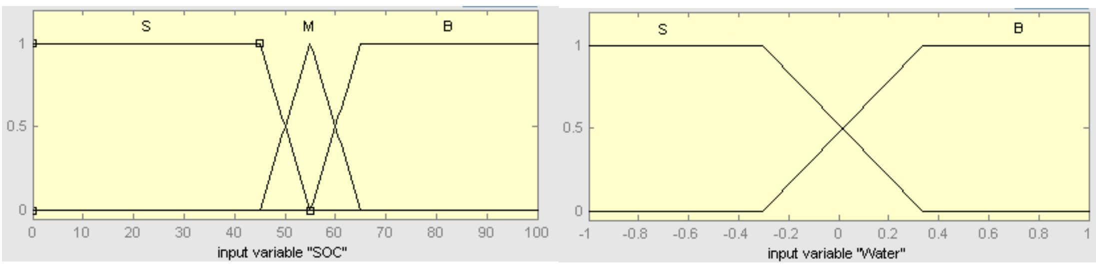


Figure 5.3 Membership functions for TLFLS inputs

This way the output with the highest weight defines which, if any, fuzzy logic system of the lower level is going to be loaded. The rules are presented in Table 5.2. TLFLS was implemented in Matlab. After the lower level has produced its outputs the top level checks if this output is less than 30% for part load operation and instead of operating the device at such a low level the device output state is OFF.

Table 5.2 TLFLS rules

SOC	Water	Decision
Big	Big	D1: Load FLS 1
Big	Small	D2: Load FLS 2
Medium	-	D3: Turn all devices off
Low	-	D4: Load FLS 3

The three lower level fuzzy logic systems (FLS) are based on Mamdani fuzzy inference using mix and max for T-norm and T-conorm operators respectively and were implemented in Matlab using the Fuzzy Logic Toolkit. The membership functions used the linguistic variables Small, Medium, Big and Very Big for the SOC and the F. For the outputs the linguistic variables OFF, Low, Medium and Max were used. The output of the fuzzy logic systems is the fractional state of operation of each of the devices with a number ranging from 0 to 100 with 0 turning the device OFF and 100 representing full load operation. Three Mamdani fuzzy logic systems were created in total. FLS 1 is used when the water in the potable water tank is more than the water needed for 3 days to determine the state of operation of the electrolyzer and desalination units, FLS 2 when the potable water is equal or less than the water needed for 3 days and FLS 3 for the control of the fuel cell.

The membership functions of the 3 fuzzy logic routines are presented in Figure 5.4, Figure 5.5 and Figure 5.6. They were designed using the control surfaces (Figure 5.7, Figure 5.8 and Figure 5.9) based on the accumulated experience. The rules for each of the routines are presented in Table 5.3, Table 5.4 and Table 5.5 respectively and were chosen intuitively based on the accumulated experience. The AND method used was MIN, the implication operator is MIN, the Aggregation is MAX and the defuzzification strategy used is the Centroid of Area (CoA). For example if SOC is High, Water is Small and Frequency is Medium, the TLFLS will choose FLS

2 which in return will decide to keep the electrolyzer Off and turn On the desalination unit at part load at a medium point.

FLEMS was realized in Matlab. TYPE 155 of TRNSYS allows the interconnection of TRNSYS with Matlab. Below are the inputs, outputs and parameters of Type 155. The Matlab M-file which contains the code for each of the above presented fuzzy logic inference systems is presented in Annex II of this thesis.

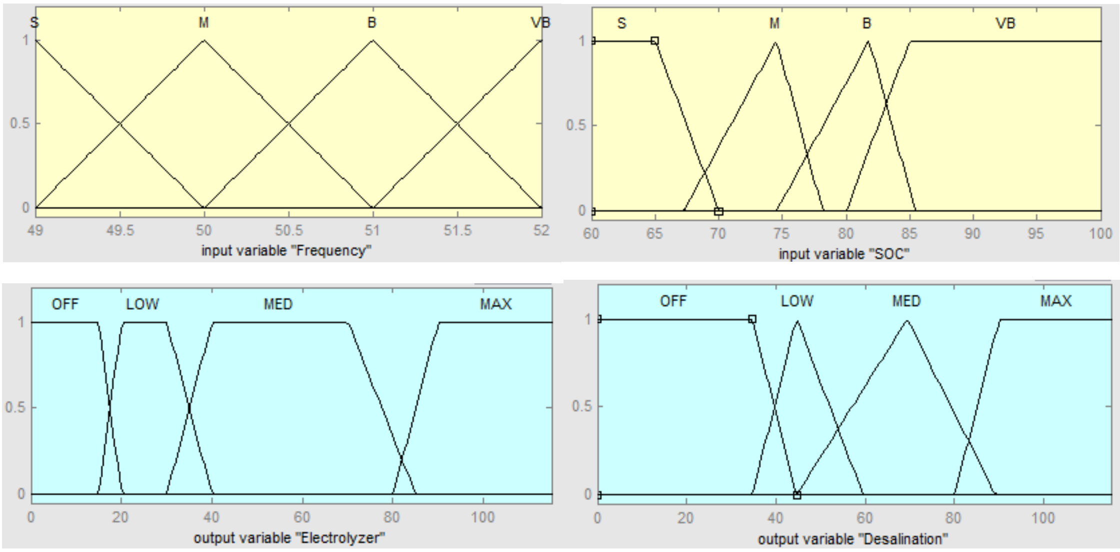


Figure 5.4 Membership functions for FLS 1

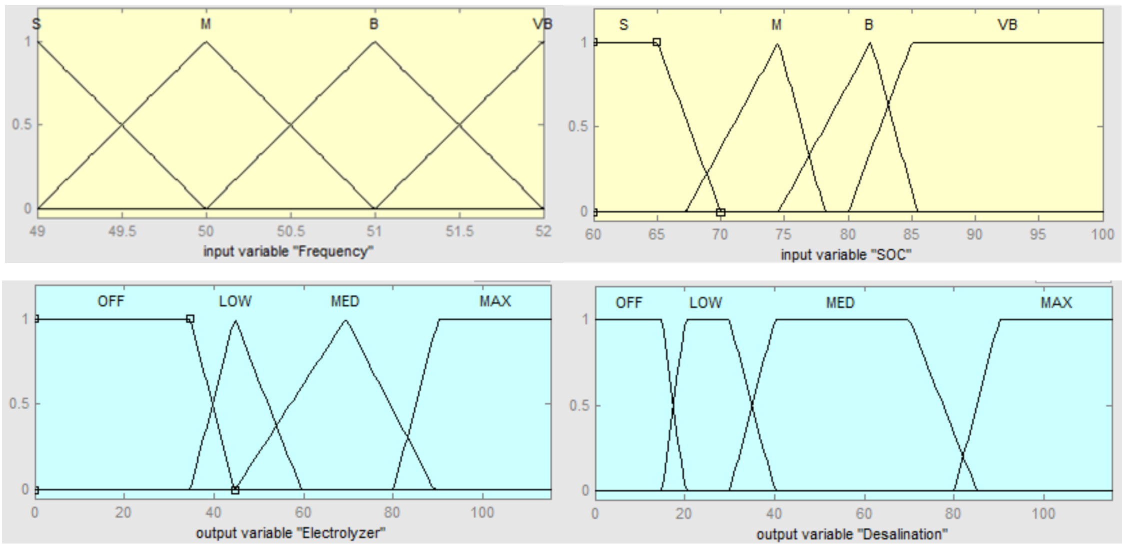


Figure 5.5 Membership functions for FLS 2

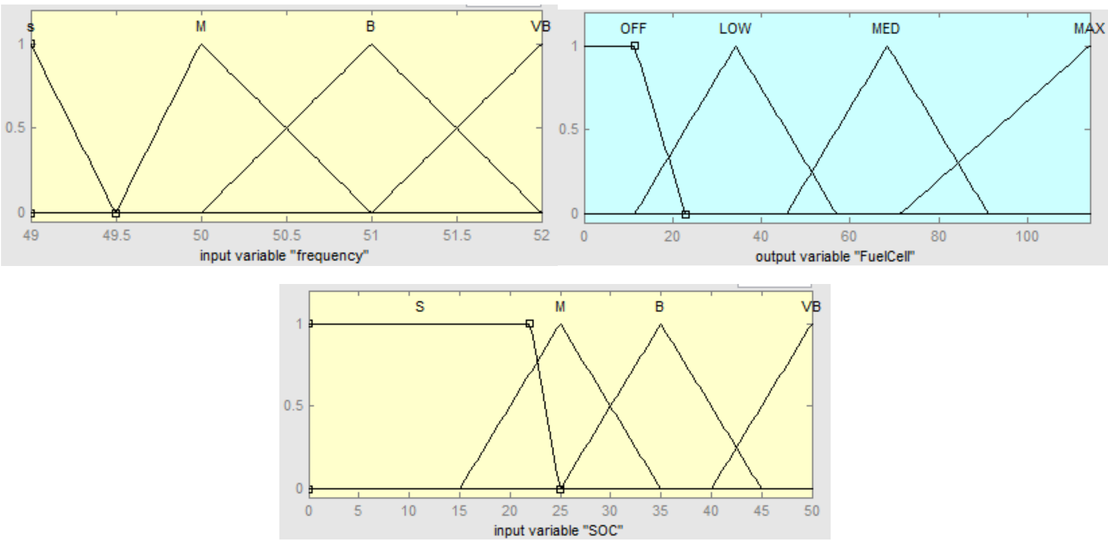


Figure 5.6 Membership functions for FLS 3

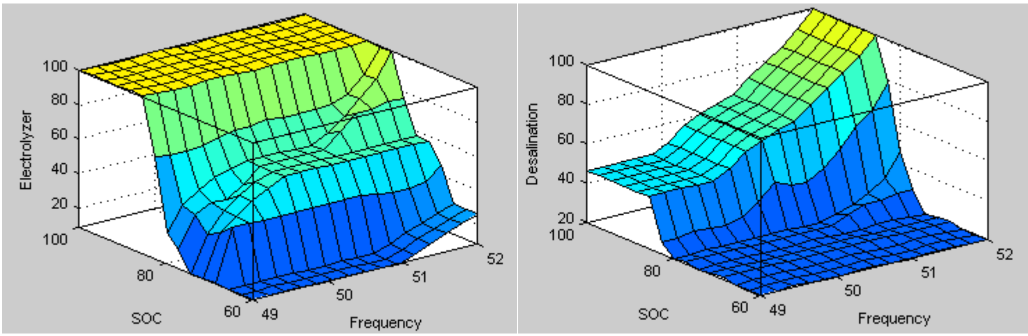


Figure 5.7 Control Surfaces for FLS 1

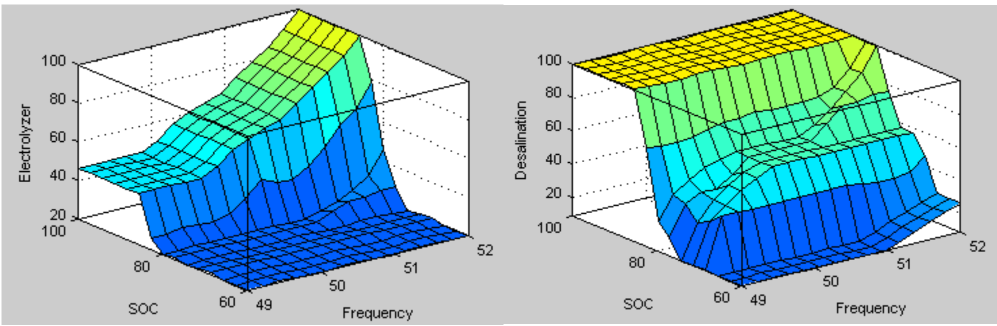


Figure 5.8 Control Surfaces for FLS 2

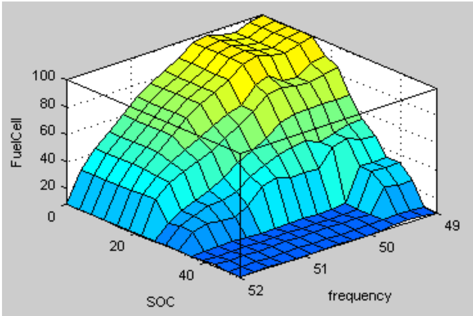


Figure 5.9 Control Surface for FLS 3

Table 5.3 IF-THEN rules for FLS 1

F (Hz) / SOC (%)	Small	Medium	Big	Very Big
Small	OFF **OFF**	OFF **OFF**	OFF **OFF**	ON/LOW **OFF**
Medium	OFF **OFF**	ON/MED **OFF**	ON/MED **OFF**	ON/MED **OFF**
Big	ON/LOW **OFF**	ON/MED **OFF**	ON/MED **OFF**	ON/MAX **ON/LOW**
Very Big	ON/MAX **ON/LOW**	ON/MAX **ON/LOW**	ON/MAX **ON/MED**	ON/MAX **ON/MAX**

Legend:
- ✓ Normal fonts are for the electrolyzer unit
- ✓ **Bold fonts are for the desalination unit**

Table 5.4 IF-THEN rules for FLS 2

F / SOC	Small	Medium	Big	Very Big
Small	OFF **OFF**	OFF **OFF**	OFF **OFF**	OFF **ON/LOW**
Medium	OFF **OFF**	OFF **ON/MED**	OFF **ON/MED**	OFF **ON/MED**
Big	OFF **ON/LOW**	OFF **ON/MED**	OFF **ON/MED**	ON/LOW **ON/MAX**
Very Big	ON/LOW **ON/MAX**	ON/LOW **ON/MAX**	ON/MED **ON/MAX**	ON/MAX **ON/MAX**

Legend:
- ✓ Normal fonts are for the electrolyzer unit
- ✓ **Bold fonts are for the desalination unit**

Table 5.5 IF-THEN rules for FLS 3

F / SOC	Small	Medium	Big	Very Big
Small	ON/MAX	ON/MAX	ON/MED	OFF
Medium	ON/MED	ON/MED	ON/LOW	OFF
Big	ON/LOW	OFF	OFF	OFF
Very Big	OFF	OFF	OFF	OFF

Table 5.6 Type155: Matlab

Number of Parameter		**Description**
1	MODE	Mode
2	NI	Number of inputs
3	NO	Number of outputs
4	CM	Calling Mode
5	SWITCH	Keep Matlab open after the end of simulation
Number of Input		**Description**
1	SOC	State Of Charge
2	F	Frequency of the microgrid [Hz]
3	W3	Emergency Water for 3 days [m^3]
Number of Output		**Description**
1	OP_{FC}	Fractional operation point of the Fuel Cell
2	OP_{EL}	Fractional operation point of the Electrolyzer
3	OP_{DS}	Fractional operation point of the Desalination Unit

5.4 Combined Petri Net – Fuzzy Cognitive Maps Energy Management System

The combined Petri Net – Fuzzy Cognitive Maps Energy Management System (FPEMS) is the second advances energy management system that was designed and implemented. PN is introduced in order to propose a supervisory strategy of an energy management system for autonomous polygeneration microgrids. FPEMS is presented in Figure 5.10 and analyzed below.

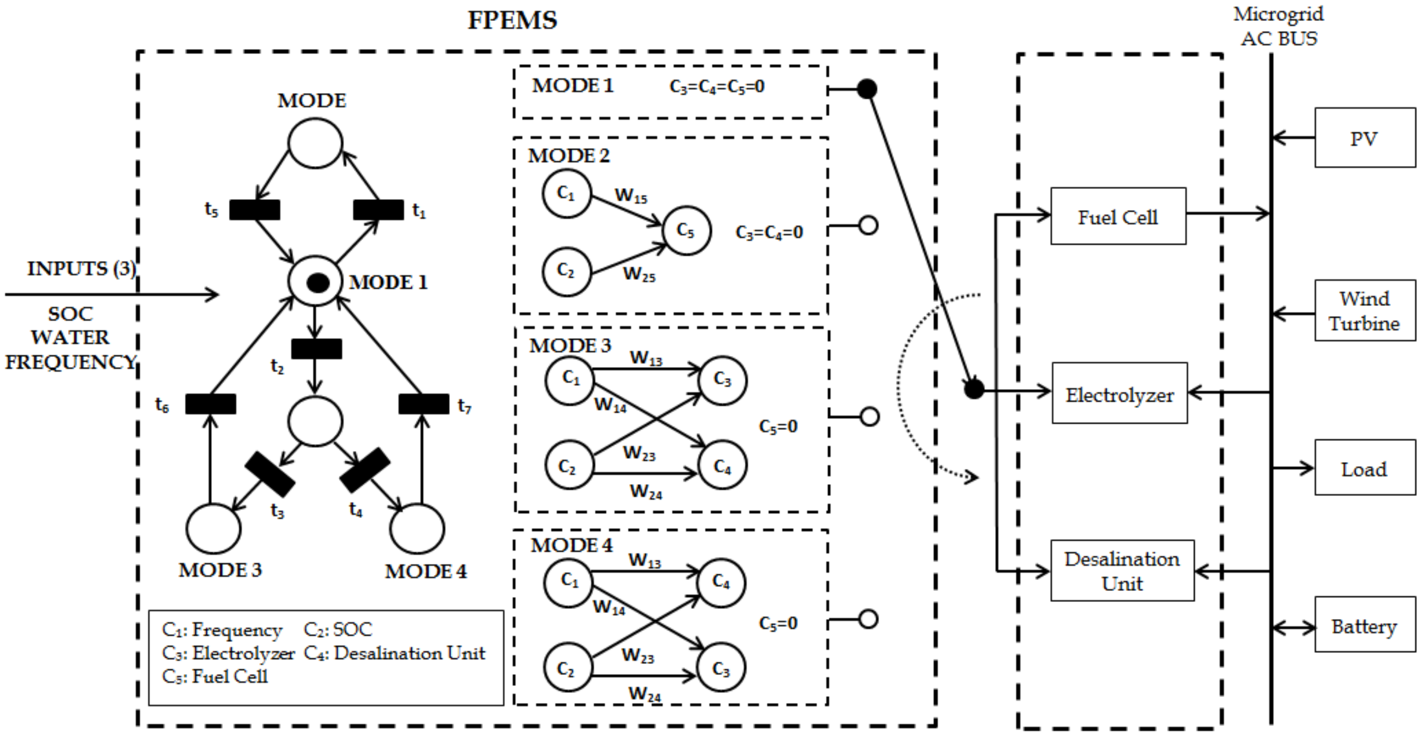


Figure 5.10 FPEMS Design

The PN is used to decide the operational modes of the microgrid, whereas three FCMs are used to determine the operational state of the fuel cell, electrolyzer and desalination unit. FPEMS uses the frequency of the microgrid, SOC and the available water in the potable water tank as inputs.

As in SEMS water is again considered to be the most important product of the system. That is why FPEMS aims to have enough water in the potable water tank for 3 days. This is a safety measure if there is some failure in the system. In three days the microgrid can be fixed or arrangements for transportation of water can take place.

The selection of the operating mode is based on a PN. The different conditions for the movement from one state to another are expressed as:

t_1: SOC<SOCL, where SOCL (SOC Low) is a set point of SOC from which and below the fuel cell should be turned on

t_2: SOC>SOCM, where SOCM (SOC Medium) is a set point of SOC from which and above one or both the consumptions (electrolyzer, desalination unit) should be turned on

t_3: $W^{TANK}>W^{3D}$, where W^{3D} is the potable water needed to cover the needs for 3 days

t_4: $W^{TANK} < W^{3D}$

t_5: SOC>SOCL

t_6: (SOC<SOCM) OR ($W^{TANK} < W^{3D}$)

t_7: (SOC<SOCM) OR ($W^{TANK} > W^{3D}$)

There are four modes that can be set which are presented in Table 5.7.

Table 5.7 Petri Net modes

Mode	Fuel Cell	Desalination Unit	Electrolyzer	Remarks
1	OFF	OFF	OFF	-
2	Decided by FCM	OFF	OFF	-
3	OFF	Decided by FCM	Decided by FCM	Priority is given to the Electrolyzer
4	OFF	Decided by FCM	Decided by FCM	Priority is given to the Desalination Unit

The flow matrix or incidence matrix FM, of this PN is as follows:

$$FM = \begin{pmatrix} -1 & 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 1 & -1 \\ 1 & -1 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & -1 & 0 \end{pmatrix}$$

With the above flow matrix and $M_k = M_{k-1} + FM^T u_k$ (EQ 21 the PN can be modeled. For example if the SOC is below SOCL the PN decides to activate Mode 2.

For the FCMs it is decided that the sigmoid activation function is going to be used with a steepness parameter of 1. This choice was made since that steepness parameter gives a linearity to the results and so not abrupt and big changes occur with changes of the inputs.

As it is seen in Figure 5.10 the FCMs of Mode 3 and Mode 4 are the same apart from Concept 3 taking the place of Concept 4 and vice versa, without changing anything else in the FCM. Because of this Mode 3 can give priority to the electrolyzer and Mode 4 to the desalination unit in the same manner. This approach simplifies the system by having only 4 weights to optimize instead of 8, where at the same time the needed operational demands from the energy management system are met.

FPEMS was realized in TRNSYS. The inputs, outputs and parameters are presented in Table 5.8. The source code is presented in Annex II.

Table 5.8 Type196: FPEMS

Number of Parameter		**Description**
1	W_{Hour}	Hourly Water Consumption [m^3]
2	W14	w_{14}
3	W23	w_{23}
4	W24	w_{24}
5	W13	w_{13}
6	W25	w_{25}
7	W15	w_{15}
8	N	Number of iterations
9	SOCL	SOCL
10	SOCM	SOCM
Number of Input		**Description**
1	SOC	State Of Charge
2	F	Frequency of the microgrid [Hz]
3	W3	Emergency Water for 3 days [m^3]
Number of Output		**Description**
1	OP_{FC}	Fractional operation point of the Fuel Cell
2	OP_{EL}	Fractional operation point of the Electrolyzer
3	OP_{DS}	Fractional operation point of the Desalination Unit

6 Comparison of the Energy Management System approaches

6.1 Case study parameters

The three Energy Management Systems (SEMS, FLEMS and FPEMS) are going to be compared directly to each other. In order to do that a case study takes place and the EMSs are compared on the basis of which one can provide the cheapest system, whereas at the same time covers all technical constraints.

An autonomous polygeneration microgrid is going to be designed in order to cover the needs of a small settlement on an island in the Cyclades islands complex in Greece. Typical meteorological data of the Cyclades islands complex is used in the simulations. The settlement comprises of two households equipped with energy saving devices, with 8 residents. The power profiles to be met are presented in Table 6.1 and Table 6.2. All the devices have an energy consumption rating of A+. For cooking an induction cooker and a grill are considered. The refrigerator and freezer are considered to be two ultra-low consumption Steca PF 166, one operating in refrigeration mode and one in freezer. For lighting led lamps are considered of 8 W rated power each.

In order to get realistic power profiles the baseline data presented in Table 6.1 and Table 6.2 where randomized by adding noise. This was done with the aid of the software package HOMER (ENERGY, 2011). Since the lighting and refrigeration profiles are dependent on the outside conditions, which are the same for the two houses, the same profiles were used. For the rest electrical consumptions random variability was added. For the first house a 10% variability was added for day to day and a 30% from timestep to timestep. For the second house a 30% variability was added for day to day and a 10% from timestep to timestep. This way the produced synthetic profiles are more realistic.

Table 6.1 Winter Power Consumption profile

Power Consumption Profile (W) - Winter																								
Hours of the day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Lighting	8	8	8	8	8	8	40	40	0	0	0	0	0	0	0	0	40	40	40	40	40	40	40	40
Cooking	-	-	-	-	-	-	500	-	-	-	-	-	1000	-	-	-	-	-	500	-	-	-	-	-
TV	-	-	-	-	-	-	-	-	-	-	-	-	-	90	-	-	-	-	90	90	90	90	90	-
Radio	-	-	-	-	-	-	2	-	-	-	2	2	2	-	-	-	-	2	-	-	-	-	-	2
Laptop	-	-	-	-	-	-	-	-	-	-	-	-	-	80	-	-	-	-	80	80	-	-	-	-
Refrigerator	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Freezer	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Various (Washing machine, dish washer etc)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	500	-	-	-	-	-	-	-	-	-
Total	**25**	**25**	**25**	**25**	**25**	**25**	**559**	**57**	**17**	**17**	**19**	**19**	**1019**	**187**	**517**	**17**	**57**	**59**	**727**	**227**	**147**	**147**	**147**	**59**

Table 6.2 Summer Power Consumption profile

Power Consumption Profile (W) - Summer																								
Hours of the day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Lighting	8	8	8	8	8	8	40	40	0	0	0	0	0	0	0	0	0	0	40	40	40	40	40	40
Cooking	-	-	-	-	-	-	500	-	-	-	-		1000	-	-	-	-	-	500	-	-	-	-	-
TV	-	-	-	-	-	-	-	-	-	-	-	-	-	90	-	-	-	-	90	90	90	90	90	-
Radio	-	-	-	-	-	-	2	-	-	-	2	2	2	-	-	-	-	2	-	-	-	-	-	2
Laptop	-	-	-	-	-	-	-	-	-	-	-	-	-	80	-	-	-	-	80	80	-	-	-	-
Refrigerator	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Freezer	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
Various (Washing machine, dish washer etc)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	500	-	-	-	-	-	-	-	-	-
Total	**58**	**58**	**58**	**58**	**58**	**58**	**592**	**90**	**50**	**50**	**52**	**52**	**1052**	**220**	**550**	**50**	**50**	**52**	**760**	**260**	**180**	**180**	**180**	**92**

The houses are modeled in TRNSYS as a 48 m^2 spaces without internal walls. A windows is present in each side of the house and the door on the south wall. Typical building elements used in Greece were considered. For the afternoon and night all people are in the house, while during the morning until noon only one. The BUI file is presented in Annex VI. The simulation of the houses took place only in order to be able to calculate the needed power for heating and cooling from an air-to-air heat pump. The air-conditioning unit chosen is a Daikin FTXR28EV1B9, which is equipped with an inverter for part load operation and has a COP rating of 5.14. Its operational characteristics are presented in Figure 6.1.

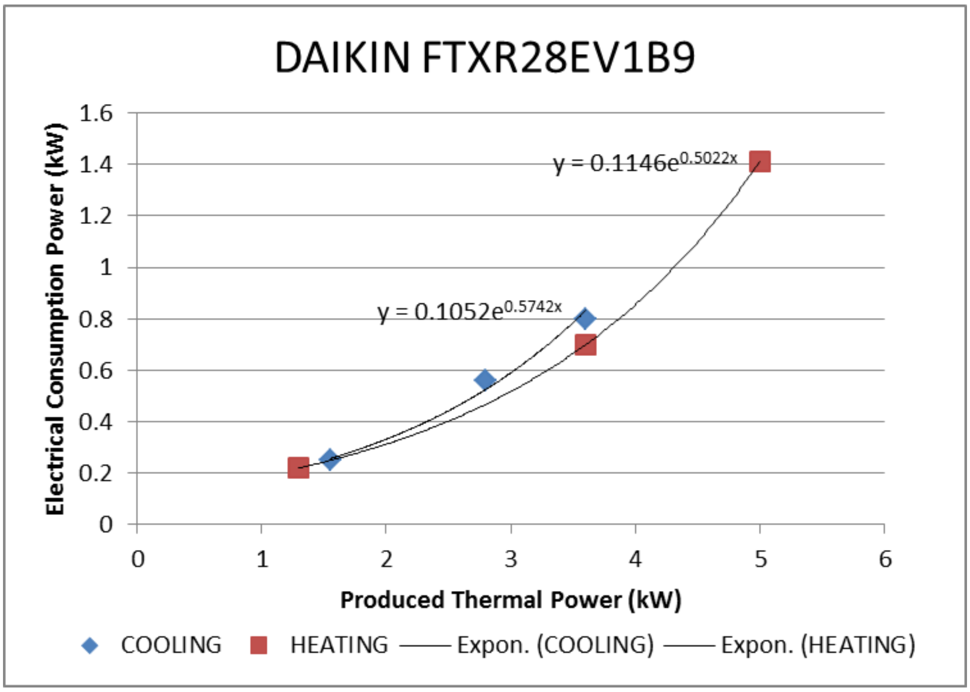


Figure 6.1 Operational characteristics of air conditioning unit

The 8 residents consume 1.92 m^3 of fresh water at a daily basis for all their needs (drinking, bathing, laundry and cooking). Two hybrid scooters are used to cover the mobility needs of all the residents. These two scooters cover 50 km each daily on average and the corresponding total daily fuel consumption is considered to be 2.4 Nm^3 H_2. The scooters are refilled daily in the afternoon. The simulation time step is equal to 1 hour.

6.2 Design through optimization

It was decided that the optimal design would be the one with the lowest net present cost for a 20 year investment, which at the same time fulfilled technical constraints. Values used in the calculations were in accordance with market prices. The four technical constraints are:

- No deep discharging of the battery bank is allowed. The fractional State Of Charge (SOC) never drops below 20%.
- No water shortage is allowed. This means that the potable water tank never becomes empty.
- No hydrogen shortage is allowed. This means that the metal hydride tank used for hydrogen storage never gets empty.
- The stored potable water and hydrogen in the end of the year is equal or higher than the stored quantities in the beginning of the year.

The penalties calculation is presented in Figure 6.2 and essentially the penalties are either zero or take a very big value in order not to be considered in the optimizations. The cost function (CF1) for the sizing of the microgrids is presented in

$$\mathrm{CF1} = \mathrm{NPC} + \sum_{t=1}^{8760} \mathrm{P_b(t)} + \sum_{t=1}^{8760} \mathrm{P_{H_2}(t)} + \sum_{t=1}^{8760} \mathrm{P_W(t)} + \mathrm{P_S} \quad \text{(EQ 24.}$$

$$\mathrm{CF1} = \mathrm{NPC} + \sum_{t=1}^{8760} \mathrm{P_b(t)} + \sum_{t=1}^{8760} \mathrm{P_{H_2}(t)} + \sum_{t=1}^{8760} \mathrm{P_W(t)} + \mathrm{P_S} \quad \text{(EQ 24)}$$

Where:

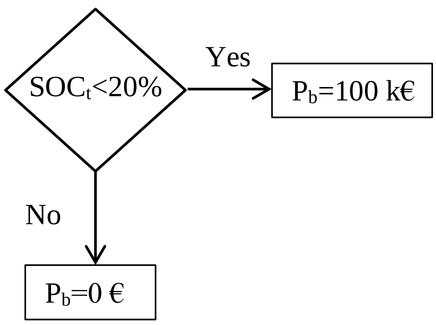
NPC: Net Present Cost for a 20 year period

P_b: Battery Penalty.

P_{H2}: Hydrogen Penalty.

P_w: Water Penalty.

P_S: Tanks Penalty. If the stored water and/or stored hydrogen are less in the end of the year than its beginning another 100000 € are added.



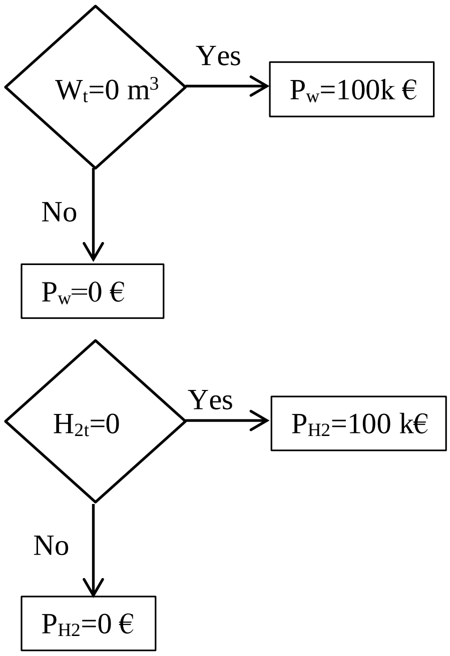


Figure 6.2 Penalties calculation

Using EQ 24 the design of the microgrids based on SEMS and FLEMS was realized. For the SEMS microgrid any other optimization is impossible. As far as the FLEMS microgrid is concerned further optimization could theoretically take place as far as the fuzzy systems' parameters are concerned. The amount of variables to be optimized are in the range of 150, which is a very big number. Every membership function needs at least 3 numbers (for a triangular one) and each input or output is described by at least 3 membership functions. Taking in consideration all the fuzzy logic systems used in FLEMS this number is reached. Also as it will be made clear after the presentation of the results, the computational time needed even it was feasible to optimize 150 variables would be unacceptable. These are the reasons for not going forward with any further EMS specific optimizations for the FLEMS.

On the other hand, the FPEMS could be further optimized, since the amount of variables is much smaller – only 8. This includes the PN transitions parameters and the FCM weights. Even as such the optimization is still complex since the weights of the FCM and the PN's transitions parameters have to be optimized simultaneously and interactively with the sizing of the components of the actual microgrid. The methodology approach realized in order to address this reality comprises of the following steps:

1. Knowledge engineer and domain experts decide on the fuzzification and defuzzification methods and the initial weights of the FCM and the transition parameters of the PN are set.

2. The microgrid is sized using PSO based on the results of step 1.

3. The FCM weights and PN transition parameters are optimized based on the sizing derived in step 2 using PSO again.

4. Finally, a new sizing of the microgrid's components takes place with the use of the optimized parameters for the FCM weights and PN transition parameters that are provided by the optimization results of step 3.

The optimizations that take place in Steps 2 and 4 use $CF1 = NPC + \sum_{t=1}^{8760} P_b(t) + \sum_{t=1}^{8760} P_{H_2}(t) + \sum_{t=1}^{8760} P_W(t) + P_S$ (EQ 24. For the optimization though, taking place in Step 3, for the optimization of the FCM weights and the PN transition parameters four technical constrictions still apply. This time the minimum SOC, minimum stored H_2 and minimum potable water in the tank are recorded throughout the year. These values are then normalized in the space [0,1] and added together. Since the software algorithm tries to minimize the cost function, this sum is deducted from the maximum possible sum in order for the best system to have the lowest value of the cost function. This is presented in $OPTP = \left(100 - SOC^{MIN}\right) \times 100 + \left(1 - \left(\frac{H_2^{MIN}}{H_2^{TANK}}\right)\right) \times 10000 + \left(1 - \left(\frac{W^{MIN}}{W^{TANK}}\right)\right) \times 10000$ (EQ 25. The FCM weights and PN transition parameters combination which presents the lowest value in $CF2 = OPTP + \sum_{t=1}^{8760} P_b(t) + \sum_{t=1}^{8760} P_{H_2}(t) + \sum_{t=1}^{8760} P_W(t) + P_S$ (EQ 26 is the best.

$$OPTP = \left(100 - SOC^{MIN}\right) \times 100 + \left(1 - \left(\frac{H_2^{MIN}}{H_2^{TANK}}\right)\right) \times 10000 + \left(1 - \left(\frac{W^{MIN}}{W^{TANK}}\right)\right) \times 10000 \quad \text{(EQ 25)}$$

$$CF2 = OPTP + \sum_{t=1}^{8760} P_b(t) + \sum_{t=1}^{8760} P_{H_2}(t) + \sum_{t=1}^{8760} P_W(t) + P_S \quad \text{(EQ 26)}$$

Where:

NPC: Net Present Cost for a 20 year period

P_b: Battery Penalty.

P_{H2}: Hydrogen Penalty.

P_w: Water Penalty.

P_S: Tanks Penalty. If the stored water and/or stored hydrogen are less in the end of the year than its beginning another 100000 € are added.

SOC^{MIN}: The minimum fractional SOC throughout the year

H_2^{MIN}: The minimum quantity of hydrogen in the metal hydride tank throughout the year

H_2^{TANK}: The volume of the metal hydride tank

W^{MIN}: The minimum quantity of water in the potable water tank throughout the year

W^{TANK}: The volume of the potable water tank

The optimizations take place using the GenOpt software package. The PSO algorithm has been used. The parameters for the PSO proposed by Papageorgiou et al (Papageorgiou, Parsopoulos et al., 2005) are used for all optimizations. They are presented in Table 6.3.

Table 6.3 PSO Settings

Topology	lbest
Neighborhood size	3
Particles	20
Generations	100
Seed	0
Cognitive acceleration constant	2.05
Social acceleration constant	2.05
Constriction gain	0.729

6.3 Optimizations

6.3.1 Parameters to be optimized

For all the systems the parameters to be optimized are:

1. The number of the PV modules. Solar world Sunmodule SW 180 PV modules were considered to be installed on 1 axis trackers.
2. Rated Power of the fuel cell
3. Rated Power of the electrolyzer

4. Rated Power of the desalination unit
5. Storage capacity of the hydrogen tank
6. Storage capacity of the water tank
7. Energy capacity of the battery bank

A 7.5 kW typical DC wind turbine (Bergey XL-R 7.5 kW) on a 16 m tower was considered for all cases. The economic data used for the calculation of the Net Present Cost are presented in Table 6.4. The prices are all according to market prices around the world. The interest rate is considered to be equal to 6% and the batteries are considered to be changed twice in the operational lifetime of the microgrid. The minimum and maximum values for each variable in the following optimizations was decided based on a number of trial and error simulations.

Table 6.4 NPC calculation values

Variable	Value (€)	Unit
PV Modules (price includes the price of the inverter)	700	Per panel
Fuel Cell	5	Per Watt
Electrolyzer Unit	8	Per Watt
Hydrogen Storage tank	1000	Per Nm^3 of H_2
Potable Water Tank Volume (m^3)	60	Per m^3
Desalination Unit (W)	10	Per Watt
Battery bank	12	Per Watt-hour of each of the 2 V batteries

6.3.2 ON-OFF Energy Management System (SEMS)

The search space for the optimal microgrid featuring the SEMS approach is presented in Table 6.5. The highest and lowest values were decided based on market availability of components and some test simulations. It has to be taken into consideration though that if the batteries are deep discharged the main inverter which creates the electrical grid will not be able to create it. The PV and wind turbine inverters consequently will not feed any electricity because they will not find a grid to synchronize to. The companies that offer these inverters suggest that an external electricity generator (usually diesel powered) is present so that the system can become operational again. The fuel cell plays that role as well as it is clearly a backup energy source for the system and thus its minimum size is 300 W. The possible microgrid component combinations amount to 18195840. The optimization process of the PSO algorithm is negligible in duration in comparison with the time that is needed for the simulations to take place. One yearly simulation needs about 2-3 seconds and for the PSO configuration that was used 1999 simulations took place. The optimal combination is presented in the last column of Table 6.5.

Table 6.5 Optimization Variables for SEMS

Variable	Lowest Value	Highest Value	Step	Optimal Value
PV Modules	35	50	1	35
Rated Power of the Fuel Cell (W)	300	800	100	700
Rated Power of the Electrolyzer Unit (W)	600	1400	100	1400
Hydrogen Storage Capacity (Nm^3 of H_2)	8	15	0.5	14.5
Potable Water Tank Capacity (m^3)	30	50	1	50
Rated Power of the Desalination Unit (W)	600	1400	100	1000
Energy Capacity rating of each of the 2 V batteries. 24 are used for a 48 V DC bus (Wh)	400,500,600, 700, 840, 980, 1200,1400,1600,2000,2400,3000			840

6.3.3 Fuzzy Logic Energy Management System (FLEMS)

The search space for the optimal microgrid featuring the fuzzy logic approach is presented in Table 6.6. The possible microgrid component combinations amount to 9676800. The optimization process of the PSO algorithm is negligible in duration in comparison with the time that is needed for the simulations to take place. One yearly simulation needs about 60 seconds and for the PSO configuration that was used 1999 simulations took place. The time was considerably more in comparison to the SEMS optimization because FLEMS was realized in Matlab. The communication between TRNSYS and Matlab works flawlessly, but there is a time delay because of the constant transfer of data between the two software packages. The optimal combination is presented in the last column of Table 6.6.

Table 6.6 Optimization Variables for FLEMS

Variable	Lowest Value	Highest Value	Step	Optimal Value
PV Modules	35	48	1	36
Rated Power of the Fuel Cell (W)	300	800	100	300
Rated Power of the Electrolyzer Unit (W)	700	1400	100	1000

Hydrogen Storage Capacity (Nm^3 of H_2)	8	15	0.5	12
Potable Water Tank Capacity (m^3)	35	50	1	32
Rated Power of the Desalination Unit (W)	500	1000	100	900
Energy Capacity rating of each of the 2 V batteries. 24 are used for a 48 V DC bus (Wh)	400,500,600, 700, 840, 980, 1200,1400,1600,2000			400

6.3.4 Combined Petri Net – Fuzzy Cognitive Maps Energy Management System (FPEMS)

6.3.4.1 Step 1

As was described in chapter 6.2 the optimization for FPEMS takes place in in 4 steps.

In order to set the weights of the FCMs and the parameters of the PN expert opinions are needed. There are very few experts of this topology because of its novelty. The opinions of the author of this thesis, of Prof. G. Papadakis (personal communication, May 17, 2011), of Assoc. Prof. K. Arvanitis (personal communication, May 17, 2011) and of Assoc. Prof. A. Dounis (personal communication, May 17, 2011) are used. First the experts' opinions on the 2 parameters of the PN's transitions were put forward (SOCL and SOCM) and are presented in Table 6.7 FPEMS parameters and weights, along with the linguistic variables used. As far as the weights of the FCMs are concerned first it was agreed unanimously by all the experts if the relations between the concepts were positive or negative. The experts' opinions are presented in Table 6.7 FPEMS parameters and weights, along with the linguistic variables used. Using the centroid defuzzification method (COG) the linguistic values are transformed in numerical values (Jang, Sun et al., 1997). These are also presented in the last column of Table 6.7 FPEMS parameters and weightsIn Figures Figure 6.3, Figure 6.4, Figure 6.5 and Figure 6.6 the membership functions for the fuzzification procedure are presented. The initial values of the FCMs weights and the PN parameters are presented in the last column of Table 6.7 FPEMS parameters and weights.

Table 6.7 FPEMS parameters and weights

Variable	Expert 1	Expert 2	Expert 3	Expert 4	Defuzzified Value
SOCL	M	VL	L	B	25
SOCM	VB	B	M	B	59

W_{15}	EB	EB	EB	EB	0.96
W_{25}	VB	RB	VB	B	0.75
W_{13}	VL	L	RL	L	-0.75
W_{14}	EL	VL	VL	EL	-0.90
W_{23}	EB	EB	EB	EB	0.96
W_{24}	EB	B	B	EB	0.82

Where:

EL: Extremely Low — EB: Extremely Big
VL: Very Low — VB: Very Big
L: Low — B: Big
RL: Relatively Low — RB: Relatively Big
M: Medium

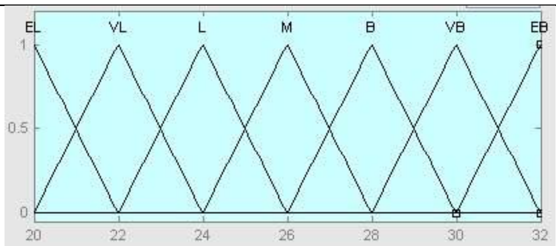


Figure 6.3 Membership functions for SOCL

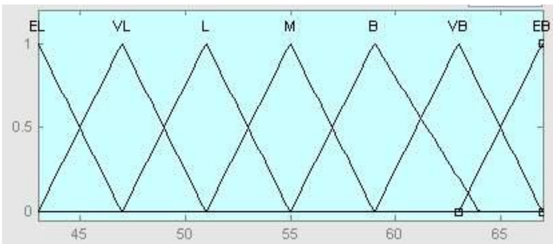


Figure 6.4 Membership functions for SOCM

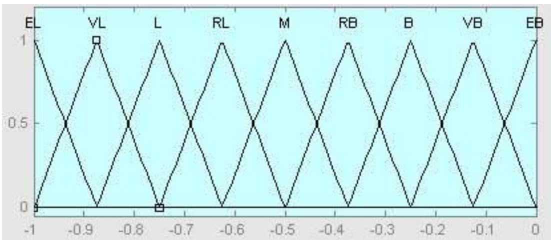


Figure 6.5 Membership functions for negative fuzzy FCM weights

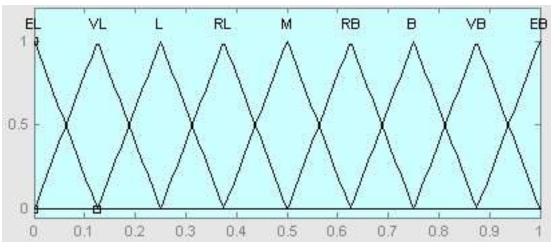


Figure 6.6 Membership functions for positive fuzzy FCM weights

The fuzzification method of the inputs of the FCM is agreed as follows:

- Frequency (F)

The modeled microgrid is based on the SMA Sunny Island topology. In this topology the frequency of the microgrid is used for the control of all the connected inverters. If the central inverter sees that the battery bank is getting fully charged it starts to increase the frequency of the microgrid from 50 Hz up to 52 Hz so as to protect the battery from overcharging. When the inverters connected to the energy producers (pv, wind, etc.) detect a higher frequency they start to decrease the power they give to the microgrid and they cut the supply completely when the frequency reaches 52 Hz. When there is an energy deficit in the microgrid the frequency is decreased gradually down to 49 Hz (Engler, Meinhardt et al., 2004). The frequency fuzzification is presented in Figure 6.7, where FF is the fuzzified Frequency. In essence for both distinct cases ($F \in [49,50]$ and $F \in (50,52]$) the value is normalized in the space [0,1].

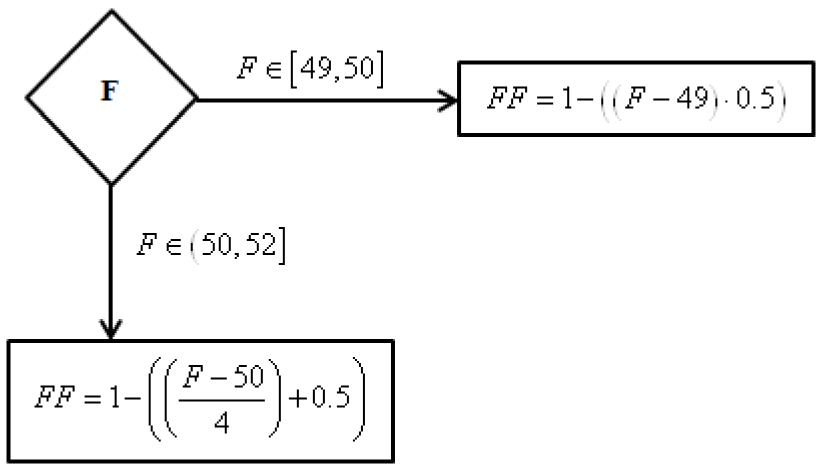


Figure 6.7 Frequency Fuzzification

- SOC

Due to the different microgrid operational characteristics especially in Mode 2 in comparison with Modes 3 and 4 two different approaches are used.

- Mode 2

  The fuzzification of the SOC in the space [0,1] for Mode 2 is presented in EQ 27.

$$FSOC = \frac{SOCL - SOC}{SOCL} \quad \text{(EQ 27)}$$

where FSOC is the fuzzified SOC

- Modes 3 and 4

  The fuzzification of the SOC in the space [0,1] for Mode 3 and Mode 4 is presented in EQ 28.

$$FSOC = \frac{SOC - SOCM}{100 - SOCM} \quad \text{(EQ 28)}$$

Since the output of the FPEMS corresponds to the operational state of the devices, this output number should be in the range $\left[0{,}100\right]$. The sigmoid activation function with a steepness parameter of 1 that was chosen gives results in the range (0,1). The minimum and maximum theoretical values of the results which depend on the weights can be far from the boundary 0 and 1 values. Defuzzification should also normalize the values in the range [0,100]. Taking in consideration $A_i(k+1) = f\left(A_i(k) + \sum_{\substack{j=1 \\ j \neq i}}^{n} W_{ji} A_j(k)\right)$ (EQ 15 and $f(x) = \frac{1}{1+e^{-cx}}$ (EQ 16, the maximum and minimum theoretical output values of the FCM in boundary operation can be calculated for any value of the weights. Based on that the normalization equations EQ 29, EQ 30 and EQ 31 are formed:

$$OP_{FC} = 100 \cdot \frac{C_5 - FCL}{FCH - FCL} \quad \text{(EQ 29)}$$

Where:

OP_{FC}: Fractional operation point of the Fuel Cell

FCL: is the value of C_5 for the frequency and SOC combination which should turn off the fuel cell, namely FF=0 and FSOC=0

FCH: is the value of C_5 for the frequency and SOC combination which should turn on the fuel cell at 100%, namely FF=1 and FSOC=1

$$OP_{EL} = 100 \cdot \frac{C_3 - ELL}{ELH - ELL} \quad \text{(EQ 30)}$$

Where:

OP_{EL}: Fractional operation point of the Electrolyzer

ELL: is the value of C_3 for the frequency and SOC combination which should turn off the electrolyzer, namely FF=1 and FSOC=0

ELH: is the value of C_3 for the frequency and SOC combination which should turn on the electrolyzer at 100%, namely FF=0 and FSOC=1

$$OP_{DS} = 100 \cdot \frac{C_4\text{-}DSL}{DSH\text{-}DSL} \quad \text{(EQ 31)}$$

Where:

OP_{DS}: Fractional operation point of the Desalination Unit

DSL: is the value of C_4 for the frequency and SOC combination which should turn off the desalination unit, namely FF=0 and FSOC=0

DSH: is the value of C_4 for the frequency and SOC combination which should turn on the desalination unit at 100%, namely FF=1 and FSOC=1

Due to technical constrictions of the devices if any of the operational states is calculated to be less than 30, the devices remain turned off.

6.3.4.2 Step 2

The search space for the optimal microgrid featuring the combined Petri Net – Fuzzy Cognitive Maps approach is presented in Table 6.8. The possible microgrid component combinations amount to 9676800. The optimization process duration of the PSO algorithm is negligible in comparison to the time that is needed for the simulations to take place. One yearly simulation needs about 2-3 seconds and for the PSO configuration that was used 1999 simulations took place. The optimal combination is presented in the last column of Table 6.8.

Table 6.8 Optimization Variables for Step 2 of FPEMS

Variable	Lowest Value	Highest Value	Step	Optimal Value
PV Modules	28	40	1	32
Rated Power of the Fuel Cell (W)	300	800	100	300

Rated Power of the Electrolyzer Unit (W)	700	1400	100	1000
Hydrogen Storage Capacity (Nm^3 of H_2)	8	15	0.5	12
Potable Water Tank Capacity (m^3)	30	50	1	49
Rated Power of the Desalination Unit (W)	500	1000	100	700
Energy Capacity rating of each of the 2 V batteries. 24 are used for a 48 V DC bus (Wh)	400,500,600, 700, 840, 980, 1200,1400,1600,2000			500

6.3.4.3 Step 3

In step 3 the optimization of the FCM weights and the Petri Net parameters takes place. The search space is presented in Table 6.9. In the last column of Table 6.9 the optimal values are presented.

Table 6.9 Optimization Variables for Step 3 of FPEMS

Variable	Lowest Value	Highest Value	Step	Optimal Value
SOCL	22	35	1	30
SOCM	45	65	1	49
W_{15}	0	1	0.01	0.76
W_{25}	0	1	0.01	0.18
W_{13}	-1	0	0.01	-0.76
W_{14}	-1	0	0.01	-0.98
W_{23}	0	1	0.01	0.32
W_{24}	0	1	0.01	0.50

6.3.4.4 Step 4

In the final step of the optimization of FPEMS the search space is presented in Table 6.10. The possible microgrid component combinations amount to 519750. The optimal values are presented in the last column of Table 6.10.

Table 6.10 Optimization Variables for Step 4 of FPEMS

Variable	Lowest Value	Highest Value	Step	Optimal Value
PV Modules	28	36	1	29
Rated Power of the Fuel Cell (W)	300	500	100	400
Rated Power of the Electrolyzer Unit (W)	700	1200	100	1000
Hydrogen Storage Capacity (Nm^3 of H_2)	8	15	0.5	11.5
Potable Water Tank Capacity (m^3)	35	50	1	41
Rated Power of the Desalination Unit (W)	600	1000	100	700

Energy Capacity rating of each of the 2 V batteries. 24 are used for a 48 V DC bus (Wh)	400,500,600, 700, 840	600

6.4 Comparison of the different Energy Management System approaches

The optimal configurations of the three energy management approaches for the case study are presented in Table 6.11 Comparisons of the different EMS.

Table 6.11 Comparisons of the different EMS

EMS	SEMS	FLEMS	FPEMS
Installed PV power (Wp)	6300	6480	5220
Rated Power of the Fuel Cell (W)	700	300	400
Rated Power of the Electrolyzer Unit (W)	1400	1000	1000
Hydrogen Storage Capacity (Nm^3 of H_2)	14.5	12	11.5
Potable Water Tank Capacity (m^3)	50	32	41
Rated Power of the Desalination Unit (W)	1000	900	700
Energy Capacity rating of each of the 2 V batteries. 24 are used for a 48 V DC bus (Wh)	840	400	600
Net Present Cost (€)	**106824**	**86617**	**85314**

It is clearly seen that part load operation of the fuel cell, electrolyzer and desalination unit can benefit the microgrid up to about 20% in NPC for this case study. Both the fuzzy logic approach and the combined petri net – fuzzy cognitive maps approach manage the microgrid more effectively, mainly because they allow part load operation of the various devices. FLEMS managed to considerably reduce the installed sizes of the fuel cell, electrolyzer and desalination unit, while, at the same time, minimizing the battery. Summarizing, FLEMS managed to lower the NPC by 20%. FPEMS even without the FCMs weights and PN parameters optimized gave a marginally cheaper system than FLEMS. After the end of Step 4 a clear reduction in the PV installed power is visible. The water tank is the cheapest component relatively of the microgrid. Because of the better management of the desalination unit it can lower its rated power to 700 W and get a relatively bigger potable water tank for less money than the other two approaches. The battery capacity is larger than FLEMS, but, still, a considerable reduction in comparison with SEMS. The NPC has dropped to 85314. As far as computational time is needed for FLEMS optimization the procedure took about 37 hours on a typical windows workstation (3 GHz cpu, 4 GB of ram and Windows XP). This big amount of time was the result of coupling two different software packages, TRNSYS and Matlab. Theoretically a new routine could be written in TRNSYS for fuzzy logic, but that could lack the intuitive graphical user interface of the Fuzzy Logic Toolkit which provides the control surfaces in order to tune the membership functions. Also as was discussed before further optimization of FLEMS can theoretically take place, but simultaneous optimization of 150 variables proves very complex and few –if any- software packages currently allow the optimization of such a big amount of variables. On the other hand FPEMS has much less variables for optimization. Because of this it was decided to optimize the weights of the FCMs and the transition parameters of the PN. Each of the steps 2,3 and 4 took about 4 hours to be completed, with a total processing time of 12 hours. Also, because the optimization takes place in discrete steps, there is no need to run the optimization for 12 hours in a row. The optimization of the variables is important, since by using this approach no excessive historical data or experience of such systems is necessary if the initial weights based on the experts' opinions are not proved very accurate. Another interesting point is that both FLEMS and FPEMS minimized the batteries in comparison to SEMS. This is the result of the high cost of the batteries and their need to be exchanged at regular intervals throughout the operational lifetime of the microgrid. Concluding, taking in consideration all aspects that were mentioned before, the combined Petri Nets – Fuzzy Cognitive Maps approach is the most promising. The FORTRAN code written in TRNSYS allows for low simulation times, but at the same time can be ported to Matlab easily. From Matlab the code can be exported to any kind of PLC, embedded processor solution or a control card with inputs and outputs for use in real world systems.

Comparative energy bar charts are presented in Figure 6.8. All configurations can cover the needs in electrical power, heating, cooling, potable water and hydrogen as fuel for transportation. FLEMS and FPEMS can cover the energy needs with less produced power. FPEMS presents a lower NPC by needing a lower rated electrolyzer and a smaller hydrogen tank. The smaller hydrogen tanks is bound to more activation time of the smaller electrolyzer unit in the case of FPEMS.

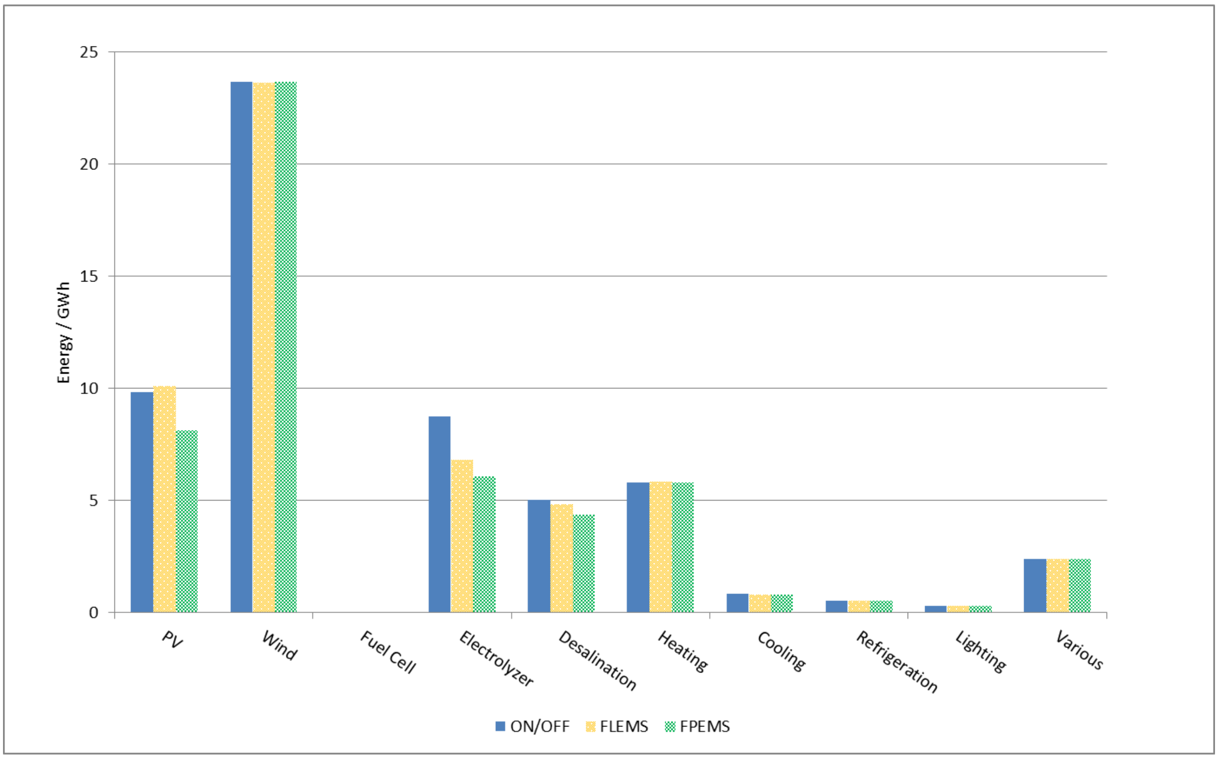


Figure 6.8 Yearly Produced and Consumed Energy

In Figure 6.9 the yearly variation of hydrogen volume in the metal hydride tank is presented. As it is seen, seasonal storage of hydrogen clearly takes place. FPEMS with a smaller tank can cover the same needs. The daily refueling of the vehicles is also presented in Figure 6.9

In Figure 6.10 the yearly variation of water volume in the potable water tank is presented. As it is seen the optimization process favors large storage tanks that are not emptied extremely in accordance with the design principle to always have at least 3 days of water in the potable water tank and the lower cost of the water tanks. The needs in water for three days amount to about 5.76 m^3 of water. The part load operation of the desalination unit of the FLEMS and the FPEMS microgrids gives more flexibility. FPEMS has a largest water tank coupled with a lower rating desalination unit in comparison to FLEMS as seen in Figure 6.10.

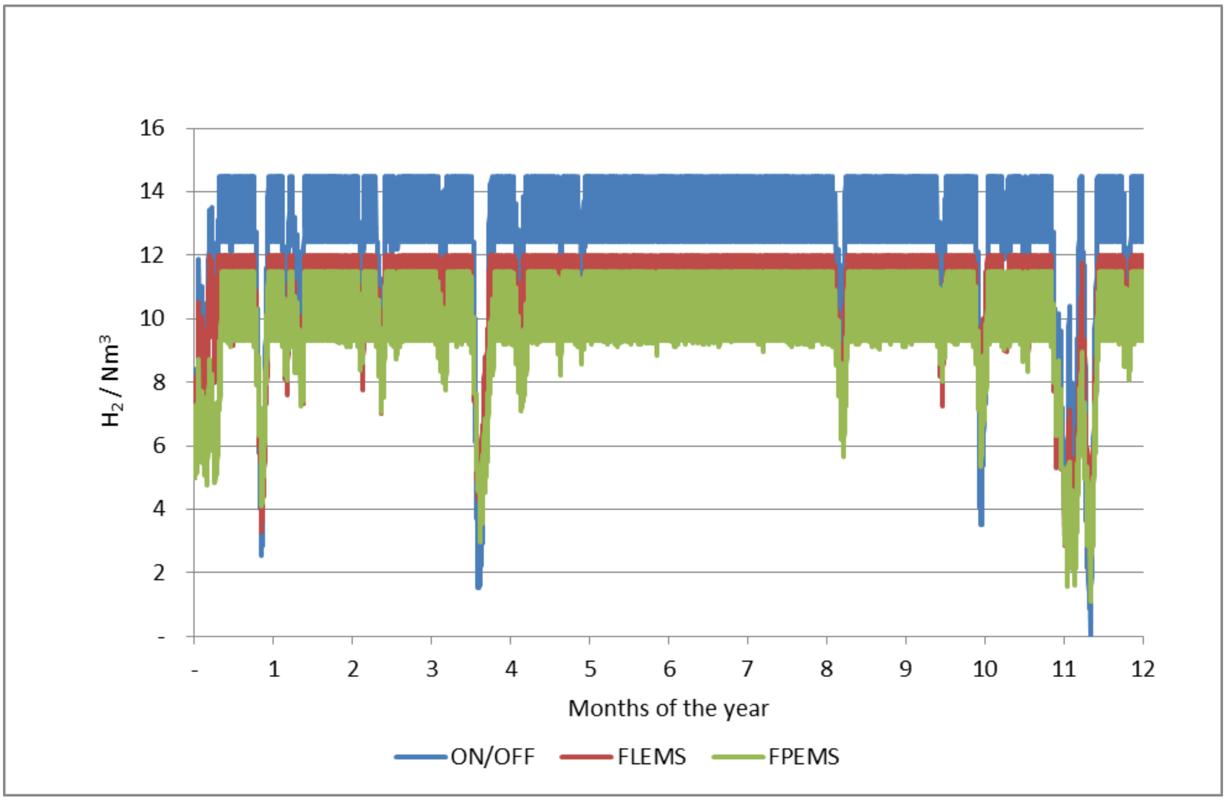


Figure 6.9 Hydrogen in the hydrogen tank

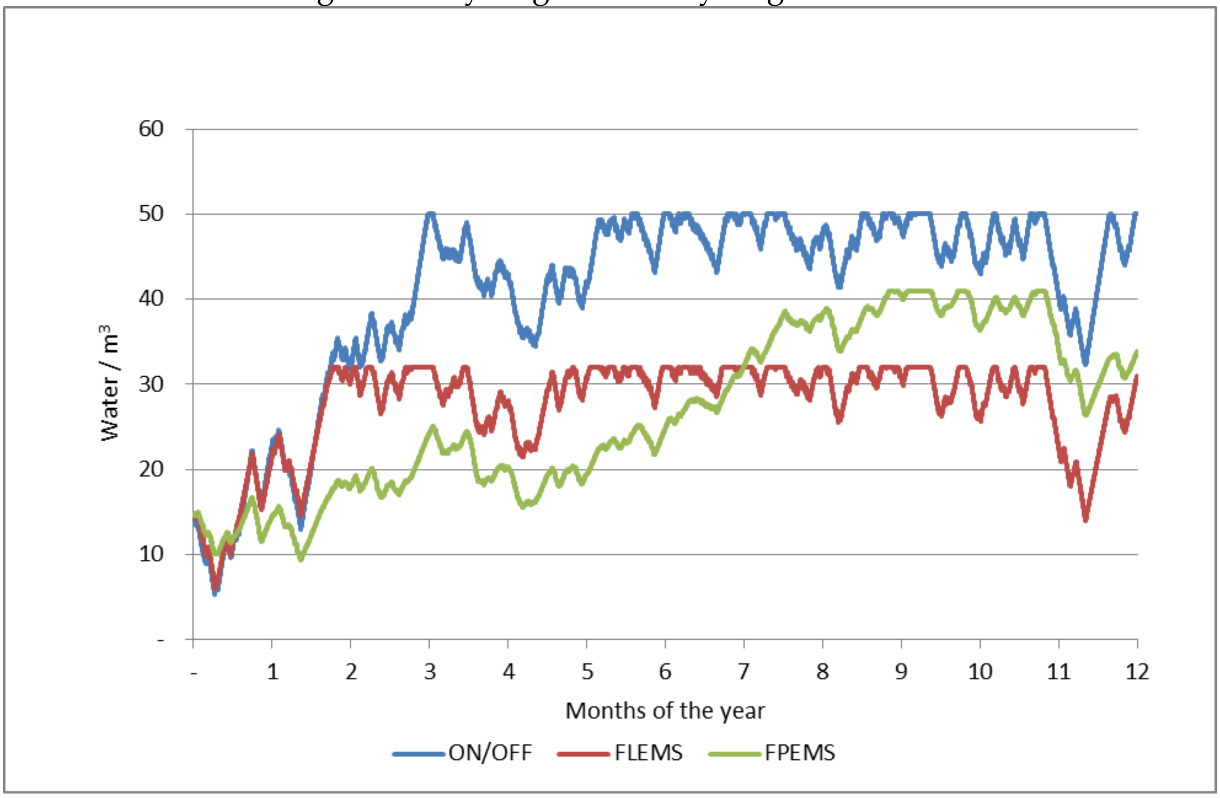


Figure 6.10 Water in the potable water tank

Three typical days were chosen in order to show the different performance of the three EMSs. One day was chosen to present operation under high energy production conditions from the PV and wind turbine, another where the microgrid operates near its technical limit because of harsh meteorological conditions and one with average conditions in between the other two extreme cases. These days are the 1st of August, the 1st of October and the 10th of December. In Figure 6.11 the power figures for the 1st of August are presented. The solar and wind potential remain high for this day. For all three EMS the battery remains fully charged throughout the day. For SEMS the electrolyzer and desalination unit remain on continuously apart from the load peak early in the morning when the desalination is turned off. For FLEMS and FPEMS the devices remain on constantly again but in two occasions they operate in a lower operational point. This happens initially in the morning and in the evening. FPEMS proves to handle better the power fluctuations in the microgrid since it cuts down the power to the electrolyzer and desalination unit at the same time the peak in the load occurs, whereas FLEMS keeps the electrolyzer which has full priority at 100% and lowers the operation point of the desalination unit considerably as seen in Figure 6.11 .

The second typical day is October 1st and it is presented in Figure 6.12. For SEMS SOC fluctuates a lot throughout the day from about 50% to almost fully charged. The wind potential is low for this day, but the PV produce considerable power. At about noon when the PV power has charged the battery both the electrolyzer and desalination units are turned on. When the sun starts to set the available power in the system drops and so the desalination unit is turned off. The electrolyzer remains on until the evening when it is turned off because of the low SOC. FLEMS presents better energy management than SEMS. Even though its battery is of lower capacity, SOC remains between 65% and 100% throughout the day. The electrolyzer is turned on in part load at 10 o'clock and a couple of hours later the desalination unit is also turned on at full load while the battery is fully charged. When in the afternoon the PV produced power drops the desalination unit is operated at part load until late in the evening both devices are turned off. FPEMS on the other hands presents the best management of the three. It is able to operate the devices in much longer time period, but in part load, utilizing the PV produced power better.

The last day is the 10th of December and its data is presented in Figure 6.13. The battery SOC was low from the previous day for all EMSs. There is no wind and the sun has not risen yet so the electrical load is drawing power from the battery bank. For SEMS and FLEMS in order to protect the battery bank from deep discharge, the fuel cell is turned on. For FLEMS the fuel cell is turned on in part load, following the load of the microgrid until the sun rises and the PV start to produce more power. FPEMS was designed with a 50 Ah larger battery bank. This small increase in the capacity is enough to keep the fuel cell off. SEMS due to the larger PV array manages to charge its battery and in the evening it is able to turn on for a couple of hours the electrolyzer. This in turn discharges the battery bank and is down to about 45% in the evening.

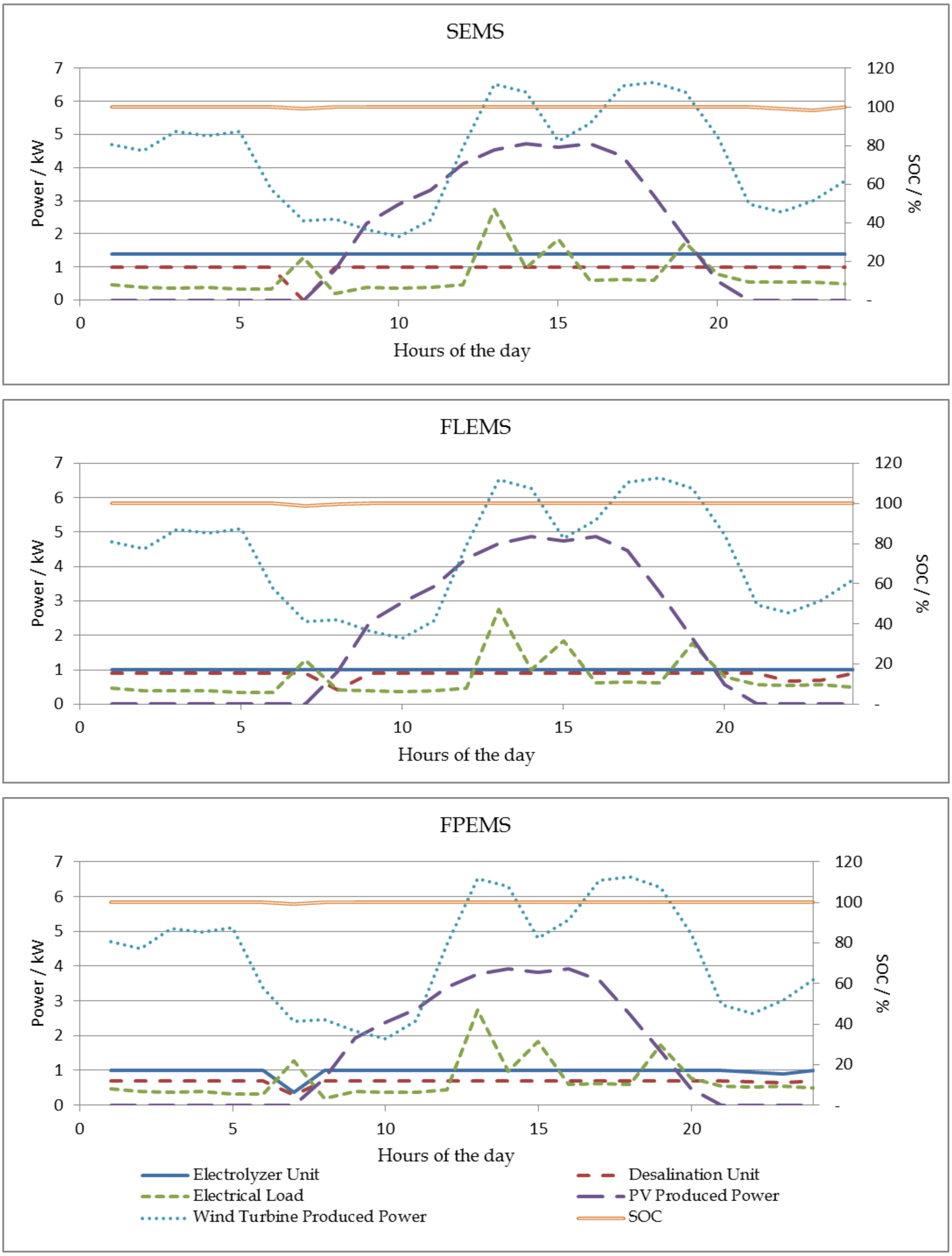


Figure 6.11 Hourly produced and consumed power from the different microgrid components for the 1st of August

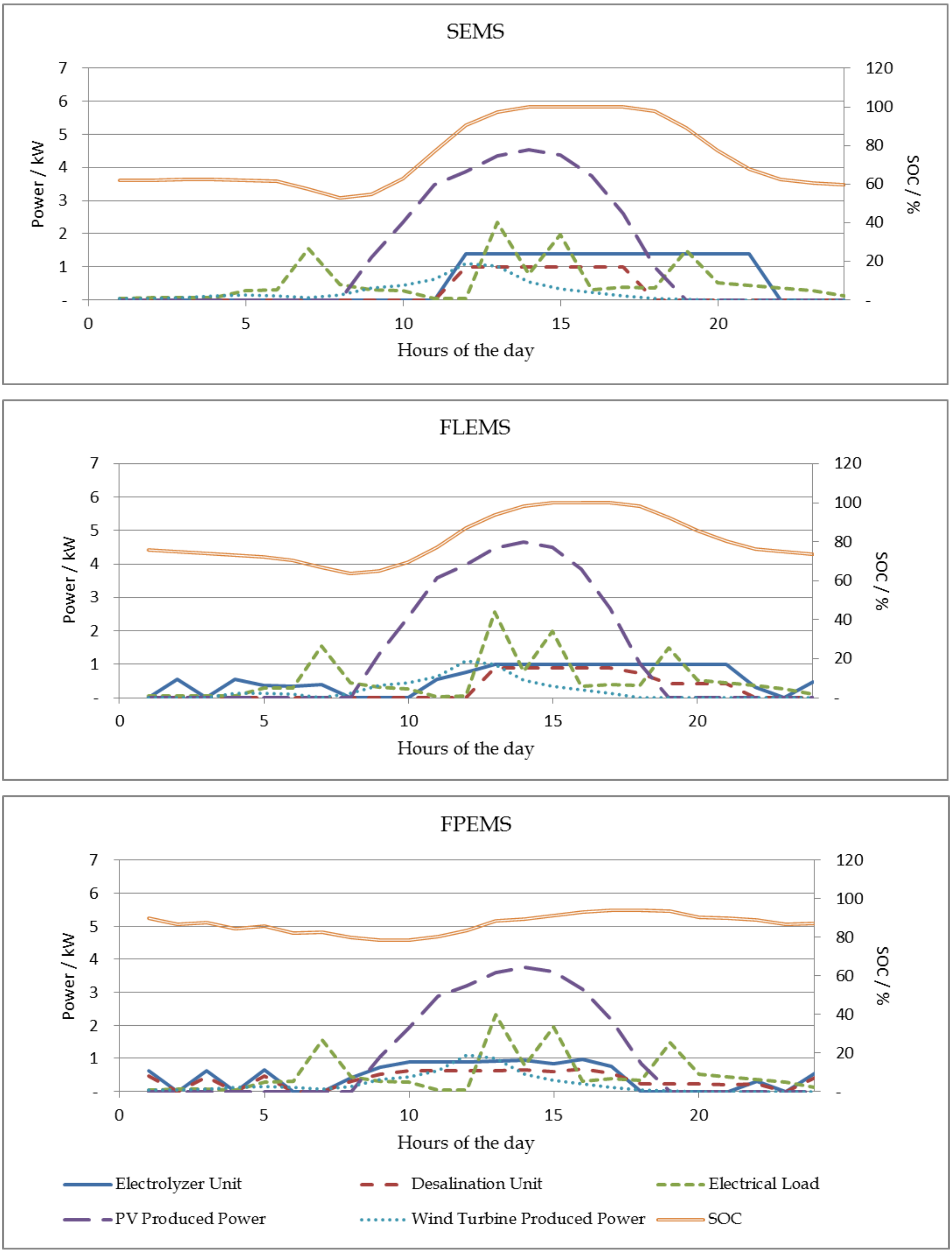


Figure 6.12 Hourly produced and consumed power from the different microgrid components for the 1st of October

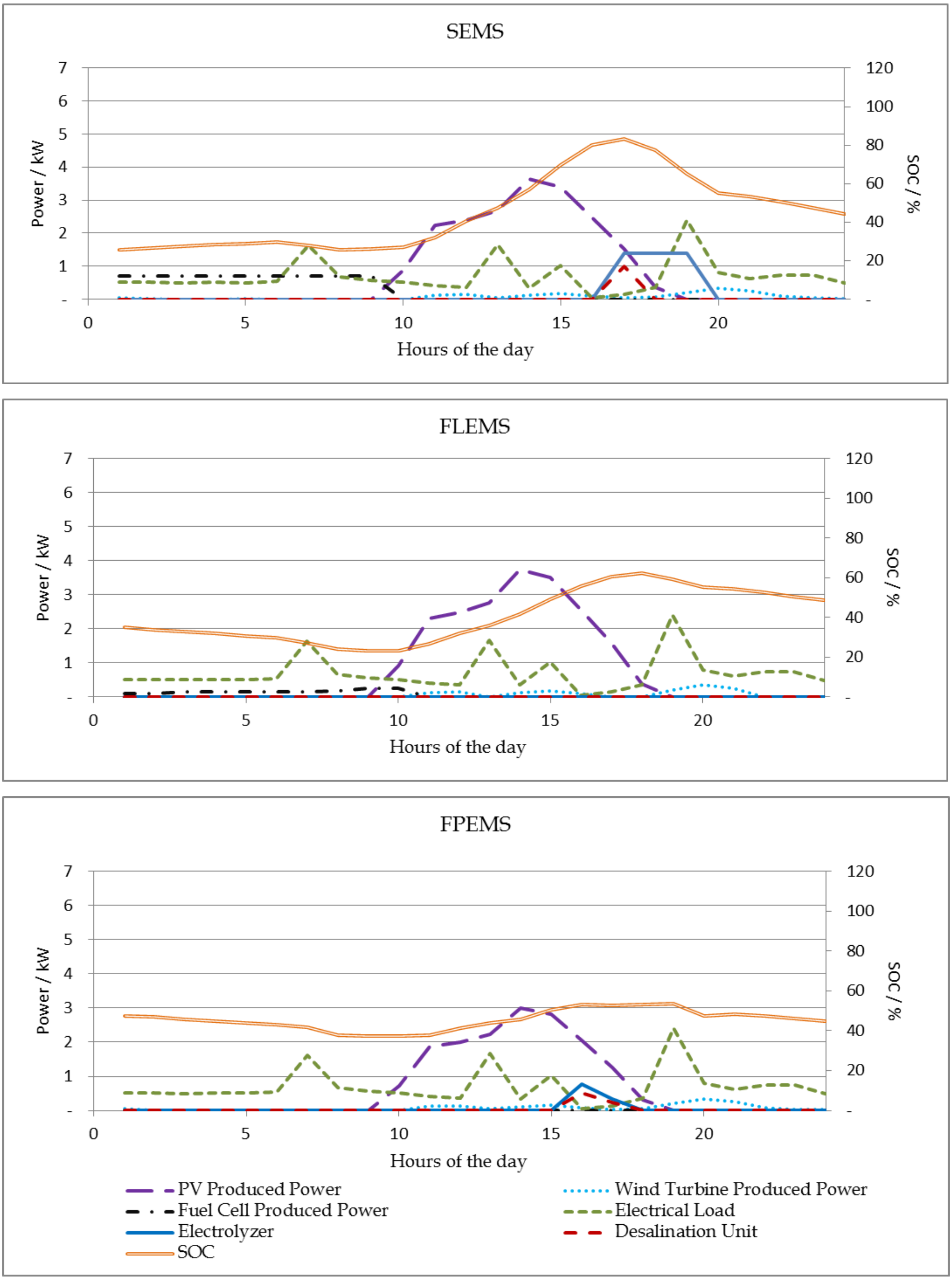


Figure 6.13 Hourly produced and consumed power from the different microgrid components for the 10th of December

7 Intelligent Demand Side Energy Management

7.1 Introduction to Demand Side Energy Management

As was discussed in Paragraph 2.3 an intelligent demand side power management of the loads has to be implemented. The optimal design of the system can meet only the design principles and needs. In reality experience has shown that most autonomous power systems operate out of specifications very shortly after installation. People especially in the developing world fail to understand that power is not limitless and thus frequent blackouts can occur, if no education of the consumers takes place while installing the system. Also many times even if the designed microgrid is able to cover the initial load after a couple of years new needs arise and it is not possible economic wise for the people to extend it. In these cases the microgrid would struggle to cover the increased needs and in the end fail, causing blackouts. It would be more preferable if partial load shedding occurred and in the long term important consumptions as refrigeration and lighting never failed, even if consumptions like television viewing were shed.

Demand side management (DSM) for microgrids has been researched considerably in the past years (Duan and Deconinck, 2008; Logenthiran, Srinivasan et al., 2010; Romanos, Hatziargyriou et al., 2010; Colson and Nehrir, 2011; Minciardi and Sacile, 2011). Most of the approaches are based on Multi Agent Systems. Moreover, research has taken place in not only the management of electrical power, but space heating and cooling as well (Alvarez, Gomez-Aleixandre et al., 2009). Most of the work in this field has to do with buildings, which are considered to represent a microgrid and through smart control to optimize the energy usage in it (Simoes and Bhattarai, 2011; Wang, Dounis et al., 2011). In almost all cases the microgrid is considered to be interconnected with a major grid and demand side management has to do with the optimal scheduling of the loads (such as washing machines) when the power is cheaper. Some work has taken place for autonomous microgrids as well (Chatzivasiliadis, Hatziargyriou et al., 2008; Alvial-Palavicino, Garrido-Echeverría et al., 2011). Based on the literature review it is decided to develop a demand side management system based on a Multi Agent System topology to be able to manage both electrical power loads and space heating and cooling.

Forecasting of the produced power from the PV array and the wind-turbine can be very important in an autonomous system. Many approaches have been used in the past for forecasting the solar irradiation and thus the PV produced power, as well as the wind speed and consequently the Wind turbine produced power. These approaches include, historical data approaches, statistical approaches and hybrid methods which take advantage of computational intelligence tools (Lydia and Kumar, 2010; Yuehui, Jing et al., 2010). Most of the approaches are based on Artificial Neural Networks (ANN). The use of ANN includes its learning which introduces complexity if there are no historical data available. A new approach has been proposed which includes the use of Grey Prediction algorithms(Dounis, Tiropanis et al., 2005). Its main advantages include the need for only 5 previous values in a time series and its simplicity in its implementation. Because of this it was decided to implement a Grey Predictor (GP) for the prediction of the PV and Wind turbine produced power to be used in the DSM.

7.2 Agents and Multi-agent systems

In the 70s a new field of research in the Artificial Intelligence domain came upon and started to evolve quickly. This field was Distributed Artificial Intelligence (DAI). DAI according to Weiss (Weiss, 2000) can be described as "the study, construction and application of multiagent systems, that is, systems in which several interacting intelligent agents pursue some set of goals or perform some set tasks". This provides better understanding for what DAI is and can act as a description of multiagent systems as well, but leaves the question of what is an agent. According to Wooldridge (Wooldridge, 2002) "an agent is a computer system situated in some environment and that is capable of autonomous action in this environment in order to meet its design objectives". An agent is depicted in Figure 7.1.

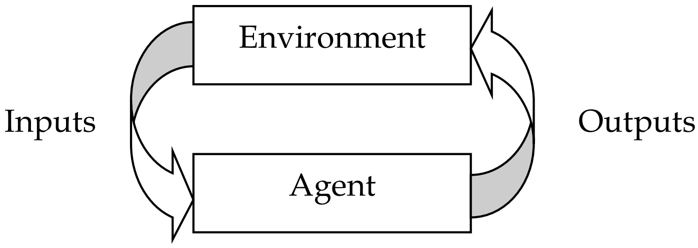


Figure 7.1 A typical Agent

It is important to note that an agent most likely will not have absolute control of its environment. That means that its actions can and will influence the environment but the reaction of the environment is not certain. An agent might react the same way to the same inputs of the environment, but the environment might evolve differently in those situations. A typical example of this found in literature is a thermostat. A thermostat can be viewed as an agent which has the environment temperature as input and the ON or OFF command to the heating unit as output. The thermostat agent will compare the environment temperature to the set temperature it has and if it is lower it will turn on the heating. Even as such it is not known whether the room temperature will reach the set temperature of the thermostat, because someone might open a window or a door.

The next important aspect to be addressed is when an agent is considered to be intelligent. According to Wooldridge (Wooldridge, 2002) and agent needs to be reactive, proactive and social in order to be considered as intelligent. Reactivity means that the agent must be aware of its environment and to respond to the inputs from the environment according to its design and programming. Proactivity of an intelligent agent can be described as the ability to take initiative in acting in a way to fulfill its design objectives. Social ability finally can be described as the ability to cooperate with other intelligent agents or even humans in order to fulfill its design objectives.

An agent has to perceive the environment in which it exists. The agent is designed in order to fulfill a specific goal or goals. In order to fulfill the goals it has to be able to undertake specific actions and finally in order to decide which actions it has to undertake, it has to be able to perceive its environment. So, for the agent to be fully described, the Percepts, Actions, Goals and its Environment (PAGE) have to be defined (Russell and Norvig, 2009).

According to Russell and Norving (Russell and Norvig, 2009) the following different properties have been proposed in order for a classification of the agents' environments to take place.

- Accessible vs. inaccessible. As the complexity of an environment increases, the environments become more inaccessible. An inaccessible environment needs more complicated agents,
- Deterministic vs. non-deterministic. Complicated systems are non-deterministic, since the same action may result in a different state of the environment.
- Episodic vs. non-episodic. When even slight changes in the environment change the performance of the whole system, the action of the agent depends only on the current episode and not previous ones.
- Static vs. dynamic. A static environment remains the same if the agent takes no action. In dynamic environments there are also other ongoing processes that will affect the new state of the environment apart from the agent's actions.
- Discrete vs. continuous. A discrete environment is one where there are a fixed and finite number of actions and percepts.

There are four different types of agent programs (Russell and Norvig, 2009),

- Simple reflex agents. Their main characteristic is simplicity. Every action is tied to a specific condition. The agent identifies the current condition and reacts according to the predetermined rules.
- Agents that keep track of the world. They are "upgraded" versions of the simple reflex agents. The difference lies in the fact that the current percept is combined with the previous state in order to generate the current state.
- Goal-based agents. Their rule structure is similar to a controller. This gives them the needed flexibility in order to accomplish the programmed goals.
- Utility-based agents. Utility can be seen as a function that maps each state to a real number usually in the range [0,1]. A high number denotes a high degree of satisfaction. In this sense the utility based agent tries through its actions to maximize the utility function. These agents are usually used in

supervisor systems. They can address situations where goals are conflicting. In this case the utility function can be seen as the description of the appropriate trade-off.

A Multi-Agent System (MAS) can be defined as a system that comprises of a number of intelligent agents. The final purpose of a MAS is to coordinate and fulfill its design goals and tasks. The intelligent agents that make up the MAS can operate in a cooperation or a competitive mode. In the first case they all cooperate in order to combine their actions in order to have an effect to the environment that an individual could not accomplish. In a competitive mode only some of the agents can accomplish their goals, so all intelligent agents are competing against each other in order to have their own objectives met. The long term of DAI is to make the interaction of intelligent agents as good or even better as human interaction and to be able to interact with the same success with any kind of intelligent entity be it machine based or human (Weiss, 2000).

According to Weiss (Weiss, 2000) the major characteristics of MAS are:

1. The information each agent possesses is incomplete and restricted
2. The control of the system is distributed
3. Data is decentralized
4. The computation is asynchronous

An example from nature can describe how a sum of many agents of low intelligence each can accomplish complex and adaptive behavior. A bee colony is comprised of three main groups of bees, the queen, the workers and the drones. Even though no single entity understands everything or is able to do all actions that are needed. But as a colony all aspects are addressed intelligently.

7.3 Grey Systems Theory

Grey Systems Theory (GST) is concerned with the study of uncertain systems with partially known information. The information samples can be small and poor in quality with high noise. GST aims to extract useful information from the available limited information (Liu and Lin, 2011). Since most real systems present such behavior it is expected that GST will have a vast range of applicability.

A Grey Model Prediction Algorithm (GP) is going to be employed for the forecasting of the produced power from the PV array and the wind turbine. The GP will run using the 4 last measured values and predict the 5th. The procedure is continuous as presented below:

First prediction

$$y_1^{(0)} = [y^{(0)}(1), y^{(0)}(2), y^{(0)}(3), y^{(0)}(4)] \xrightarrow{GP} \hat{y}^{(0)} \text{ (EQ 32)}$$

Second prediction

$$y_2^{(0)} = [y^{(0)}(2), y^{(0)}(3), y^{(0)}(4), y^{(0)}(5)] \xrightarrow{GP} \hat{y}^{(0)} \text{ (EQ 33)}$$

Where:

$y^{(0)}(n)$ is the nth measured value

$\hat{y}^{(0)}(n)$ is the predicted value

GP was realized according to the methodology proposed by Dounis et al (Dounis, Tiropanis et al., 2005) and is a 4 step procedure.

1st Step

The data is checked whether negative numbers appear in it. Negative values are prohibited in Grey Modeling. In order to overcome this the absolute maximum negative value is added to the rest in order to shift data in the range $[0, +\infty)$ (Dounis, Tiropanis et al., 2005).

2nd Step

This step includes the pre-processing of the original raw data. Through the use of the first order Accumulated Generating Operations (AGO) algorithm the sequence $y^{(0)}$ is transformed to sequence $y^{(1)}$. This procedure weakens randomness in the available data.

$$y_1^{(1)}(k) = AGO \cdot y_1^{(0)} = \sum_{m=1}^{k} y_1^{(0)}(m), \quad k = 1, 2, 3, 4 \text{ (EQ 34)}$$

$$y_1^{(1)}(k) = [y_1^{(1)}(1), y_1^{(1)}(2), \ldots, y_1^{(1)}(n)] \text{ (EQ 35)}$$

3rd Step

The new sequence generated in step 2, $y^{(1)}$ can be modeled by a first order differential equation which is called whitening equation as follows:

$$\frac{dy^{(1)}}{dt} + a_g \cdot y^{(1)} = u_g \text{ (EQ 36)}$$

Where:

a_g: the development coefficient

u_g: grey input

This is referred to as the basic form of the GM(1,1) model and stands for first order grey model with a single variable.

The sequence $z^{(1)}(k)$ is obtained by applying the adjacent neighbor means (MEAN) operation to sequence $y^{(1)}$.

$$z_1^{(1)}(k) = \text{MEAN} \cdot y_1^{(1)} = \frac{1}{2} \cdot [y_1^{(1)}(k) + y_1^{(1)}(k\text{-}1)], \quad k = 2,3,4 \text{ (EQ 37)}$$

The MEAN operation generally is expressed by the following equation (Dounis, Tiropanis et al., 2005):

$$z^{(1)}(k) = ay^{(1)}(k) + (1\text{-}a)\,y^{(1)}(k\text{-}1),\ a \in [0,1] \text{ (EQ 38)}$$

Since the prediction sampling time is equal to 1:

$$\frac{dy^{(1)}}{dt} = y^{(1)}(k) - y^{(1)}(k\text{-}1) \overset{AGO}{=} y^{(0)}(k) \text{ (EQ 39)}$$

By substitution to the Grey Differential Equation is formed

$$y^{(0)}(k) + a_g z^{(1)}(k) = u_g \text{ (EQ 40)}$$

For solving the GDE the development parameter and the grey input must be calculated. In order to do that the Least Square Error Method is applied as follows (Dounis, Tiropanis et al., 2005):

$$\underbrace{\begin{bmatrix} y^{(0)}(2) \\ y^{(0)}(3) \\ y^{(0)}(4) \\ . \\ . \\ . \\ y^{(0)}(n) \end{bmatrix}}_{\mathbf{Y}} = \underbrace{\begin{bmatrix} -z_1^{(1)}(2) & 1 \\ -z_1^{(1)}(3) & 1 \\ -z_1^{(1)}(4) & 1 \\ . & . \\ . & . \\ . & . \\ -z_1^{(1)}(n) & 1 \end{bmatrix}}_{\mathbf{B}} \cdot \underbrace{\begin{bmatrix} a_g \\ u_g \end{bmatrix}}_{\hat{a}}, \quad \hat{a} = (B^T \times B)^{-1} \times B^T \times Y \text{ (EQ 41)}$$

After the calculation of a_g, u_g, $\hat{y}^{(1)}(4)$ and $\hat{y}^{(1)}(5)$ can be in turn calculated through the use of $\hat{y}^{(1)}(k+1) = (y^{(0)}(1) - \frac{u_g}{a_g}) \cdot e^{-a_g k} + \frac{u_g}{a_g}$ (EQ 42.

$$\hat{y}^{(1)}(k+1) = (y^{(0)}(1) - \frac{u_g}{a_g}) \cdot e^{-a_g k} + \frac{u_g}{a_g} \text{ (EQ 42)}$$

Step 4

Through the use of the inverse AGO (IAGO) on sequence $\hat{y}^{(1)}(k)$, $\hat{y}^{(0)}(5)$ can be calculated, according to $\hat{y}^{(0)}(k+1) = \hat{y}^{(1)}(k+1) - \hat{y}^{(1)}(k)$ (EQ 43.

$$\hat{y}^{(0)}(k+1) = \hat{y}^{(1)}(k+1) - \hat{y}^{(1)}(k) \quad \text{(EQ 43)}$$

The procedure described in Steps 1 to 4 can be summarized by the following scheme (Dounis, Tiropanis et al., 2005):

$$\hat{y}^{(1)}(n+1) = IAGO \cdot GM(1,1) \cdot AGO \cdot y^{(0)} \text{ (EQ 44)}$$

7.4 Intelligent Demand Side Management System

In the proposed topology a demand side management system is proposed to be used when the needs increase in the future, the installed power cannot meet the load, and the people cannot pay for the installation of a new PV array or wind turbine. Its implementation in the topology is presented in Figure 7.2.

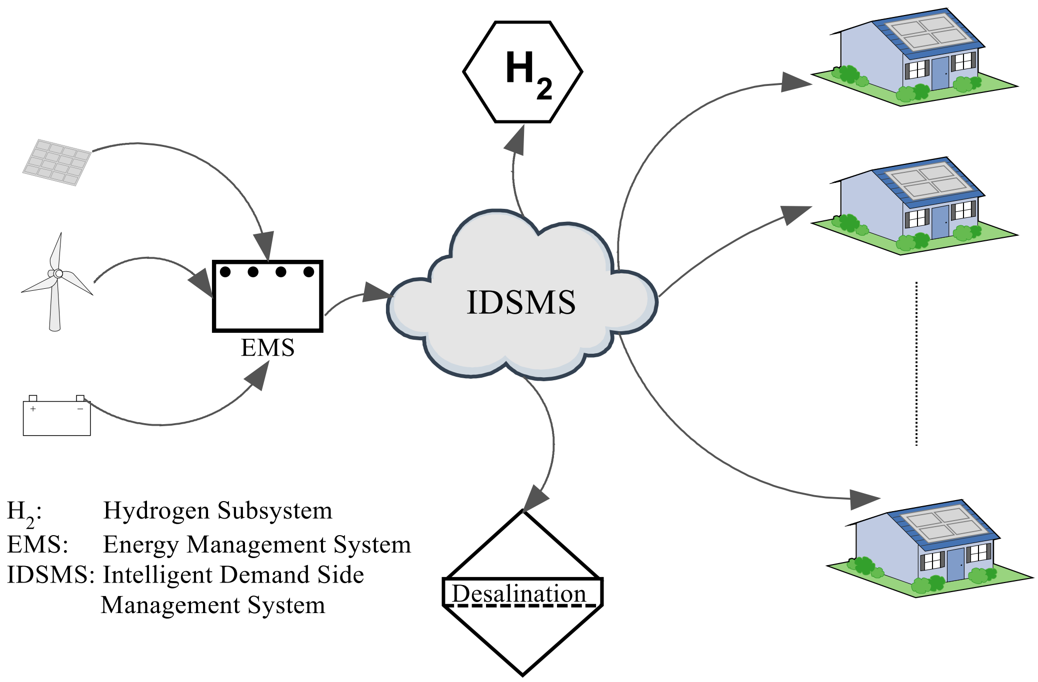


Figure 7.2 Polygeneration Smartgrid topology

In order to design a Demand Side Management system for a polygeneration microgrid, the potable water, the hydrogen and the electrical consumptions of the houses need to be taken in consideration. Potable water is of the upmost essence to the people there. Also some hydrogen should always be available, first to be used in an emergency situation to travel to a nearby city and secondly if out of a result of a malfunction the batteries get empty an external charger is needed to charge them. Without any voltage from the batteries no microgrid can be formed and as a result the PV arrays and the wind turbines will not be able to charge the batteries. The fuel cell with some hydrogen can charge the batteries in such a situation. This way it is understood that the top priority of the demand side management system is to guaranty that there is a minimum quantity of water, as well as hydrogen available at all times. This way, two agents, one for the desalination unit and one for the electrolyzer unit activate the devices when the quantity in the tanks drops below a set threshold. This quantity can be set as the needs for 1 day. Also the operation point of the devices can be set as equal to the point where the device would produce in 1 hour the average hourly consumption of potable water and hydrogen. The PAGE description of the IDSMS is presented in Table 7.1 PAGE of the MAS.

Table 7.1 PAGE of the MAS

Percepts	Power that is produced and consumed in all parts of the microgrid, Battery SOC, Frequency of the microgrid, Solar Irradiation, Dry bulb temperature both for outside and inside each of the houses, wind speed, available water in the potable water tank, available hydrogen in the hydrogen tank, PMV in each house
Actions	To evaluate and change if necessary EMS commands, to be able to cut individually all power lines in all of the houses.
Goals	To have zero potable water and hydrogen shortage, not to let the battery get deep discharged and to meet the maximum technically feasible power demands of the users
Environment	All components of the microgrid, the houses that are connected to it and the local climatic environment.

Furthermore, the developed Intellignet Demand Side Management System (IDSMS) categorizes the household loads in four categories:

1. Lighting
2. Refrigeration (fridge and freezer)
3. Various Consumptions (white appliances, electronic devices etc)
4. Space heating/cooling

The lights of the household have the highest priority of all loads. Their installed power is minimal in comparison with the other loads. This means that their disconnection would have minimal impact on system stability. The refrigeration loads have the second highest priority. This is because food is stored there, which is essential for the wellbeing of the people. The last priority category includes the space heating/cooling and the rest of the electrical consumptions. The priority of the load categories is presented in Figure 7.3 Priority of the load categories. In each time step if it is decided to shed more loads one power line from all the houses gets disconnected. All the power lines from the same priority category need to be disconnected from all households before a disconnection of a higher priority load takes place. This means for example that no house will have its refrigeration line disconnected, when at the same there is at least one house with its air conditioning units turned on.

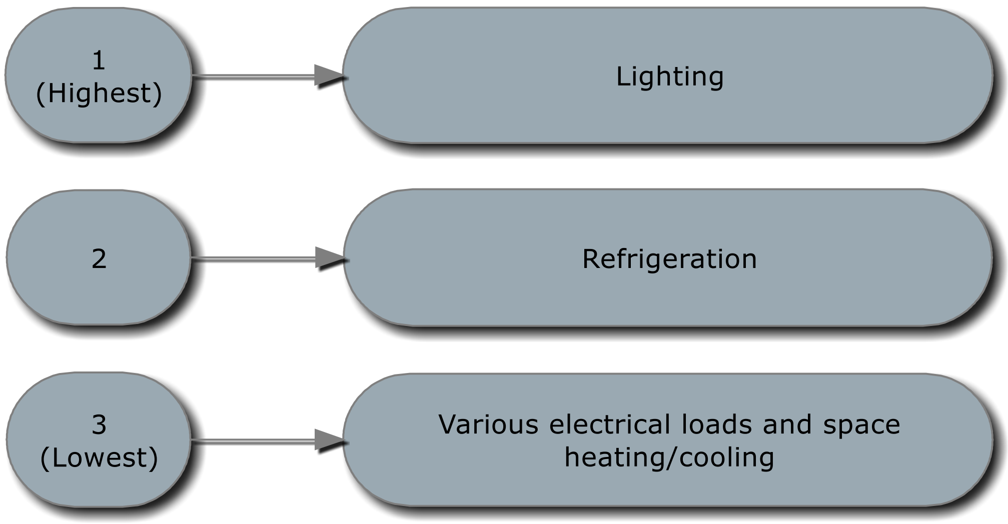


Figure 7.3 Priority of the load categories

Since the various consumptions and the space heating/cooling belong to the same priority category a scheme was designed in order to give priority inside this category. Thermal comfort is taken in consideration. As a measure of thermal comfort the Predicted Mean Vote (PMV) is used. PMV predicts the mean response of a larger group of people according to the ASHRAE thermal sensation scale based on P.O. Fanger's model presented in ISO 7730. If the indoor climate is ok then priority is given to the rest of the consumptions. If the indoor climate is outside of acceptability margins then priority is given to the air conditioning units.

Based on the state of the microgrid the IDSMS can activate and deactivate any of the above load categories in any of the households. IDSMS is based on a Multi Agent System (MAS) approach. The MAS approach comprises of 4 layers and is presented in Figure 7.4. IDSMS operates automatically, but it can also interact with the users through information LEDs which can inform of eminent load disconnections, so that the users can decide on their own if they want, which loads to disconnect, so as to cancel the need for the IDSMS activation. A good rule of thumb in deciding the control time step is to be certain that all big power consumptions of all households need to be turned off after 1 hour of the activation of the IDSMS.

The decision on which power line of which house to cut first is the result of the negotiation of the intelligent supervisor with the four control agents of each house and then the negotiation of all intelligent supervisors together. The main criterion in the negotiation of the intelligent house agents of each house is the consumption of the household for the last 3 days. This is done in order to compliment the users who have consumed the least energy the past days. At the same time, though, DMS has to make certain that load shedding is taking place globally in accordance with the priority of each load category (e.g. so that no house gets its refrigeration line disconnected while at another house the people are watching television). Two numbers would have to be communicated along the intelligent supervisor agents of each household for negotiation; the consumed power of the past 3 days and number which would declare if and which load categories of each house have been shed. In order to simplify this it was decided to create a small algorithm that produces a single number to be communicated from each intelligent agent to the rest. This algorithm is presented in Figure 7.5.

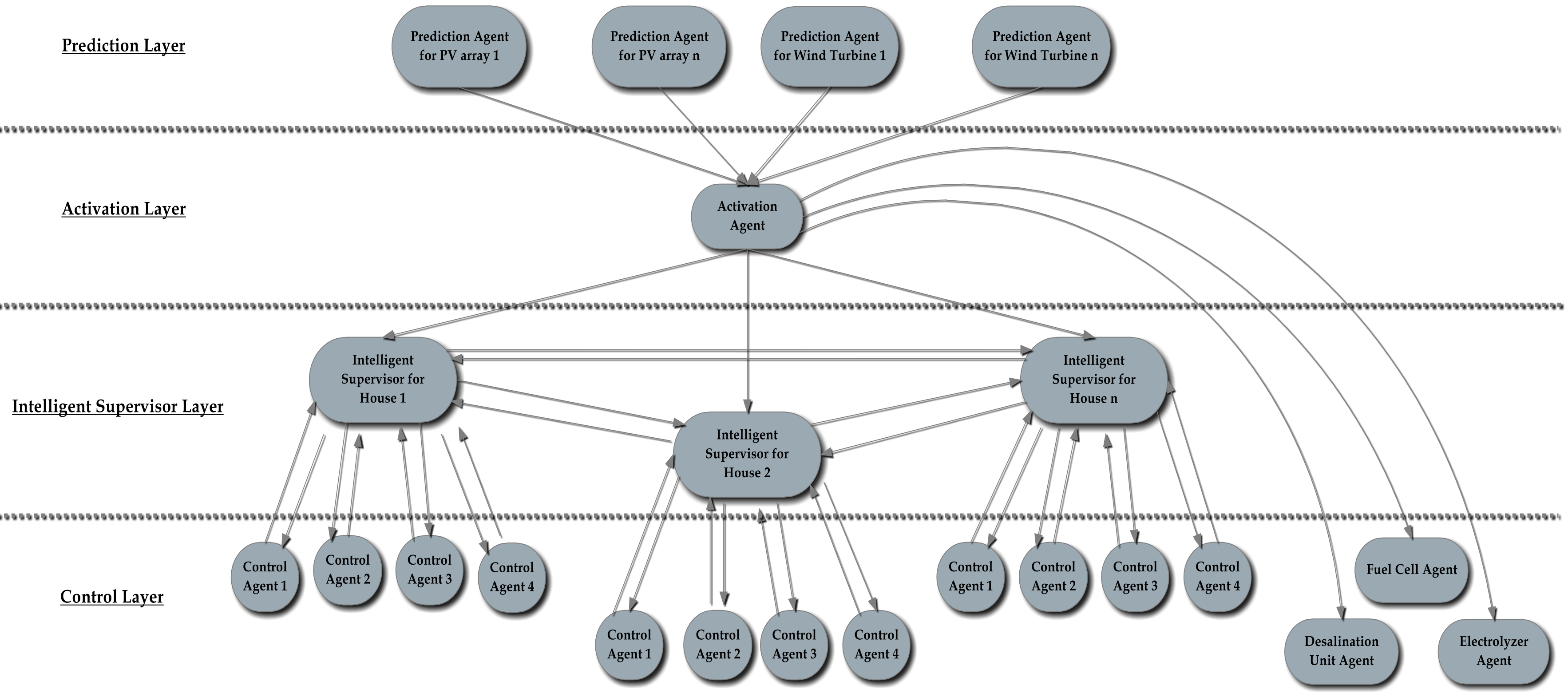


Figure 7.4 Intelligent Demand Side Management System structure

The first action that takes place when the IDSMS is activated is a horizontal action affecting the thermostats of all air conditioning units in all households. The set point temperature is changed from the default set values to adaptive temperature values that are calculated in real time in accordance with the outside temperature. For heating the model proposed by the European Committee for Standardization standard EN 15251 is used and for cooling the equation proposed by Nicol et al is used (Nicol, Humphreys et al., 1995). The indoor comfort temperature equations for heating and cooling are presented in EQ 45 and EQ 46.

$T_c = 18.8 + 0.33 \cdot T_o$, for heating (EQ 45)

$T_c = 18.6 + 0.16 \cdot T_o$, for cooling (EQ 46)

Where:

T_c: Indoor comfort temperature

T_o: Outside Temperature

Then for each control time step one more line in one of the houses will get disconnected, so long as the activation layer decides so. That decision is based on the power balance present at the microgrid. Below are presented in detail all the agents in the MAS and in is presented the overall operation of the IDSMS.

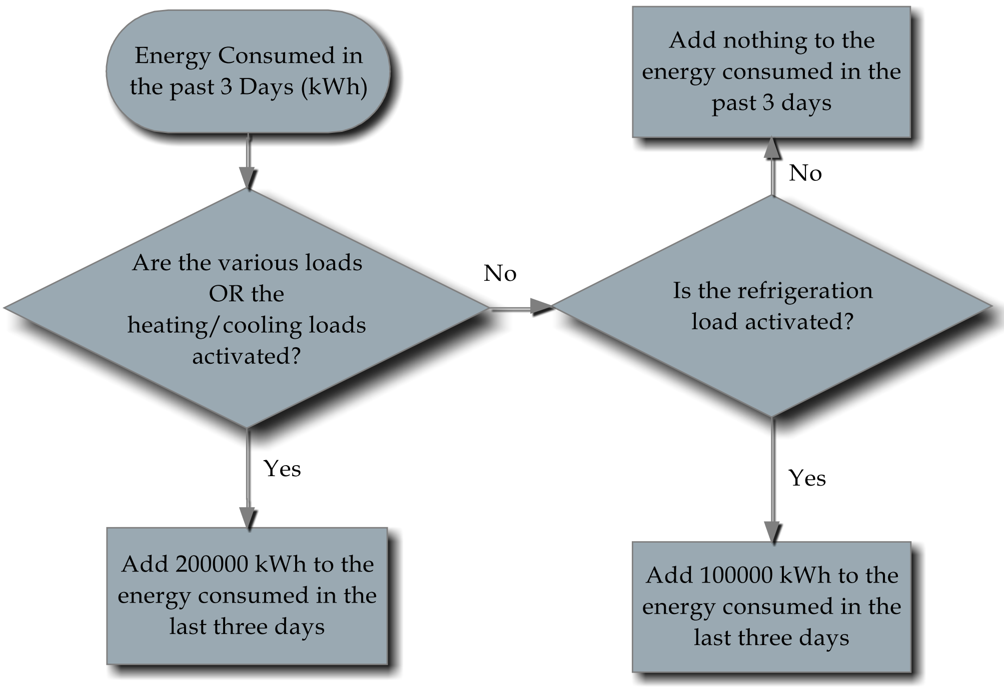


Figure 7.5 Negotiation value calculation algorithm

7.4.1 Prediction Layer

Two prediction agents are needed, one for the photovoltaic array(s) and one for the wind turbine(s) used in the microgrid. A first order grey model with one variable is used for both cases. In the first case the global solar radiation is predicted, and in the second case the wind speed. These predictions are then fed to a model and the power to be produced in the next time step of the IDSMS from the photovoltaic array(s) and the wind turbine(s) is calculated.

7.4.2 Activation Layer

The activation layer comprised of a single activation agent. This intelligent agent decides whether the IDSMS has to be activated and if further load disconnections should occur. Its Inputs and Outputs are presented in Table 7.2. It is a goal-based agent.

Table 7.2 Activation Agent Inputs/Outputs

Inputs	Outputs
1. State of Charge of the Battery	Activation of the Demand Side Management (Activated/Deactivated)
2. Frequency of the microgrid	Shedding of more loads (Activated/Deactivated)
3. Prediction for PV produced power	Inform the users for imminent automatic load disconnections so that they could on their own disconnect some loads (Activated/Deactivated)
4. Prediction for Wind Turbine produced power	Emergency disconnection of all loads (Activated/Deactivated)

The activation of the Demand Side Management (Output 1) is based on a double Hysteresis Scheme, which is presented in Figure 7.6.

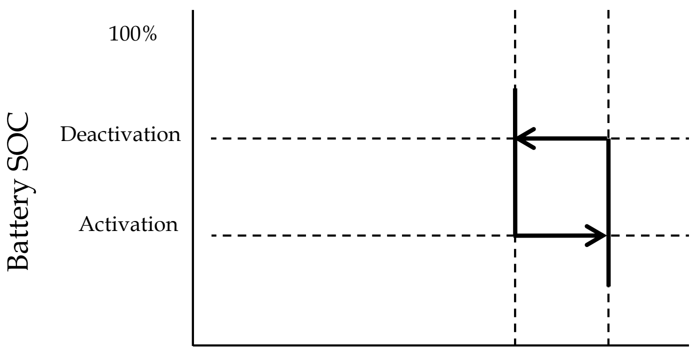


Figure 7.6 Activation & Deactivation of IDSMS

In the topology used the frequency of the microgrid presents the power balance in the system. If it is below 50 Hz there is a power deficit in the microgrid and if it is above 50 Hz the produced power is more than the consumed. If in the last control time step the frequency is positive no more loads need to be shed. If it is negative the prediction of the produced power for the next time step is compared with the current load. If the prediction is more than the current load then no more shedding takes place. If it is less more loads need to be shed.

If the SOC is 5% above the activation set SOC, then the interaction led with the users is activated. This gives a chance to the users to decrease their consumptions in order. All loads will be disconnected if the battery SOC drops below 15% in order to protect it.

7.4.3 Controller Agents Layer

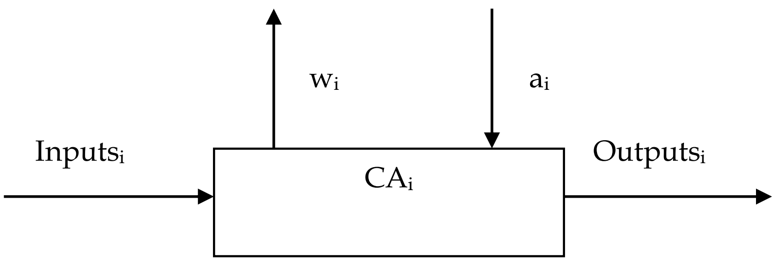
7.4.3.1 Controller Agents

These intelligent agents will be responsible for the disconnection of different power lines. Each household will have 4 such agents, each one controlling the power line of each of the four categories. The agent is presented in Where:

wi: activation signal

ai: acknowledge signal

Figure 7.7. These agents are simple reflex agents.



Where:

w_i: activation signal

a_i: acknowledge signal

Figure 7.7 Control Agent

7.4.3.2 *Lighting Agent*

The lighting agent controls the power lines from the electrical circuit board of each house to all the lights. The Inputs, Outputs and the state of activation are presented in Table 7.3 Lighting agent.

Table 7.3 Lighting agent

Inputs	Activation	Outputs
1. State of connection of lighting power line (0 deactivated, 1 activated) 2. State of connection of refrigeration power line (0 deactivated, 1 activated) 3. State of connection of heating/cooling power line (0 deactivated, 1 activated) 4. State of connection for the rest electrical consumptions(0 deactivated, 1 activated)	The agent gets activated IF Input 1=1 AND Inputs 2,3,4=0	If the agent's activation signal is acknowledged by the house's intelligent supervisor agent, the lighting lines are disconnected from mains

7.4.3.3 *Refrigeration agent*

The refrigeration agent controls the power lines from the electrical circuit board of each house to the fridge and the freezer. The Inputs, Outputs and the state of activation are presented in Table 7.4 Refrigeration agent.

Table 7.4 Refrigeration agent

Inputs	Activation	Outputs
1. State of connection of refrigeration power line (0 deactivated, 1 activated) 2. State of connection of heating/cooling power line (0 deactivated, 1 activated) 3. State of connection for the rest electrical consumptions(0 deactivated, 1 activated)	The agent gets activated IF Input 1=1 AND Inputs 2,3=0	If the agent's activation signal is acknowledged by the house's intelligent supervisor agent, the refrigeration lines are disconnected from mains.

7.4.3.4 *Space heating/cooling agent*

The space heating/cooling agent controls the power lines from the electrical circuit board of each house to the air conditioning units (air to air heat pumps). This agent utilizes a Predicted Mean Vote (PMV) sensor. PMV is an indicator of thermal comfort in the building. It takes values from -3 to 3, with 0 representing optimal comfort, -3 very cold and 3 very hot. The Inputs, Outputs and the state of activation of this agent are presented in Table 7.5.

Table 7.5 Space Heating/Cooling agent

Inputs	Activation	Outputs
1. State of connection of heating/cooling power line (0 deactivated, 1 activated) 2. State of connection for the rest electrical consumptions(0 deactivated, 1 activated) 3. PMV (+3 … -3, where 0 is neutral, -3 very cold, +3 very hot)	The agent gets activated IF Input 1=1 AND Input 2=1 AND $\lvert Input3 \rvert < 1.5$ OR Input 1=1 AND Input2=0	If the agent's activation signal is acknowledged by the house's intelligent supervisor agent, the air conditioning lines are disconnected from mains

7.4.3.5 *Various Consumptions Agent*

The various consumptions agent controls the power lines from the electrical circuit board of each house to the rest of the electrical loads. This agent utilizes the Predicted Mean Vote (PMV) sensor as well. The Inputs, Outputs and the state of activation of this agent are presented in Table 7.6.

Table 7.6 Various consumptions agent

Inputs	Activation	Outputs
1. State of connection of heating/cooling power line (0 deactivated, 1 activated) 2. State of connection for the rest electrical consumptions(0 deactivated, 1 activated) 3. PMV (+3 … -3, where 0 is neutral, -3 very cold, +3 very hot)	The agent gets activated IF Input 2=1 AND Input 2=1 AND $\lvert Input3 \rvert > 1.5$ OR Input 1=0 AND Input2=1	If the agent's activation signal is acknowledged by the house's intelligent supervisor agent, the power lines for the rest of electrical loads are disconnected from mains

7.4.3.6 *Desalination Unit Agent*

This agent is activated if the water in the water tank is lower than a set value and if there is power production at the current time step. It calculates the point of operation of the desalination unit in order to cover the average hourly water consumption and it checks if the output of the EMS is higher or lower than this value. If it is higher, it overrides the operation point of the EMS. This agent is a simple reflex agent.

7.4.3.7 Electrolyzer Unit Agent

This agent is activated if the hydrogen in the hydrogen tank is lower than a set value and if there is power production at the current time step. It calculates the point of operation of the electrolyzer unit in order to cover the average hourly water consumption and it checks if the output of the EMS is higher or lower than this value. If it is higher, it overrides the operation point of the EMS. This agent is a simple reflex agent.

7.4.3.8 Fuel Cell Agent

If the IDSMS is activated then the fuel cell is deactivated since IDSMS can manage the power deficit in the system. The fuel cell is activated only if the system enters emergency mode and all loads are disconnected in order to protect the batteries and keep a minimum SOC. This keeps the microgrid operational so that the PV array and the wind turbine can, in turn, charge the battery bank. This agent is a simple reflex agent.

7.4.4 Intelligent Supervisor Layer

Each house will have one Intelligent Supervisor agent. This agent evaluates the power consumption in the house after negotiation with its subordinate controller agents and then decide whether to turn off some or all of the loads after negotiating with the other Intelligent Coordinator agents. When the IDSMS is activated all intelligent supervisor agents activate the adaptive temperature for space heating and cooling. If the signal for further load activation is active from the Activator agent then all intelligent supervisor agents transmit to each other value calculated using the algorithm of Figure 7.5 Negotiation value calculation algorithm. Then an internal sorting takes place. If the intelligent supervisor agent find its own value on top of the list then it sends acknowledge signals to its subordinate control agents, otherwise it sends the signals of the previous control time step, which are stored internally. If the Activation Signal for IDSMS is turned off, then then all the loads are reconnected at once. The inputs and outputs of the intelligent supervisor agents are presented in Table 7.7, and the algorithm is presented in detail in Figure 7.8. This agent is a goal-based agent.

Table 7.7 Intelligent Supervisor Agent

Inputs	Outputs
1. Activation Signal for Intelligent Demand Side Management	1. Transmit the consumed energy for the past 3 days
2. Activation Signal for further load shedding	2. Acknowledge/ Renounce signal for CA_1
3. Activation of Adaptive Temperature thermostat for space heating/cooling	3. Acknowledge/ Renounce signal for CA_2
4. Activation Signal for the information of the users for imminent automatic load disconnections	4. Acknowledge/ Renounce signal for CA_3
5. Consumed energy for the past 3 days.	5. Acknowledge/ Renounce signal for CA_4
6. Activation Signal of CA_1	6. Set temperature for space heating/cooling
7. Activation Signal of CA_2	7. Reconnect all 4 lines
8. Activation Signal of CA_3	8. Activation of LED for imminent activation of IDSMS
9. Activation Signal of CA_4	
10. Consumed energy for the past 3 days of house 1	
11. Consumed energy for the past 3 days of house 2	
n. Consumed energy for the past 3 days of house n	

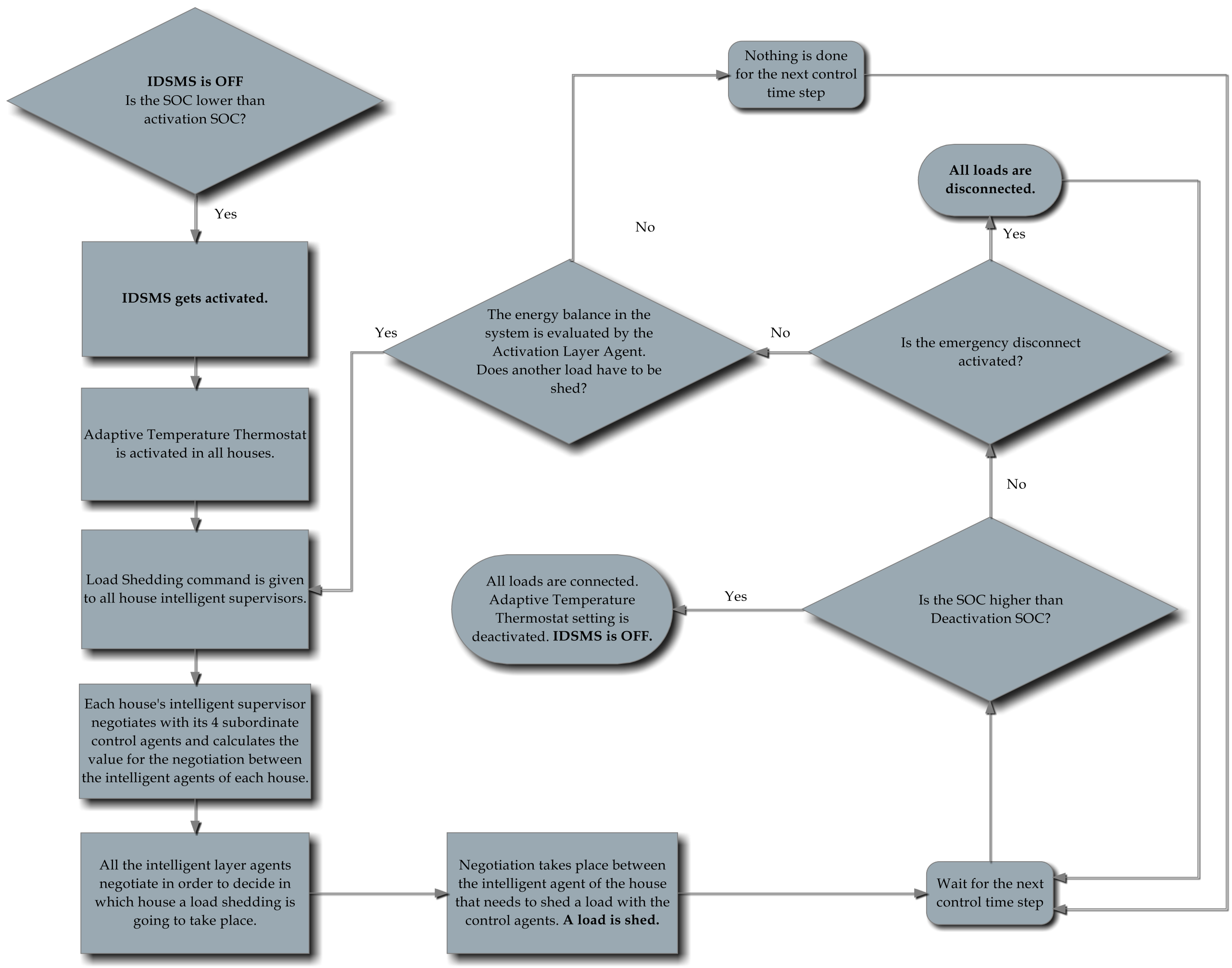


Figure 7.8 Intelligent Supervisor Agent Algorithm

7.5 Validation of the Demand Side Management system through simulation

The basis of this investigation is the optimal system of paragraph 6.4. It is assumed that for after a few years of operation of that microgrid a summer house is built in that settlement. Four people occupy that house from the beginning of June until the end of August. The house is comparable to the other two. The load profile of this house is obtained with the process described in paragraph 6.1. This time a 15% variability was added for day to day and a 15% from time step to time step from the base load. Also since the desalination unit and electrolyzer cannot produce more than their ratings it is assumed that the people there decided that they would cover their mobility needs without adding a new scooter and also that they would lower their daily consumption of water so that their needs could be covered by the installed desalination unit. The average daily consumption of the settlement thus rose from 1.92 m^3 of water to 2.16 m^3. IDSMS was realized in TRNSYS

7.5.1 IDSMS TRNSYS Routines

Some parts of the IDSMS were simulated using the equation component of TRNSYS and integrators and for the rest new routines were written. The air conditioning units, the electrical switch boards of each house and the comparisons between the energy consumption of each household were simulated using equations. The kWh meters were simulated using periodic integrators. The newly written routines are presented below. The source code of the types is presented in Annex II.

7.5.1.1 TYPE 366: GREY PREDICTOR

This type can predict the value of the next time step using the values of the 4 previous ones. Its input, parameters and output is presented in Table 7.8.

Table 7.8 TYPE 366: GREY PREDICTOR

Number of Parameter		Description
1	V1	Value of unit 3 time steps before the beginning of the simulation
2	V2	Value of unit 2 time steps before the beginning of the simulation
3	V3	Value of unit 1 time step before the beginning of the simulation
Number of Input		**Description**
1	CV	Current Value
Number of Output		**Description**
1	PrV	Predicted Value for the next time step

7.5.1.2 TYPE 250: ACTIVATION AGENT

This type simulates the activation agent of the IDSMS. Its inputs, parameters and outputs are presented in Table 7.9.

Table 7.9 TYPE 250: ACTIVATION AGENT

Number of Parameter		Description
1	SOCL	SOC below which the IDSMS is activated
2	SOCH	SOC above which the IDSMS is deactivated

3	SOCU	SOC below which the users are informed by a LED that load disconnections are imminent
4	SOCE	SOC below which everything is disconnected in order to protect the batteries
Number of Input		**Description**
1	SOC	State Of Charge
2	F	Frequency of the microgrid [Hz]
3	PRPV	Predicted value of the PVs production in the next time step [W]
4	PRWIND	Predicted value of the Wind Turbines in the next time step [W]
5	PBAT	Power to or from the battery for the current time step [W]
Number of Output		**Description**
1	DSMA	DSM activation signal
2	MORS	More load shedding activation signal
3	USERS	Activation of the information LED for the users
4	EMER	Emergency deactivation of all loads signal

7.5.1.3 TYPE 251: AGENT NEGOTIATION

This type simulates the wireless negotiation between the intelligent supervisor agents in order for them to see which one is going to disconnect a load if it is needed. The algorithm presented in Figure 7.2 is realized also in this Type. This type was written in order to facilitate the case study of the three households, but can be easily updated for as many households as needed. The inputs and outputs of this type are presented in Table 7.10.

Table 7.10 TYPE 251: AGENT NEGOTIATION

Number of Parameter		**Description**
-	-	-
Number of Input		**Description**
1	KWH1	Energy consumed in the last 3 days from Household 1 [kWh]
2	KWH2	Energy consumed in the last 3 days from Household 2 [kWh]
3	KWH3	Energy consumed in the last 3 days from Household 3 [kWh]

4	SL1	State of lighting line of house 1 (Connected/Disconnected)
5	SR1	State of refrigeration line of house 1 (Connected/Disconnected)
6	SHC1	State of heating/cooling line of house 1 (Connected/Disconnected)
7	SA1	State of the various other appliances line of house 1 (Connected/Disconnected)
8	SL2	State of lighting line of house 2 (Connected/Disconnected)
9	SR2	State of refrigeration line of house 2 (Connected/Disconnected)
10	SHC2	State of heating/cooling line of house 2 (Connected/Disconnected)
11	SA2	State of the various other appliances line of house 2 (Connected/Disconnected)
12	SL3	State of lighting line of house 3 (Connected/Disconnected)
13	SR3	State of refrigeration line of house 3 (Connected/Disconnected)
14	SHC3	State of heating/cooling line of house 3 (Connected/Disconnected)
15	SA3	State of the various other appliances line of house 3 (Connected/Disconnected)
16	MORS	Signal if more loads need to be disconnected in this time step
17	DSMA	Activation signal of the IDSMS

Number of Output		**Description**
1	AC1	Activation signal that House 1 needs to shed a load
2	AC2	Activation signal that House 2 needs to shed a load
3	AC3	Activation signal that House 3 needs to shed a load
4	CC1	Energy for negotiation for House 1 (algorithm in Figure 7.4)
5	CC2	Energy for negotiation for House 2 (algorithm in Figure 7.4)
6	CC3	Energy for negotiation for House 3 (algorithm in Figure 7.4)

7.5.1.4 TYPE257-9: INTELLIGENT SUPERVISOR AGENT

This type simulates the intelligent supervisor agent present in each household. It inputs, parameters and outputs are presented in Table 7.11.

Table 7.11 TYPE257-9: INTELLIGENT SUPERVISOR AGENT

Number of Parameter		Description
1	PMVL	Absolute value of the PMV above which the indoor climate is considered very annoying
2	TH	The thermostat temperature the habitants of the house choose for heating [^{0} C]
3	TC	The thermostat temperature the habitants of the house choose for cooling [^{0} C]
Number of Input		**Description**
1	ADSM	Activation signal of the IDSMS
2	AC	Signal from Type 251 to disconnect a load
3	AU	Signal for the LED activation informing the users for imminent load disconnections
4	AE	Signal for emergency disconnection of all loads
5	PMV	PMV inside the house
6	Tout	Outside dry bulb temperature [^{0} C]
Number of Output		**Description**
1	LSL	State of the lighting line for the previous timestep
2	LSR	State of the refrigeration line for the previous timestep
3	LSHC	State of the heating and cooling line for the previous timestep
4	LSA	State of the other electrical appliances line for the previous timestep
5	LED	State of the user's information LED
6	TH	Set temperature for heating [^{0} C]
7	TC	Set temperature for cooling [^{0} C]
8	SL	State of the lighting line for the current timestep
9	SR	State of the refrigeration line for the current timestep
10	SHC	State of the heating and cooling line for the current timestep
11	SA	State of the other electrical appliances line for the current timestep

7.5.1.5 TYPE390: ELECTROLYZER,FUEL CELL AND DESALINATION AGENTS

This type simulates the fuel cell, electrolyzer and desalination agents. It inputs parameters and outputs are presented in Table 7.12.

Table 7.12 TYPE390: ELECTROLYZER,FUEL CELL AND DESALINATION AGENTS

Number of Parameter		Description
1	WM	Minimum water that must be present in the water tank [m^3]
2	H2M	Minimum hydrogen that must be present in the hydrogen tank [Nm^3]
3	WA	Average hourly water consumption [m^3]
4	H2A	Average hourly hydrogen consumption [Nm^3]
Number of Input		**Description**
1	FCOP	Fractional operation point of the fuel cell given by the EMS
2	ELOP	Fractional operation point of the electrolyzer given by the EMS
3	DSOP	Fractional operation point of the desalination unit given by the EMS
4	WAT	Water in the water tank [m^3]
5	H2	Hydrogen in the hydrogen tank [Nm^3]
6	PP	Produced Power by the PV arrays and wind turbines [W]
Number of Output		**Description**
1	OP_{FC}	Fractional operation point of the Fuel Cell
2	OP_{EL}	Fractional operation point of the Electrolyzer
3	OP_{DS}	Fractional operation point of the Desalination Unit

7.5.2 IDSMS Simulation Results

First a simulation was run without any kind of demand side management. As was expected for many days the residents were left without any water or hydrogen. The increased production of the PV array because of the higher solar irradiation was not enough to cover all the increased needs. When the proposed IDSMS was taken in consideration the microgrid performed much better. The first important result is that the minimum SOC was 17.46 %. This means that the emergency disconnect set at 15% was never activated. A SOC below 20% was observed for only about 5 and a half hours throughout the summer.

The second important result, as can be seen also in Figure 7.9 and Figure 7.10, is that the primary objective of having enough water and enough hydrogen was met. As far as water is concerned much water had been produced the previous months, and so most of it is used until about the half of the summer. After that the IDSMS makes certain that there is enough production to guaranty the security reserve. It is important to note that the water consumption rose almost 20% in comparison with the original potable water needs. For the electrolyzer unit, it is clear that IDSMS also makes certain that there is always the minimum available reserve in the tank in August. Since both the electrolyzer and desalination unit draw power in order to cover day by day the needs it is very hard for the hydrogen tank to get completely filled up again. For the second half of August both devices manage to just cover the load.

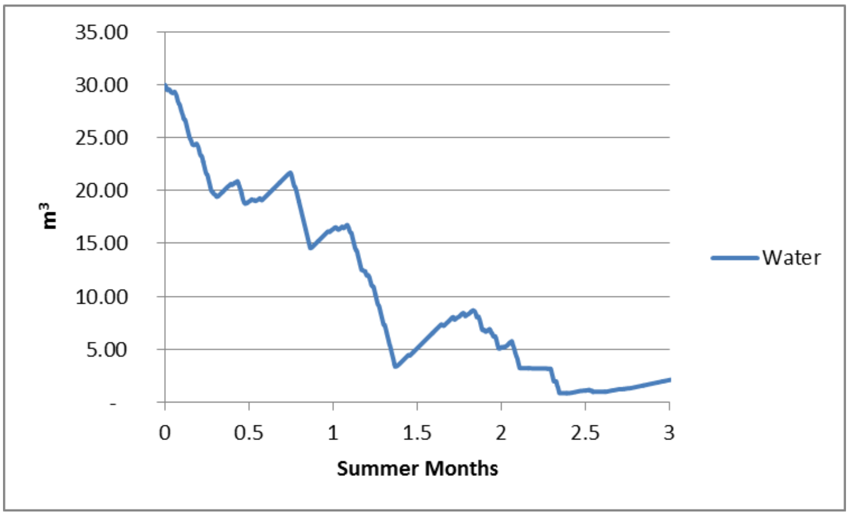


Figure 7.9 Water in the Potable Water Tank

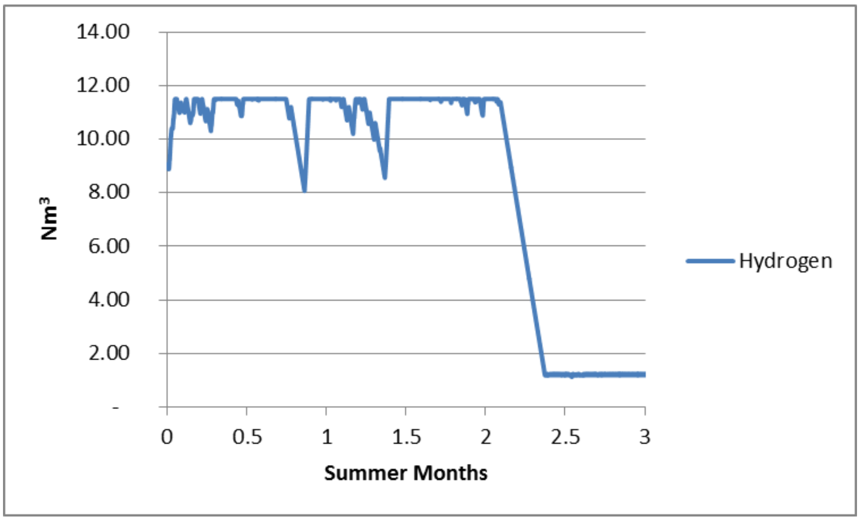


Figure 7.10 Hydrogen in the Hydrogen Tank

Load shedding occurred only for about 33 hours throughout the summer. Two examples will be presented. The first is beginning in the evening of the 10th of August and ends at about half a day later. The various loads connections and disconnections are presented in Table 7.13. IDSMS gets activated and the 1st house has consumed the most energy for the past 3 days. In the first control time step the various electrical appliances are turned off. The activation agent sends a signal for more load shedding in the second time step and so the 1st house turns off the air conditioning unit as well. Since more loads need to be shed in the next time step a different house is chosen, since the refrigeration of the 1st house is considered more important than the appliances or air conditioning units of the rest of the houses. The 3rd house has to shed a load and the air conditioning unit is disconnected. The microgrid seems to be finding equilibrium after that and so no more loads are shed. After about 12 hours the battery has been charged to the deactivation limit of the IDSMS and so all loads are again connected.

Table 7.13 10-11th of August Load Shedding

	House 1				House 2				House 3			
	L	R	H/C	A	L	R	H/C	A	L	R	H/C	A
21:00:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
21:07:30	ON	ON	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON
21:15:00	ON	ON	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON
21:22:30	ON	ON	OFF	OFF	ON	ON	ON	ON	ON	ON	OFF	ON
…	…	…	…	…	…	…	…	…	…	…	…	…
09:22:30	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON

L: Lighting Line
R: Refrigeration Line
H/C: Space Heating/Cooling Line
A: Other Electrical Appliances Line

The second example is from the 24th and 25th of June. A little after half past six in the afternoon IDSMS gets activated. All loads are disconnected throughout the next one and a half hour as it is presented in Table 7.14. Even with all loads disconnected not enough energy is produced to charge the batteries. Throughout the night the wind turbine produces very low to absolute zero power. After the sun rises in the morning the battery bank is getting charged again through the PV array. The IDSMS gets deactivated and all loads are connected again at a quarter to ten.

Table 7.14 10th-11th of August Load Shedding

	House 1				House 2				House 3			
	L	R	H/C	A	L	R	H/C	A	L	R	H/C	A
18:22:30	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
18:30:00	ON	ON	OFF	ON	ON	ON	ON	ON	ON	ON	ON	ON
18:37:30	ON	ON	OFF	OFF	ON	ON	ON	ON	ON	ON	ON	ON
18:45:00	ON	ON	OFF	OFF	ON	ON	ON	ON	ON	ON	OFF	ON
18:52:30	ON	ON	OFF	OFF	ON	ON	ON	ON	ON	ON	OFF	OFF
19:00:00	ON	ON	OFF	OFF	ON	ON	OFF	ON	ON	ON	OFF	OFF
19:07:30	ON	ON	OFF	OFF	ON	ON	OFF	OFF	ON	ON	OFF	OFF
19:15:00	ON	OFF	OFF	OFF	ON	ON	OFF	OFF	ON	ON	OFF	OFF
19:22:30	ON	OFF	OFF	OFF	ON	ON	OFF	OFF	ON	OFF	OFF	OFF
19:30:00	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF
19:37:30	OFF	OFF	OFF	OFF	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF
19:45:00	OFF	OFF	OFF	OFF	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF
19:52:30	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
…	…	…	…	…	…	…	…	…	…	…	…	…
21:45:00	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON

L: Lighting Line
R: Refrigeration Line
H/C: Space Heating/Cooling Line
A: Other Electrical Appliances Line

Concluding, through the use of an advanced IDSMS the polygeneration microgrid concept becomes more flexible and versatile. If for any reason in the future the needs rise and there is no possibility of installing a new power source, through the IDSMS system the existing equipment will be used in the most efficient way possible. Also a IDSMS system can be used for designing a polygeneration microgrid where there is a limitation on the available capital, and that capital is not enough to guaranty 0% power, water and hydrogen deficit throughout the year. Using the methodology explained in the previous chapters it becomes possible to design and size the optimal system under those limitations, by just formulating a new cost function, using the investor's priorities as constraints.

8 Economic Evaluation of the Autonomous Polygeneration Smartgrid

8.1 Overview of the Economic Evaluation

The Autonomous Polygeneration Smartgrid topology proved to be technically feasible and has also been optimized. In this chapter an economic evaluation of the proposed topology takes place. In the first step the net present value (NPV) of the system is calculated, along with the payback period using the discounted cash flow method. Discounted cash flow (DCF) analysis uses future cash flow projections and discounts them to arrive at a present value. The polygeneration microgrid produces electrical energy, potable water and fuel for transportation, heating and cooling. For the value of potable water and fuel for transportation actual market prices are used (November 2011). The heating and cooling were considered to be electrical power consumptions. In order to set the price of an electrical kWh a typical diesel-battery system was designed and evaluated for a 20 year period, a usual technique for satisfying electricity needs of a remote area.

Factors used in the calculation of net present value, such as gasoline and diesel prices, interest rate and the price of the electrochemical components add uncertainty to various degrees in the net present value. In order to have a better understanding of the profitability of a polygeneration microgrid a Monte Carlo Simulation (MCS) was carried out, a method that has been used successfully for renewable energy systems appraisal (Yu and Tao, 2009). The principle of Monte Carlo sampling is based on the frequency interpretation of probability and requires a steady stream of random numbers (Winston, 1991). For continuous distributions random numbers are generated using the inverse transformation method. This method requires a cumulative distribution function (CDF) f(x) in closed form and consists of giving to f(x) a random value and to solve for x.

Data from the simulation can be analyzed using a terminating simulation approach. N independent replications of the model take place using the same initial conditions but running each replication with a different sequence of random numbers. If the measure of performance is represented by the variable X, this approach gives the estimators $X_1 \ldots, X_n$ from the n replications. These estimators are n±tn−1,a2S2nn (EQ 47) where $t_{n-1,a/2}$ is the upper 1-a/2 critical point for a t distribution with n-1 degrees of freedom.

$$\overline{X}(n) \pm t_{\left(n-1,\frac{a}{2}\right)}\sqrt{\frac{S^2(n)}{n}} \quad \text{(EQ 47)}$$

Where: $\overline{X}(n) = \frac{\sum_{i=1}^{n} X_i}{n}$ and $S^2(n) = \frac{\sum_{i=1}^{n}[X_i - \overline{X}(n)]^2}{n-1}$

For a fixed value of n, it returns the confidence interval for a population mean. In other words after simulation the question on the probability of a negative NPV can be posed and answered.

The steps proposed by Schade and Wiesenthal (Schade and Wiesenthal, 2011) were followed:

1. The influence of each of the important parameters in the calculation of the NPV is determined.
2. A review in the literature takes place in order to identify uncertainty ranges and probability density functions for the important parameters. Where no information about the probability density function was available it has been constructed with available data.
3. The actual MCS is carried out.

The above mentioned methodology is carried out for the best smartgrid of the case study in Chapter 0.

8.2 Deterministic Investment Appraisal

The avoided cost of potable water is considered to be 5.5 €/m^3 and for the unleaded gasoline fuel 1.72 € / l. Both values are in accordance with market prices on Aegean Sea islands in 2011. In order to estimate the avoided cost of the electrical kWh a diesel-battery system was designed and evaluated for a 20 year period. This system comprises of a typical 4 kW diesel genset (equipped with a low rpm engine which extends its life time beyond 12000 hours), a 350 Ah battery bank at 48 V, a charge controller, an inverter and a diesel tank. The diesel genset has a lifetime of 12000 hours and consequently needs to be replaced every 4 years and the battery bank needs to be changed every 7 years. The interest rate is considered to be 6%. The system yearly operation and maintenance costs apart from the diesel fuel are estimated to be 600 euros. This also includes the transportation cost for the diesel fuel from the gasoline station to the remote area. The price of the diesel genset is considered to be 5000 €, the battery bank 8000 €, the inverter and charge controller 3000 € and the diesel tank 1000 €. The investment cost of the polygeneration smartgrid is calculated based on market prices of its corresponding components. The Net Cash Flows (NCF) are presented in Table 8.1 and are in essence the sum of all the flows that occur for each year.

Table 8.1 Net Cash Flows

Type of Monetary flow	**Item**	**Years**					
		0	1-6	7	8-13	14	15-20
Inflows (or avoided costs)	Electricity		8662	8662	8662	8662	8662
	Water		3854	3854	3854	3854	3854
	Fuel		1324	1324	1324	1324	1324
Outflows	PV	20300					
	Windturbine	12000					
	Fuel Cell	2000					
	Electrolyzer Unit	8000					
	Metal Hydride Tank	11500					
	Battery bank	7200		7200		7200	
	Scooters	20000					
	Desalination Unit	7000					
	Water Tank	2460					
	Energy Management Sensors and Equipment	3000					
	Installation Cost	5000					
	OM	0	500	500	500	500	500
NCF		-98460	13341	6141	13341	6141	13341.82

The NPV for the polygeneration microgrid is 46585 € and the Payback Period is 11.7 years.

8.3 Stochastic Investment Appraisal

The first step for the MCS includes the definition of the most influential parameters. A sensitivity analysis was carried in this scope (Schade and Wiesenthal,

2011) and the results are presented in Table 8.2. The price of diesel, the price of potable water and the interest rate influence the NPV most. For the rest of the components, the PV panels and the scooters pricing influences the NPV. The influence of the electrochemical components is low, but their cost is expected to drop significantly in the near future (Khan and Iqbal, 2005), and thus it will be taken in consideration for the MCS. Prices of diesel and gasoline fuel, potable water and the interest rate also present high uncertainty and will be taken into consideration for the MCS. The cost of the PV panels and the battery bank do not present major fluctuations in the market at the present time, but it is expected that their cost will drop in the years to come (Hoffmann, 2006). Hybrid scooter costs are also expected to decrease because of the increase in the production capacities. Because of this it was decided to investigate two scenarios with MCS, one for the year 2011 and one for the year 2015. The cost of the desalination unit, potable water tank, inverters, installation cost, controller and wind turbine are expected to have comparable pricing in the near future so they will not be taken into account in the MCS.

Table 8.2 Influence of changes in parameters on NPV

Change of NPV as percentage	Change of Output (Relative to NPV)			
Parameter	-30%	-15%	+15%	+30%
PV array with inverter	13.1	6.5	-6.5	-13.1
Windturbine	7.7	3.9	-3.9	-7.7
Fuel Cell	1.3	0.6	-0.6	-1.8
Electrolyzer Unit	5.2	2.6	-2.6	-5.2
Metal Hydride Tank	7.4	3.7	-3.7	-7.4
Battery bank	9.8	4.9	-4.9	-9.8
Scooter	12.9	6.4	-6.4	-12.9
Desalination Unit	4.5	2.3	-2.3	-4.5
Water Tank	1.6	0.8	-0.8	-1.6
Gasoline Fuel	-9.8	-4.9	4.9	9.8
Diesel Fuel	-35.9	-17.9	17.9	35.9
Interest Rate	45.7	21.5	-19.3	-36.5
Potable Water	-28.5	-14.2	14.2	28.5

The fuel prices cannot be predicted with confidence. Also because of the global financial crisis the interest rate could fluctuate considerably. Finally the hydrogen components present a steady decline in their prices. If hydrogen penetration is increased in the automotive sector the prices for stationery applications will also drop. The hybrid scooter is estimated to be considerably cheaper in 2015 because of the expected decreased prices for its hydrogen and battery subsystems.

There are two groups of variables that may be correlated. The first depends on Brent oil price (fossil fuels) and the second one comprises of the electrochemical components. For these two groups a triangular distribution will be considered for generating a number between 0 and 1 and this number is going to be used in equations that calculate the actual price. The actual price will be the lowest price plus this number multiplied by the difference of the highest minus the lowest price. The mode for this triangular distribution for the fuel prices is 0.4 which means that the probability of the prices increasing is smaller than remaining stable or move decreasing. This was decided because the current (2011) fuel prices in Greece reached all-time peak. For the electrochemical equipment the mode is 0.2 because it is expected that hydrogen component prices will follow a price decrease trend (Khan and Iqbal). It has to be mentioned that one company considerably cut down the electrolyzer prices in its product catalogue of Autumn 2011 and other companies are expected to follow due to rising competition. The interest rate, potable water, PV array and battery bank costs are considered to follow a uniform distribution. For the calculation of 10000 iterations about 1 minute is needed in a typical pc (CPU of 3 GHz and 2 GB of ram). Since the calculation time is minimal it was decided to carry out 32000 iterations (which is the top limit in the MS Excel VBA macro that was created) in the MCS simulation in order to achieve higher accuracy. The VBA macro for the triangular distribution and the MCS simulation are presented in Annex 1.

Thus a MCS was performed in order to have a clearer view of the profitability of this investment. The minimum and maximum cost of each of the variables for the two scenarios are presented in Table 8.3 Parameters for MSC for year 2011 and in parenthesis for year 2015. NPV cumulative distributions are presented in Figure 8.1.

Table 8.3 Parameters for MSC for year 2011 and in parenthesis for year 2015

Parameter	Unit	Distribution	Minimum	Mode	Maximum
Gasoline Fuel	€/l	Triangular	1.60 (1.40)	1.68 (1.62)	2.00 (2.50)
Diesel Fuel	€/l	Triangular	1.35 (1.20)	1.42 (1.36)	1.70 (2.00)
Fuel Cell	€/400 W	Triangular	1200 (500)	1400 (700)	2200 (1500)
Electrolyzer Unit	€/1000 W	Triangular	6000 (3000)	7200 (4000)	12000 (8000)
Metal Hydride Tank	€/11.5 Nm^3H_2	Triangular	10000 (2500)	10700 (4000)	13500 (10000)
Interest Rate	-	Uniform	0.04 (0.04)	N/A	0.08 (0.08)
Potable Water	€/m^3	Uniform	2 (2)	N/A	10 (10)
PV array with inverter	€/array	Uniform	12500 (8000)	N/A	27500 (18000)
Battery Bank	€/(300 Ah/48 V)	Uniform	5500 (3000)	N/A	8500 (7000)
Hybrid Scooters	€	Uniform	18000 (8000)	N/A	22000 (12000)

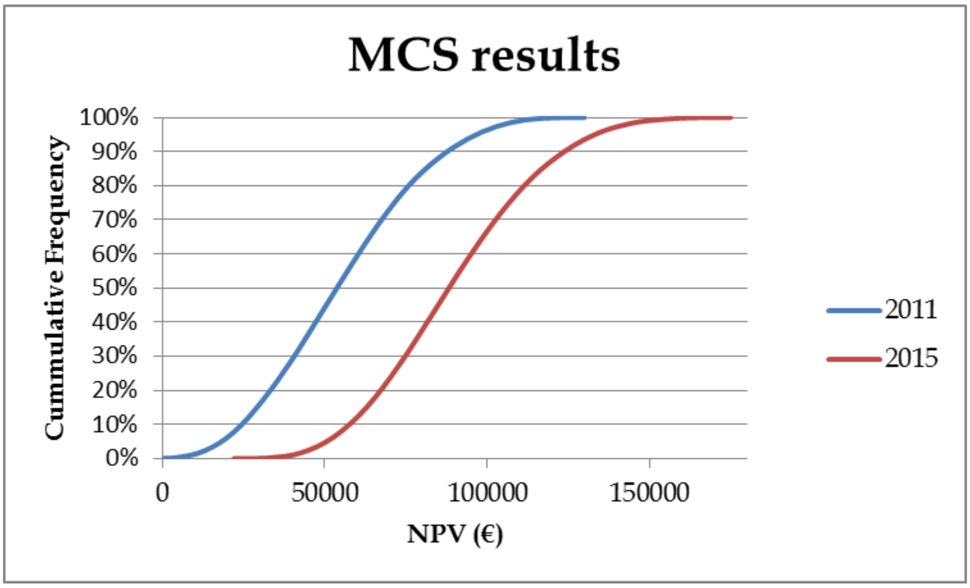


Figure 8.1. Net Present Value distribution curve

Both scenarios present risk free investments, since no negative NPV is calculated during the MCS. Average NPV for the 2011 scenario is equal to 54922 € and for the 2015 scenario the average NPV is equal to 89582 €.

9 Conclusions – Future Research Paths

In this thesis a novel approach in covering the needs in remote areas was proposed, optimized and validated both technically and economically. In order for a community to survive in a remote area nowadays the following needs should be addressed.

- Food
- Potable Water
- Appropriate housing with space heating and cooling
- Lighting
- Refrigeration
- Household needs (cooking, washing etc.)
- Transportation
- Telecommunications
- Entertainment

All the above needs apart from food, which can only be addressed through agriculture, can be successfully met by the proposed topology. On top of that the carbon footprint of the community can be minimized, since the system is based solely on renewable energy technologies. Thus the development of such community can be sustainable and friendly to the environment.

All the hardware parts and devices used for such as smartgrid are already available in the market and are offered by more than one company. Intuitive interconnection of all these devices coupled with the Energy Management System based on soft computing can make this topology fully functional.

A design tool was created so that such systems can be designed and deployed in any part of the world easily. The inputs this tool needs are:

- The meteorological conditions of the area so that solar and wind potential can be evaluated, as well as outside temperature for the optimal covering of space heating and cooling needs.
- The actual needs in terms of electrical power consumption profile, potable water needs and fuel for transportation needs.

- The availability of any other renewable energy in the area (such as the possibility of a micro-hydro installation or a geothermal installation).
- Technical data of locally/regionally available hardware parts and devices of the system so that imports are minimized.

This tool can be used with new types of photovoltaics, wind turbines, hydrogen components and desalination systems as they become available in the future. The power modeling approach used allows that.

Soft computing tools proved to be valuable for the design methodology and also for the Energy Management System. The combined Petri Net – Fuzzy Cognitive Maps approach proved to be simpler calculation wise and easier to be optimized. Also this controller's operation is based on power balances of the microgrid. With the change of a couple of parameters it can still operate if the smartgrid expands to the maximum this technology allows (about 500 kW/3 phase currently). The hardware implementation of the controller is pretty straight forward, since the code can be ported to Matlab or Labview software packages and from then on to a PLC, embedded solution or a PC card with inputs and outputs.

The battery bank of the system is still the Achilles' heel of renewable technologies systems. With the use of the advanced Energy Management Systems the size of the battery was minimized considerably.

Finally the system is fully modular. If in the future the needs grow it is very easy to add some more distributed photovoltaics or another wind turbine. Even if there is no money available the demand side management system will drive the installed smartgrid to its operational limits.

Future research ought to be focused on energy storage technologies. The lead acid solar batteries have reached their technological peak, and have the shortcomings of having to be changed every few years and are also containing heavy metals, which have proved to be an environmental hazard. Lithium ion batteries are already on the market and have very promising operational characteristics. Their pricing is following a decreasing trend because of the expanding electrical car applications. Zebra batteries and redox flow batteries are advancing fast and are currently available for purchase, even though it has to be acknowledged that availability is in very small numbers coupled with very high prices. Ultra capacitors and hybrid ultra capacitors ought to be investigated to be used alone or in hybrid solutions with the rest energy storage possibilities.

The developed power Demand Side Management system needs to be tested under real conditions so it can be further optimized and prototypes of the wireless agents to be manufactured with low cost being an important parameter.

There is much research going on in the field of soft computing tools for optimization purposes. Some of the novel approaches such as the ant colony and bee colony algorithms are getting new extensions in order to be able to optimize both discrete and continuous variables. An investigation of the performance of all these novel algorithms for use in the optimization of energy systems can take place.

Finally the proposed topology is suited very well to be used in off-grid farms. Even in the developed countries many animal husbandry buildings are erected far from the main grid, and the cost to extend the grid can sometimes rise to many tenths of thousands of Euros. In Africa and Asia greenhouses are usually far from a main grid. Because of the lowering costs of many technologies nowadays as well as the improving efficiencies of the various devices, solutions that were economically not viable even 5 years ago should be reevaluated again. Research in completely autonomous farms should also be a priority.

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