ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ

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Τοπική αγορά ενέργειας βασισμένη σε blockchain τεχνολογία: μελέτη εφαρμογής στην κοινότητα Los Molinos del Rio Aguas

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

Χρήστος Καρυστινός

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Αθήνα, Φεβρουάριος 2021

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Εγκρίθηκε από την τριμελή εξεταστική επιτροπή την 22 Φεβρουαρίου 2021.

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Ν. Χατζηαργυρίου	Σ.Παπαθανασιου	Π. Γεωργιλάκης
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Αθήνα, Φεβρουάριος 2021

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Χρήστος Καρυστινός

Διπλωματούχος Ηλεκτρολόγος Μηχανικός και Μηχανικός Υπολογιστών Ε.Μ.Π

Απαγορεύεται η αντιγραφή, αποθήκευση και διανομή της παρούσας εργασίας, εξ ολοκλήρου ή τμήματος αυτής, για εμπορικό σκοπό. Επιτρέπεται η ανατύπωση, αποθήκευση και διανομή για σκοπό μη κερδοσκοπικό, εκπαιδευτικής ή ερευνητικής φύσης, υπό την προϋπόθεση να αναφέρεται η πηγή προέλευσης και να διατηρείται το παρόν μήνυμα. Ερωτήματα που αφορούν τη χρήση της εργασίας για κερδοσκοπικό σκοπό πρέπει να απευθύνονται προς τον συγγραφέα. Οι απόψεις και τα συμπεράσματα που περιέχονται σε αυτό το έγγραφο εκφράζουν τον συγγραφέα και δεν πρέπει να ερμηνευθεί ότι αντιπροσωπεύουν τις επίσημες θέσεις του Εθνικού Μετσόβιου Πολυτεχνείου.

Περίληψη

Η παρούσα διπλωματική διερευνά την υπόθεση μελέτης της δημιουργίας ενός νησιδοποιημένου μικροδίκτυο στη Νότια Ισπανία και μιας ενσωματωμένης ενεργειακής αγοράς με βάση το blockchain. Εξετάζει την υπάρχουσα βιβλιογραφία σχετικά με τις εφαρμογές που προτείνονται από ερευνητές σχετικά με το blockchain στον ενεργειακό τομέα και δημιουργεί μια ανασκόπηση για αυτές. Αυτή η ανασκόπηση χρησιμεύει ως έμπνευση για τη δημιουργία μιας εικονικής αγοράς με βάση την πλατφόρμα D3A και την τεχνολογία Grid Singularity, προκειμένου οι χρήστες του μικροδίκτυο να αντισταθμίσουν το κόστος δημιουργίας του μικροδίκτυο. Η έρευνα λαμβάνει υπόψη όλες τις κοινωνικές πτυχές του σχεδιασμού για τη διαχείριση ιδιωτικών και κοινοτικών περιουσιακών στοιχείων που προέρχονται από προσωπική επί τόπου έρευνα .

Λέξεις κλειδιά

Νησδιποιημένα συστήματα, μικροδίκτυο, αγορά ενέργειας, blockchain

Abstract

The present dissertation investigates the study case of the creation of an off-grid microgrid in South Spain and an embedded blockchain-based market in it. It goes through the existing literature on the applications proposed by researchers on blockchain in the energy sector and creates a review on them. This review serves as an inspiration to create a virtual market based on D3A platform and Grid Singularity technology in order for the users of the microgrid to compensate for the costs of creating the microgrid. The investigation takes into account all the social aspects of the design on the management of private and communal assets sourced by personal investigation on-site.

Key words

Off-grid, microgrid, energy market, blockchain

Ευχαριστώ τον Νάσο για την στήριξη
στην ιδέα μου
Ευχαριστώ τους φίλους μου
για την στήριξη στις δύσκολες ώρες

Thanks to Sunseed Desert Technology
for letting me experience
this alternative

Περίληψη διπλωματικής στα ελληνικά

Η παρούσα διπλωματική εργασία χωρίζεται σε δύο μέρη. Στο πρώτο μέρος, γίνεται μια εισαγωγή στα θεωρητικά στοιχεία στα οποία αναφέρεται η παρούσα εργασία, τα οποία είναι αποκεντρωμένα συστήματα παραγωγής ενέργειας, μικροδίκτυα, αυτόνομα οικιακά συστήματα και blockchain. Ακολουθεί μια βαθύτερη έρευνα στο blockchain και μια έρευνα σχετικά με την αρχιτεκτονική της. Στη συνέχεια, γίνεται μια ανασκόπηση της υπάρχουσας βιβλιογραφίας σχετικά με τις εφαρμογές του blockchain στον ενεργειακό τομέα που παρουσιάζει εν συντομία τις προτάσεις περισσότερων από 50 διαφορετικών ομάδων ερευνητών μέσω των επιστημονικών τους δημοσιεύσεων.

Στο δεύτερο μέρος, η εργασία εισέρχεται στο κύριο μέρος της μελέτης της, η οποία αφορά στην μελέτη περίπτωσης, το Lo Molinos del Rio Aguas (LMRA) ,έναν οικισμό στη ν. Ισπανία και τους λόγους για τους οποίους επιλέχθηκε σαν μελέτη περίπτωσης (κεφάλαιο Α). Ακολουθεί μια περιγραφή των υπαρχόντων ηλεκτρικών στοιχείων και μια εκτίμηση του φορτίου όλων των υπαρχόντων κατοίκων. Κατασκευάζεται μελλοντικό σενάριο για να προβλέψει το προφίλ φορτίου της κοινότητας για τα επόμενα 20 χρόνια και η πρόταση δημιουργίας ενός μικροδίκτυο σχηματίζεται με τη δημιουργία ενός κοινοτικού μέσου παραγωγής ενέργειας και ενός κοινοτικού μέσου αποθήκευσης ενέργειας (κεφάλαιο Β). Για την προσωμοίωση δύο διαφορετικών περιπτώσεων για το μικροδίκτυο χρησιμοποιείται το πρόγραμμα προσωμοίωσης Homer Pro και τα αποελέμσατα που εξάγονται αποδεικνύουν ότι η μελέτη περίπτωσης είναι εφικτή με χαμηλό επενδυτικό κόστος και υψηλότερο από πριν στην παραγωγή ενέργειας από μόνο ανανεώσιμες πηγές. (κεφάλαιο Γ)

Η έρευνα συνεχίζεται στο (κεφάλαιο Δ) με την πρόταση δημιουργίας μιας αγοράς ενέργειας βασισμένη σε blockchain ενσωματωμένη στη δημιουργία του μικροδικτύου για την επίλυση ζητημάτων ιδιοκτησίας και την αποζημίωση του κόστους επένδυσης και συντήρησης. Τα ηλεκτρικά περιουσιακά στοιχεία του μελλοντικού σεναρίου διαμορφώνονται σύμφωνα με την πλατφόρμα D3A που δημιουργήθηκε από την εταιρεία GridSingularity. Η προσομοίωση διερευνά δύο

πιθανά σενάρια με διαφορετική τιμολόγηση και στα συμπεράσματα επιλέγεται το καταλληλότερο σενάριο προκειμένου να πληρούνται τα κριτήρια του σχεδιασμού.

Εισάγοντας την θεωρία την διπλωματικής εργασίας έμφαση δίνεται στις τωρινές ενεργειακές πολιτικές της Ευρώπης ως εφαλτήριο κίνητρο για την παρούσα έρευνα. Η κλιματική αλλαγή και η εισαγωγή νέων τεχνολογιών οδήγησαν σε αλλαγή στην πολιτική παραγωγής και κατανάλωσης ενέργειας στην Ευρώπη. Η Ελλάδα, ως μέλος της ΕΕ, υποχρεούται να ακολουθήσει την ενεργειακή πολιτική που έχει θέσει η ΕΕ. Η ΕΕ έχει εκδώσει τρία σχέδια όσον αφορά την ενεργειακή της πολιτική, ένα για το 2020, ένα για το 2030 και ένα για το 2050. Η βιωσιμότητα είναι ένας από τους πρωταρχικούς στόχους της Ευρώπης. Ενόψει της απειλής της κλιματικής αλλαγής, ο τομέας της ενέργειας, ένας τομέας που είναι υπεύθυνος για ένα μεγάλο μέρος των ρύπων που οδηγούν στην αλλαγή του κλίματος, θα διαδραματίσει βασικό ρόλο στην καταπολέμηση του φαινομένου. Οι ενεργειακοί στόχοι της ΕΕ για το 2030 είναι: μείωση των εκπομπών αερίων θερμοκηπίου κατά 40% παραγωγή τουλάχιστον 32% ενέργειας στην ΕΕ από ανανεώσιμες πηγές, αύξηση της ενεργειακής απόδοσης κατά 32,5% 15% της διασύνδεσης ηλεκτρικής ενέργειας (δηλαδή το 15% της ενέργειας που παράγεται στην ΕΕ να μπορεί να μεταφερθεί σε άλλες χώρες της ΕΕ). Θα μπορούσε κανείς να πει ότι υπάρχει μια αλλαγή, αργή αλλά σταθερή, από την κεντρική παραγωγή σε μια πιο αποκεντρωμένη παραγωγή ηλεκτρικής ενέργειας, όχι μόνο στην Ελλάδα και σε όλες τις χώρες της Ευρώπης.

Στην παρούσα εργασία θα χρησιμοποιείται ο ακόλουθος ορισμός: Η αποκεντρωμένη παραγωγή ορίζεται ως οι μονάδες παραγωγής με ονομαστική παροχή ισχύος από 1kW έως 100 MW, συνήθως συνδεδεμένες στο δίκτυο διανομής και οι οποίες δεν έχουν σχεδιαστεί ή ελεγχθεί από το κέντρο ελέγχου ισχύος. Ένα μικροδίκτυο ορίζεται ως δυνητικά ηλεκτρικά απομονωμένο σύνολο γεννητριών που παρέχουν αποκλειστικά όλη τη ζήτηση ενός συνόλου καταναλωτών. Οι εν λόγω γεννήτριες περιλαμβάνουν πηγές κατανεμημένης παραγωγής ενέργειας από μερικά kW έως 1-2 MW, συσκευές αποθήκευσης - όπως πυκνωτές, μπαταρίες, σφόνδυλοι - και ελεγχόμενα φορτία. Τ

α μικροδίκτυα είναι ένας τύπος συστήματος ηλεκτρικής ενέργειας που αναμένεται να διαδραματίσει σημαντικό ρόλο στο μέλλον. Ένα μικροδίκτυο ορίζεται ως ένα δίκτυο που εκτελεί όλες τις λειτουργίες που εκτελούνται από ένα κεντρικό ηλεκτρικό σύστημα, δηλαδή διαχειρίζεται τη ροή ισχύος μεταξύ καταναλωτών και παραγωγών, όπου στις περισσότερες περιπτώσεις είναι παραγωγοί ΑΠΕ ή prosumers όπου και οι δύο είναι παραγωγοί και καταναλωτές, η αποθήκευση υπερβολικής ενέργειας (σε μπαταρίες), η καταγραφή της ανταλλαγής ενέργειας στο δίκτυο και η διαχείρισή του. Τα μικροδίκτυα χωρίζονται σε δύο κατηγορίες, αυτά που δεν είναι συνδεδεμένα με το υπόλοιπο ΣΗΕ (νησιδοποιημένο μικροδίκτυο) και αυτά που είναι συνδεδεμένα (μικροδίκτυα με βοηθητική διασύνδεση) όπου αυτά είναι οι πιο κοινά.

Ένα παράδειγμα αποκεντρωμένης παραγωγής σε ένα μικροδίκτυο στην Ελλάδα βρίσκεται στην περιοχή Γαϊδουρόμαντρα της Κύθνου και είναι μονοφασικό μικροδίκτυο. Δίνει ρεύμα σε δώδεκα σπίτια σε μια μικρή κοιλάδα της Κύθνου. Στο δίκτυο περιλαμβάνονται μπαταρίες και μετατροπείς, μια γεννήτρια ντίζελ καθώς και ένας υπολογιστής ελέγχου και εξοπλισμός επικοινωνίας. Κάθε μετατροπέας μπαταρίας έχει μέγιστη ισχύ εξόδου 3,6 kW. Το δίκτυο περιλαμβάνει, επίσης, διακόπτες ελέγχου φορτίου που χρησιμοποιούνται για να διατηρήσουν τις μπαταρίες από υπερφόρτωση ή υποφόρτωση. Το σύστημα αποτελείται από 10 kWp φωτοβολταϊκών χωρισμένων σε μικρότερα υποσυστήματα, μια μπαταρία με ονομαστική χωρητικότητα 53 kWh και μια γεννήτρια ντίζελ με ονομαστική ισχύ 5 kVA.

Το Brooklyn Microgrid είναι το παράδειγμα από το οποίο εμπνέεται και το προτεινόμενο stuy case. Λειτουργει ως εξής: οι χρήστες ανταλλάσσουν (τοπικά παραγόμενη) ενέργεια με τους γείτονές τους. Το έργο αποτελείται από δύο κύρια στοιχεία, την πλατφόρμα εικονικής κοινότητας για την αγορά ενέργειας η οποία παρέχει την τεχνική υποδομή για την τοπική αγορά ηλεκτρικής ενέργειας και βασίζεται σε ένα ιδιωτικό blockchain χρησιμοποιώντας το πρωτόκολλο Tendermint.

Το φυσικό μικροδίκτυο, ένα μικροδίκτυο που δημιουργήθηκε επιπλέον του υπάρχοντος δικτύου διανομής. Αποσυνδέοντας το από το κύριο δίκτυο, μπορεί να λειτουργήσει σε κατάσταση εκτός δικτύου. Οι κρίσιμες εγκαταστάσεις (π.χ. νοσοκομεία) λαμβάνουν ενέργεια σε σταθερές τιμές. Τα σπίτια και οι επιχειρήσεις πρέπει να υποβάλλουν προσφορές για το υπόλοιπο δίκτυο. Το φυσικό μικροδίκτυο περιλαμβάνει σήμερα 10 σπίτια και θα επεκταθεί.

Στην παρούσα εργασία διερευνάται το blockchain και οι πολλαπλές λειτουργίες του που αυξάνονται καθημερινά περισσότερο. Ωστόσο, θα επικεντρωθεί στην ανταλλαγή ενέργειας peer to peer, και πιο συγκεκριμένα τοπικά σε αποκεντρωμένα συστήματα ηλεκτρικής ενέργειας. Το blockchain είναι μία κατανεμημένη βάση δεδομένων όπου ένας υπολογιστής ονομάζεται κόμβος εάν συνδεθεί στο δίκτυο. Κάθε κόμβος έχει πλήρη γνώση όλων των συναλλαγών που έχουν πραγματοποιηθεί, οι πληροφορίες κοινοποιούνται. Οι συναλλαγές ομαδοποιούνται σε ομάδες που προστίθενται διαδοχικά στην κατανεμημένη βάση δεδομένων. Μόνο ένα μπλοκ κάθε φορά μπορεί να προστεθεί. Για να προστεθεί ένα νέο μπλοκ πρέπει να περιέχει μια μαθηματική απόδειξη ότι ακολουθεί μια ακολουθία από το προηγούμενο μπλοκ. Τα μπλοκ συνδέονται μεταξύ τους με χρονολογική σειρά. Οι πιο δημοφιλείς εφαρμογές του blockchain είναι στον τομέα των κρυπτονομισμάτων, με το bitcoin και το ethereum να ξεχωρίζουν.Υπάρχουν πολλά διαφορετικά είδη blockchain ανάλογα με την προσβασιμότητα του και τον αλγόριθμο συναίνεσης.

Από την έρευνα πάνω στην υπάρχουσα βιβλιογραφία όσο αφορά τις εφαρμογές του blockchain στην ενέργεια προέκυψαν 6 κατηγορίες εφαρμογών:

1) Αγορές, συναλλαγές και πλατφόρμες: Εφαρμογές που, με βάση την τεχνολογία blockchain, δημιουργούν νέες αγορές ηλεκτρικής ενέργειας, πλατφόρμες όπου οι καταναλωτές μπορούν να ανταλλάσσουν ισχύ χωρίς κεντρικό διαχειριστή, πλατφόρμες που χρησιμοποιούν το υπάρχον δίκτυο για ανταλλαγές p2p και χρησιμοποιούν κρυπτονομίσματα που βασίζονται σε blockchain για πληρωμή. Σύνολο εφαρμογών: (13)

2) Χρεώσεις: Εφαρμογή τεχνολογίας blockchain για ταχύτερη και αποτελεσματικότερη χρέωση πελατών μιας εταιρείας ηλεκτρικής ενέργειας ή πληρωμή μικρών παραγωγών ΑΠΕ συνήθως μέσω έξυπνων συμβάσεων τεχνολογίας (έξυπνες συμβάσεις). Σύνολο εφαρμογών: (2).

3) Διαχείριση δικτύου: Εφαρμογές βασισμένες σε blockchain για διαχείριση έξυπνων δικτύων, μικροδικτύων, δικτύων εξοπλισμένων με έξυπνους μετρητές. Τρεις μεγάλες κατηγορίες είναι η διαχείριση απωλειών δικτύου, η αυτοματοποίηση και η διαχείριση της ζήτησης ενέργειας. Σύνολο εφαρμογών: (8) .

4)Διαχείριση δεδομένων: Εφαρμογές που βασίζονται σε blockchain για τη διαχείριση δεδομένων από ανταλλαγές ενέργειας, συνήθως από έξυπνους μετρητές σε ένα έξυπνο δίκτυο Σύνολο εφαρμογών: (5).

5)Ασφάλεια και διαχείριση ταυτότητας: Εφαρμογές βασισμένες σε blockchain που δίνουν έμφαση και χρησιμοποιούν λειτουργίες κρυπτογράφησης και blockchain για ασφαλή αποθήκευση δεδομένων κατανάλωσης, συναλλαγών χρημάτων που προκύπτουν από την ανταλλαγή ενέργειας. Σύνολο εφαρμογών: (7).

6)Κοινή χρήση πόρων: Εφαρμογές που βασίζονται σε blockchain για κοινή χρήση πόρων, όπως μπαταρίες κοινότητας ή σταθμοί φόρτισης για ηλεκτρικά αυτοκίνητα. Σύνολο εφαρμογών: (2).

Στη συνέχεια, σε κάθε κατηγορία αναφέρεται συνοπτικά οι ιδέες των διαφορετικών ερευνητών.

Στο δεύτερο μέρος της διπλωματικής εργασίας, αναλύεται η ιδιαιτερότητα του οικισμού Los Molinos del Rio Aguas(LMRA). Η ιδιαιτερότητα αυτή έγκειται στα εξής χαρακτηριστικά:

1. **Η ειδική ενεργειακή υποδομή του χωριού**, η οποία αποτελείται από 18 σπίτια από τα οποία 14 είναι αυτόνομα ηλιακά συστήματα, που στην πλειονότητά τους δεν είναι διασυνδεδεμένα μεταξύ τους και όλα βρίσκονται εκτός του κυρίως δικτύου.

2. **Προσωπική εργασιακή εμπειρία επί τόπου**, η οποία συνιστάται στην εργασία

σε τρία από τα αυτόνομα σπίτια

3. **Η δυνατότητα υλοποίησης της υπόθεσης της μελέτης**, από την πλευρά της κοινότητας των χρηστών στο LMRA λόγω της ύπαρξης ενός τεχνολογικού κέντρου έρευνας στον οικισμό, το Sunseed Desert Technology. Παράλληλα, η διαχείριση του νερού ως κοινοτικό αγαθό είναι ένα σημάδι κοινοτικής διαχείρισης ενός κοινού αγαθού που είναι ένας σημαντικός κοινωνικός παράγοντας που επηρεάζει το σχεδιασμό μας του προτεινόμενου μικροδίκτυο. Αυτό δείχνει στον ερευνητή ότι η ηλεκτρική ενέργεια θα μπορούσε δυνητικά να λειτουργήσει ως κοινό αγαθό και να γίνει κοινοτική διαχείριση της.

Στη συνέχεια, εξετάζονται τα υπάρχοντα ηλεκτρικά μέσα παραγωγής και αποθήκευσης της ενέργειας στον οικισμό, και υπολογίζεται το προφίλ φορτίου χωρίζοντας τα σπίτια σε 3 κατηγορίες: υψηλού, μεσαίου και χαμηλού καταναλωτικού προφίλ. Τέλος, υπολογίζεται το συνολικό προφίλ φορτίου υποθέτοντας ότι τα σπίτια είναι συνδεδεμένα μεταξύ τους σε ένα μικροδίκτυο με συντελεστή ταυτοχρονισμού 0,8. Συνοπτικά η συνολική παραγωγή όλων των υπάρχων Φ/Β πλαισίων είναι σχεδόν 15 kWp με ετήσια παραγωγή 25,3 MWh και χρήσιμη χωρητικότητα των μπαταριών 130 kWh, με το δίκτυο να έχει ετήσιο φορτίο 32,7 MWh. Αυτό σημαίνει ότι η χρήση ΑΠΕ στο σύνολο του οικισμού κατα μέσο όρο είναι στο 84 %. Με δεδομένη μια μικρή αύξηση της κατανάλωσης και την πιθανή εισχώρηση 3 νέων σπιτιών στο δίκτυο, υπολογίζεται το νέο συνολικό φορτίο και οι ανάγκες για επιπλέον μέσα παραγωγής ενέργειας για την μείωση της χρήσης των γεννητριών και την αύξηση της ασφάλειας παροχής ηλεκτρικής ενέργειας. Σύμφωνα με τους υπολογισμούς, το νέο υπολογιζόμενο ετήσιο φορτίο είναι 44,5 MWh.

Με βάση την πρόβλεψη αυτή, ξεκινάει η διαδικασία σχεδιασμού του μικροδικτύου με ορίζοντα χρόνου τα επόμενα 20 χρόνια. Αρχικά, θεωρούμε ότι τα υπάρχοντα μέσα (Φ/Β, μπαταρίες,γεννήτριες diesel) ενσωματώνονται στο δίκτυο με την διασύνδεση μεταξύ τους και το δίκτυο παραμένει εκτός σύνδεσης με το κυρίως δίκτυο. Η ανάγκη για επιπλέον μέσα παραγωγής και αποθήκευσης της ενέργειας καλύπτεται από την προσθήκη νέων Φ/Β πλαισίων αποκαλούμενα κοινοτικά Φ/Β και την προσθήκη νέων μπαταριών αποκαλούμενες κοινοτικές μπαταρίες. Τα δύο αυτά στοιχεία θα αποτελούν ιδιοκτησία της κοινότητας και θα προσφέρουν ενέργεια στο δίκτυο και ειδικότερα στους χρήστες που δεν έχουν μέσα παραγωγής. Το δίκτυο σχεδιάστηκε ως ένα δίκτυο AC ακτινική τοπολογίας με δύο εναλλακτικές διαδρομές για το κοινοτικό κτίριο για χρήση της κοντινότερης απόστασης. Το ακριβές μέγεθος των στοιχείων αυτών υπολογίζεται χρησιμοποιώντας το πρόγραμμα Homer Pro το οποίο είναι ένα πρόγραμμα προσομοίωσης από την εταιρία Homer Energy, που προσφέρει εργαλεία για την προσομοίωση μικροδικτύων, βελτιστοποίηση των επιμέρους στοιχείων του και ανάλυση ευαισθησίας του δικτύου.

Τα υπάρχοντα στοιχεία μοντελοποιήθηκαν με βάση την πλατφόρμα του Homer Pro χωρίζοντας τα υπάρχοντα ΦΒ πλαίσια από τα κοινοτικά των οποίων το μέγεθος βελτιστοποιείται. Το ίδιο συνέβει για τις μπαταρίες. Το αποτέλεσμα των προσομοιώσεων προσέδωσε δύο πιθανές λύσεις όπου στη μία η διείσδυση ΑΠΕ στο μικροδίκτυο ήταν 90 % με προσθήκη 10 kWp Φ/Β ενώ στην άλλη 95% με 15 kWp Φ/Β με μικρή διαφορά στο τελικό συνολικό κόστος. Η δεύτερη επιλογή κρίθηκε πιο κατάλληλη σύμφωνα με τα κριτήρια του σχεδιασμού , οπότε τα αποτελέσματα της προσομοίωσης για την δεύτερη επιλογή παρουσιάστηκαν αναλυτικά. Πέρα από την παραγωγή των Φ/Β τα οποία στο σύνολο τους κάλυπταν το 95% της παραγωγής, οι γεννήτριες diesel μεγέθους 6 kWp κάλυπταν το υπόλοιπο 5% με οριακό κόστος λειτουργίας τα 0,273 €/kWh. Οι κοινοτικές μπαταρίες διαστασιολογήθηκαν στις 50 kWh όπου μαζί με τις υπάρχουσες προσέφεραν 33,5 ώρες μέγιστης αυτονομίας με πολιτική χρήσης που το 50 % είναι η ελάχιστη κατάσταση φόρτισης που μπορούν να βρεθούν. Με μετατροπείς μεγέθους 18,5 kWp, το συνολικό κόστος κεφαλαίου ανέρχεται στις 23.767 €, κόστος αντικατάστασης μέσων παραγωγής σχεδόν 10.000 €, κόστος diesel 8.735 € και τρέχοντα κόστη σχεδόν 5.000 € όπου στο σύνολο τους ανέρχονται 41.275 € για τα επόμενα 20 χρόνια. Η αντισταθμισμένη τιμή ενέργειας συστήματος είναι 0,08 €/kWh.

Η πρόταση δημιουργίας του μικροδικτύου αποδείχθηκε ότι θα έχει μία αύξηση 11% στο ποσοστό διείσδυσης των ΑΠΕ στο σύστημα, εγγύηση κάλυψης ενός αυξημένου φορτίου όλο το χρόνο και κάλυψη ενεργειακών αναγκών 3 νέων σπιτιών. Ωστόσο, το έργο του μικροδικτύου LMRA έχει δύο σημαντικούς παράγοντες-προβλήματα: α) κόστος κεφαλαίου 23.000 € που καλύπτεται από την υπάρχουσα κοινότητα και β) ανάγκη για διαχειριστή δικτύου με ικανότητα και γνώση του εξοπλισμού και υπεύθυνο για την παραγωγή και αποθήκευση του κοινοτικού κτιρίου ,μετάδοση της ενέργειας και διαχείριση των ελεγκτών που επιτρέπουν την ανταλλαγή ενέργειας μεταξύ σπιτιών. Μέσα στην υπάρχουσα υποδομή υπάρχουν χρήστες που έχουν περισσότερα μέσα παραγωγής από άλλους, έτσι τα κίνητρα για τη δημιουργία του δικτύου από υπάρχοντες ή νέους κατοίκους είναι διαφορετικά. Για αυτό προτείνεται μια εσωτερική αγορά που θα προσπαθήσει να λύσει τα προβλήματα αυτά.

Όπως η θεωρητική μας έρευνα έδειξε, οι αγορές ηλεκτρικής ενέργειας είναι ήδη καλά διαδεδομένες στην ανάπτυξη μικροδικτύων και τώρα όλο και περισσότερο χρησιμοποιώντας τεχνολογίες blockchain. Στην περίπτωση της μελέτης μας, παρατηρούμε ότι υπάρχουν ιδιωτικά και κοινοτικά περιουσιακά στοιχεία στο σύστημα που σημαίνει ότι υπάρχει η ανάγκη ενός μηχανισμού για τη σύνδεση αυτών των δύο στοιχείων. Τα σπίτια λειτουργούν ως prosumers και το κοινοτικό κτίριο ως παραγωγός, εκ των οποίων οι ιδιοκτήτες είναι τα ίδια σπίτια. Ο τρόπος ρύθμισης αυτών των οικονομικών σχέσεων καλύπτεται μέσω της δημιουργίας μιας αγοράς ενέργειας και έξυπνων συμβάσεων μεταξύ τους. Η σχεδιασμένη αγορά ενέργειας θα καλύψει την ανάγκη για: α) Δημιουργία συμβάσεων χρήσης μεταξύ των διαφορετικών χρηστών που αντισταθμίζουν τα διάφορα περιουσιακά στοιχεία που κάθε χρήστης συνεισφέρει στο δίκτυο (π.χ. το House A χρησιμοποιεί τη δύναμη του σπιτιού B επειδή το σπίτι B διαθέτει περισσότερα φωτοβολταϊκά πάνελ) β) Ρύθμιση της προτεραιότητας της χρήσης ενέργειας που παράγεται στο δίκτυο. γ) Αποζημίωση των μελών της υπάρχουσας κοινότητας για την επένδυση κεφαλαίου για τη δημιουργία του δικτύου δ) Αποζημίωση του κόστους αντικατάστασης και συντήρησης του δικτύου ε) Αντιστάθμιση των λειτουργικών εξόδων της διαχείρισης δικτύου (μισθοί, εξοπλισμός κ.λπ.)

Η αγορά ενέργειας LMRA θα μπορούσε να οδηγήσει σε δύο διαφορετικές περιπτώσεις: 1) Περίπτωση Α: Η κοινοτική ισχύς έχει προτεραιότητα στην πώληση, που σημαίνει φθηνότερες τιμές γι 'αυτήν 2) Περίπτωση Β: Η ισχύς των σπιτιών έχει προτεραιότητα στην πώληση, πράγμα που σημαίνει φθηνότερες τιμές για αυτά. Αυτά τα δύο αντικατοπτρίζουν δύο διαφορετικές νοοτροπίες για το δίκτυο. Στην περίπτωση Α, η κοινοτική ισχύς λειτουργεί όπως ο πάροχος δικτύου που παρέχει την επιπλέον ενέργεια που χρειάζονται όλα τα σπίτια και στην περίπτωση Β, το δίκτυο λειτουργεί ως πλατφόρμα ομότιμης ενέργειας και η κοινοτική ισχύς λειτουργεί ως εφεδρικό σύστημα ισχύος. Στην πρώτη περίπτωση, οι ιδιοκτήτες κοινοτικών ακινήτων θα απολαμβάνουν εξίσου το όφελος της αγοράς, ενώ στη δεύτερη περίπτωση, οι χρήστες με μεγαλύτερα περιουσιακά στοιχεία θα ωφελούνται περισσότερο δημιουργώντας μια σχέση παραγωγού-καταναλωτή μεταξύ των σπιτιών.

Η αγορά πρέπει να βασίζεται σε σαφείς συμφωνίες σχετικά με τις ιδιοκτησίες. Έτσι, η έρευνα προχωρά σε συγκεκριμένες προτάσεις για το πώς θα κατανεμηθεί το κόστος του δικτύου μεταξύ των ιδιοκτητών των σπιτιών, προκειμένου να προσδιοριστεί η κοινοτική ιδιοκτησία. Κατόπιν αυτής της πρότασης, μπορεί να καθοριστεί το μερίδιο των εσόδων της κοινής ιδιοκτησίας και ο τρόπος με τον οποίο αυτά τα έσοδα μπορούν να αντισταθμίσουν το κόστος καθώς και το χρονικό διάστημα θα χρειαστεί κάνοντας μερικές προβλέψεις. α) Όλες οι υπάρχουσες κατοικίες (18) συνεισφέρουν έως και ένα ποσοστό στο κόστος κεφαλαίου.β) Θα μπορούσε να δημιουργηθεί ξεχωριστή νομική οντότητα προκειμένου να κατέχει και να διαχειρίζεται την κοινοτική ιδιοκτησία και το δίκτυο .γ) Αυτή η οντότητα λαμβάνει τα έσοδα της κοινής ιδιοκτησίας και τα διανέμει ανάλογα.

Διερευνώντας την έρευνά μας στο κεφάλαιο της θεωρίας για παρόμοια έργα, επιλέγουμε ότι η αγορά βασίζεται σε blockchain για την αποθήκευση των δεδομένων των συναλλαγών και τη χρήση έξυπνων συμβάσεων για τις ενεργειακές συναλλαγές. Αντί για κρυπτονομίσματα, στην περίπτωσή μας χρησιμοποιούμε ευρώ, επειδή στόχος της αγοράς μας είναι να αντισταθμίσουμε μια επένδυση που πραγματοποιείται σε ευρώ. Κρίνεται απαραίτητη η εισαγωγή ενός μηνιαίου λογαριασμού με όλες τις ενεργειακές συναλλαγές και το κόστος. Η πλατφόρμα που ανταποκρίθηκε περισσότερο στις ανάγκες μας ήταν το D3A (Decentralized Autonomous Area Agent) το οποίο αναπτύσσεται από την Grid Singularity ως εφαρμογή και βάση κώδικα για τη μοντελοποίηση, προσομοίωση, βελτιστοποίηση μιας προσαρμοσμένης ανταλλαγής ενέργειας. Το D3A έχει σχεδιαστεί για τη δημιουργία «ψηφιακών διδύμων» αναπαραστάσεων φυσικών ενεργειακών συστημάτων και αγορών ενέργειας.

Στη νέα αυτή πλατφόρμα απαιτείται μια διαφορετική μοντελοποίηση. Κάθε σπίτι αντιπροσωπεύεται ως αγορά με 4 διαφορετικά στοιχεία. Φωτοβολταϊκά πάνελ και γεννήτριες diesel ως μονάδες παραγωγής, μπαταρίες ως μονάδες αποθήκευσης και το φορτίο τους. Εδώ να σημειωθεί ότι η πλατφόρμα που προσφέρει το D3A είναι πιο περίπλοκη από ό,τι χρειάζεται το σύστημα που διερευνούμε. Στην περίπτωση του LMRA, θα χρειαζόταν ένας μοναδικός ελεγκτής για κάθε σπίτι με τιμή αγοράς και πώλησης για ολόκληρο το σπίτι και όχι το σύστημα D3A που εφαρμόζει έναν ελεγκτή για κάθε περιουσιακό στοιχείο του σπιτιού. Το δίκτυο δημιουργήθηκε συνολικά γιας τους 21 χρήστες, οι οποίοι εκπροσωπούνται με τα στοιχεία τους όπως εμφανίζονται στο μελλοντικό σενάριο του κεφαλαίου C. Κάθε χρήστης αντιπροσωπεύει μια αγορά, καθώς και στο σύνολο του το μικροδίκτυο αποτελεί μία αγορά.

Τα Φ/Β πλαίσια πέρα από την ισχύ τους έχουν ξεχωριστή τιμολόγηση ως εξής: α) αρχική τιμή πώλησης που θα καθοριστεί εκ των υστέρων ανάλογα με την περίπτωση β) τελική τιμή πώλησης γ) ρυθμός μείωσης της τιμής και δ) διάστημα ανανέωσης της τιμής. Κάθε γεννήτρια έχει σταθερό ρυθμό πώλησης που στην περίπτωσή μας αντιστοιχεί στο σταθερό κόστος παραγωγής που παράγεται από την προσομοίωση HOMER, 30 σεντ / kWh. Οι μπαταρίες, παρόμοια, εχουν αρχική και τελική τιμή αγοράς πώλησης της ενέργειας και ελάχιστη και μέγιστη τιμή πώλησης της ενέργειας. Το φορτίο υπολογίζεται με βάση τους υπολογισμούς μας στο κεφάλαιο Β και με αυτό τον τρόπο αποδίδεται κατάλληλο καταναλωτικό προφιλ στους χρήστες. Με βάση αυτά τα δεδομένα προκύπτουν δύο περιπτώσεις τιμολογήσεων:

Περίπτωση Α	**Τιμολόγηση για σπίτι με γενήτρια**	**Τιμολόγηση για σπίτια χωρις γενήτρια**
Τιμή πώλησης για Φ/Β σπιτιών	0<x<8	0<x<8
Τιμή πώλησης για κοινοτικά Φ/Β	0<x<7	
Τιμή αγοράς για τις μπαταριές των σπιτιών	5<x<30	5<x<8
Τιμή αγοράς για τις κοινοτικές μπαταρίες	5<x<8	
Τιμή πώλησης για τις μπαταρίες των σπιτιών	30<x<35	9<x<20
Τιμή πώλησης για τις κοινοτικές μπαταρίες	9<x<18	
Τιμή πώλησης για τις γεννήτριες	30	-
Τιμή αγοράς για το φορτίο	x<35	

Η περίπτωση Β έχει ανάποδα τις τιμές πώλησης των Φ/Β των σπιτιών και των κοινοτικών και την τιμή πώλησης των μπαταριών μεταξύ των ίδιων. Με αυτό τον τρόπο δημιουργούμε τις δύο περιπτώσεις τις οποίες αναφέραμε προηγουμένως. Δύο βασικοί παράγοντες της προσομοίωσης είναι η αυτάρκεια και η αυτοκατανάλωση. Η αυτάρκεια είναι η αυτοκαταναλισκόμενη ενέργεια διαιρεμένη με τη συνολική απαιτούμενη ενέργεια. Η συνολική απαιτούμενη ενέργεια μετρά τη συνολική ενέργεια που απαιτείται από τα φορτία. Αυτοκατανάλωση είναι η αυτοκατανάλισκόμενη ενέργεια διαιρούμενη με τη συνολική παραγόμενη ενέργεια.

Τα αποτελέσματα και για τις δύο περιπτώσεις είναι πανομοιότυπα. Η αυτάρκεια φτάνει το 99,8% και η αυτοκατανάλωση το 100%. Κάθε σπίτι που χρειάζεται παραπάνω ενέργεια φαίνεται να έχει αγοραπωλησίες με σχεδόν όλα τα υπόλοιπα σπίτια ωστόσο όπως αναμενόταν, το μεγαλύτερο ποσοστό καλύπτεται από τα κοινοτικά περιουσιακά στοιχεία. Η τιμή κυμαίνεται ανάλογα την ώρα της ημέρας όπου κατα τη διάρκεια της ημέρα ξεκινά χαμηλά και τις βραδινές ώρες φτάνει στη μέση τιμή των 25 cent/ kWh. Η μέση ημερήσια τιμή υπολογίζεται στα 16 cent/ kWh για την περίπτωση Α και 0,17 cent/ kWh στην περίπτωση Β. Σε διάστημα 6 ημερών το οι κοινοτικές μπαταρίες και Φ/Β υπολογίζεται να έχουν έσοδα 7,49 € και 7,09 € αντίστοιχα ενώ ένα σπίτι χωρίς Φ/Β αντίστοιχα να έχουν έξοδα 7-8 €. Παρατηρήθηκε επίσης ότι το διάγραμμα των συναλλαγών δεν ακολουθεί το διάγραμμα του φορτίου με υψηλότερο ρυθμό ανταλλαγών τις πρωινές ώρες. Αυτό συμβαίνει εφόσον τα στοιχεία ανταλάσσουν ενέργεια παράλληλα μεταξύ τους όχι μόνο για λόγους εκπλήρωσης του φορτίου της στιγμής.

Η στρατηγική των στοιχείων καθορισμένη από την πλατφόρμα του D3A δεν αντικατοπτρίζει πλήρως την αγορά την οποία επιθυμούμε ωστόσο είναι μία καλή αναπαράσταση μιας πιθανής αγοράς όπου καθοδηγεί την ανταλλαγή ενέργειας μέσα στο σχεδιαζόμενο μικροδίκτυο. Η αγορά του D3A είναι σχεδιασμένη έτσι ώστε κάθε στοιχείο να αγοράζει την φθηνότερη ενέργεια και όχι αυτή που παράγεται πιο κοντά χωρικά. Η κυρίως διαφορά ανάμεσα στη στρατηγική του σχεδιασμένου μικροδικτύου στη παρούσα έρευνα και αυτή του D3A είναι η έμφαση στην αυτοκατανάλωση σε ένα σπίτι όπου στα αποτελέσματα φάνηκε να μην είναι στόχος του δικτύου.

Από την προσομοίωση συμπεραίνουμε ότι η περίπτωση Α οδηγεί σε μεγαλύτερα έσοδα για την κοινοτική περιουσία και χαμηλότερη τιμή παραγωγής ενέργειας, οπότε προτείνεται ως βέλτιστη λύση. Αποδεχόμενοι ότι η χρέωση της υπόθεσης Α επιβάλλεται και η χρέωση δεν αλλάζει δραστικά καθ 'όλη τη διάρκεια του έτους, οι τιμές της προσομοίωσης ανά kWh μπορούν να θεωρηθούν ως η τιμή kWh για ολόκληρο το έτος. Σε αυτήν την περίπτωση, η μέση τιμή kWh για την κοινόχρηστη ιδιοκτησία είναι 0,065 € / kWh Έτσι, το εισόδημα της κοινής ιδιοκτησίας θα είναι τουλάχιστον: 22,750 kWh / έτος * 0,065 € / kWh = 1,478 € / έτος και 1,478 € / έτος * 20 έτη = 29,560 € συνολικό εισόδημα για κοινοτική ιδιοκτησία για την προγραμματισμένη περίοδο

Υπολογίζεται επίσης ότι 29.560 € - 20.000 € = 9.560 € κέρδος της κοινότητας αν ληφθούν υπόψη 20.000 €: το κόστος συντήρησης του δικτύου (5.119 €), συμπεριλαμβανομένων ιδιωτικών και κοινοτικών περιουσιακών στοιχείων, το κόστος αντικαταστάσεων (9,962 €), το κόστος της υποδομής διασύνδεσης (τουλάχιστον 2500 €). και κόστος καυσίμου (8,735 €). Το κέρδος της κοινότητας δεν είναι αρκετό για να καλύψει το κόστος κεφαλαίου όλων των σπιτιών. Έτσι, το κόστος κεφαλαίου πρέπει να καλύπτεται από προσωπικά κέρδη. Υπολογίζοντας, παράλληλα, τα έσοδα ενός σπιτιού όπου έχει πλεονάζουσα ενέργεια ,όποτε βρίσκεται συχνά στη πλευρά των πωλητών, με βάση το λογαριασμό χρέωσης έχει 239 € έσοδα τον χρόνο. Οπότε, εάν θεωρήσουμε ότι κάθε σπίτι συμμετείχε ισάξια στην επένδυση, η επένδυση του συγκεκριμένου σπιτιού θα έχει επιστραφεί σε σχεδόν 5,5 χρόνια.

Συμπερασματικά, στο δίκτυο δημιουργούνται δύο διακριτοί ρόλοι:α) ο ρόλος των prosumers όπου θα έχουν επιστροφή της επένδυσης τους β) ο ρόλος των κατανωλωτών οι οποίοι θα έχουν μία σταθερή χρέωση. Επίσης, η τιμολόγηση μεταξύ σπιτιών και κοινοτικής περιουσίας μπορεί να επιταχύνει ή να επιβραδύνει τον χρόνο απόδοσης της επένδυσης. Εξαρτάται από την κοινότητα για να αποφασίσει ποια κριτήρια θέλει να θέσει για τον κανονισμό τιμολόγησης. Η σχετικά χαμηλή τιμολόγηση που εφαρμόστηκε είναι ένα ρεαλιστικό σενάριο για μια κοινότητα αυτής της κλίμακας που υπάρχουν προσωπικές σχέσεις μεταξύ κατοίκων και ο στόχος δεν είναι το όφελος αλλά η επιστροφή του ποσού της επένδυσης σε αρχικό στάδιο.

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Preface

The present dissertation is divided into two parts. In the first part, it is made an introduction to the theoretical elements that this dissertation is investigating which are decentralized energy production systems, microgrids, home autonomous systems and blockchain. A deeper research in blockchain is followed and an investigation on its architecture. Afterwards, there is a review on the existing literature on applications of blockchain on the energy sector demonstrating in brief the proposals of more than 50 different group of researchers through their scientific publications.

In the second part, the dissertation enters to the main part of its study. In the beginning it is explained the case study that is undertaken and the reason why Los Molinos del Rio Aguas was chosen (chapter A). It is followed by a description of the existing electrical assets and an estimation of the load of all the existing residents. An future case scenario is constructed in order to predict the load profile of the community for the next 20 years and the proposal of creating a microgrid is formed by creating a communal energy production asset and a communal energy storage asset(chapter B). The simulating program Homer Pro is used to simulate two different cases for the possible microgrid and the results are demonstrated, resulting in that the case study is feasible with a low investment cost and higher than before energy production by renewable sources. (chapter C)

The investigation continues on (chapter D) creating a blockchain-based energy market embedded in the creation of the microgrid in order to solve property issues and the compensation of the investment and maintenance costs. The electrical assets of the future case scenario are modeled according to the D3A platform created by GridSingularity company. The simulation investigates two possible scenarios with different pricing and in the conclusions the most appropriate scenario is chosen in order to meet the criteria of the design.

First part: Theoretical concepts and blockchain in the energy sector

1.Energy policies of Greece and Europe

Current energy policies have been an initial motive for starting this investigation. Climate change and the introduction of new technologies have led to a change in energy production and consumption policy in Europe. Greece, as an EU member, is obliged to follow the energy policy set by the EU. The EU has issued three plans in terms of its energy policy, one for 2020, one for 2030 and one for 2050. Sustainability is one of Europe's overriding goals. In the face of the threat of climate change, the energy sector, a sector responsible for a large share of the pollutants leading to climate change, will play a key role in combating the phenomenon. The EU's energy targets for 2030 are:

1. reduction of greenhouse gas emissions by 40%
2. producing at least 32% of energy in the EU from renewable sources
3. increase energy efficiency by 32.5%
4. 15% of electricity interconnection (i.e. 15% of energy produced in the EU must be able to be transferred to other EU countries).[1]

In this context, there are specific policies that have been implemented to increase energy efficiency and reduce energy consumption. The technologies we refer to in this paper aim to contribute in this direction and that is why research on them is growing in Europe.

Based on these instructions, Greece, αccording to the Ministry of Environment, has developed the strategic plan for 2050 which was issued on 2020 and states: “In all scenarios, electricity generation from RES shows a significant increase, reaching 2050 to cover 88% -90% of the gross demand for the year 2050, with the RES of variable production, mainly wind and solar, to produce most of it, from 68% to 72%.” [2] The Report of the National Action Plan for achieving the contribution of Renewable Energy Sources to the final energy consumption at a rate of 20% by

2020, derives from Directive 2009/28 / EC, and includes estimates for the development of the energy sector and the penetration of RES technologies by 2020. This plan was met by significant steps in industrial RES (>1MW) but not in the direction of Collective Self Consumption (CSC).

As it is stated in the work of RESCoop [2], With the “Clean Energy for all Europeans” package, the European Union (EU) introduced new provisions on the energy market design and frameworks for new energy initiatives. Specifically, the recasts of the **renewable energy directive** (REDII) and the **electricity market directive** (EMD) provide basic definitions and requirements for the activities of individual and **collective self-consumption** (CSC) as well as for **renewable energy communities** (RECs) and **citizen energy communities** (CECs). These concepts allow citizens to collectively organise their participation in the energy system and open the way for new types of energy initiatives. Thereby, smaller actors shall be empowered to participate in the energy market, contributing to an increased decentral renewable energy production and consumption (prosumption).

It seems that through the Law N4513/2018 and the possibility of Net-Metering and virtual Net-Metering introduced in 2016 on energy communities, one of the main goals of Greece for the immediate future is the development of a decentralized way of generating electricity and finding the appropriate economic and technological measures that will help in this direction. The decentralized production is addressed beyond large RES development projects but also to the development of small energy sources and the strengthening of the network for their integration. Therefore, the strengthening of initiatives of citizens and small businesses that seek to contribute to the energy balance of the country through the development of small-scale RES is envisaged.

2. Decentralized energy production

Decentralized production in the first years of power generation was how most generation of electricity was done. The first units to provide energy to customers were the ones who were close to them. In the last decade the interest in decentralized production has been renewed due to the development of renewable energy sources, mainly photovoltaic and wind, as well as their integration into distribution networks. Decentralized production is a concept for which in the literature there are several definitions that do not completely agree with each other. Some definitions focus on the voltage level at which the connection is made while others focus on the fact that dispersed production is connected to the distribution system, directly to load points. In the present work we will use the following definition: Decentralized production is defined as the production units with nominal power supply from 1kW to 100 MW, normally connected to the distribution network and not designed or controlled by the power control center. Decentralized Generation often refers to electricity generation with application of Renewable Energy Sources (RES) technology. But it is possible for the implementation of decentralized production to use any production technology. RES are generally decentralized systems excluding large-scale hydroelectric plants or large offshore wind farms. But apart from the RES, the decentralized production includes other technologies used conventionally fuel.

The penetration of Decentralized Production in Distribution Networks (DN) is growing worldwide. The increase in this type of production has led to several changes in the philosophy of operation and configuration of Distribution Networks. The dynamic nature (greater involvement of power electronics) of connected loads and distributed generation creates new challenges for the operation of distribution networks, so network operators are called upon to provide assistance and support to the network. When the decentralized production reaches certain levels of penetration, then it has an effect in the stability and dynamic behavior of the transmission network. Also, Increased power injection into the Distribution Network can cause problems of overvoltage and reverse flow of power that may affect the settings protection within the distribution network.

A distribution network with increased penetration of decentralized Production affects the overall stability of the energy system and its dynamic behavior. The main generation units connected to the distribution networks are wind and photovoltaic units production. In the medium voltage network can be entire parks with installed power up to some MW while in the low voltage network and in Secondary distribution networks can be roof photovoltaic or small wind generators. The important thing about the above units is that all units interfaces with power electronics and reactive power and power factor can be adjusted to the grid needs. Decentralized Production can provide support to the distribution network supporting the reactive power demand from the network loads and flow reduction in case of congestion.

3. Microgrids

In this chapter it is provided useful information about microgrids (MGs) and basic definitions that will help in our further research. A microgrid is defined in the IEEE standard 2030.7 [3] as ‘‘a group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes.’’. Similarly, CIGRE [4] defines MGs as ‘‘sections of electricity distribution systems containing loads and DER, (such as DGs, storage devices, or controllable loads) that can be operated in a controlled, coordinated way, either while connected to the main power network and/or while islanded’’

Mgs, according to the work “Modeling and Simulation of Microgrids [5] , include sources of distributed power generation from a few kW to 1-2MW, storage devices -

such as capacitors, batteries, flywheels - and controllable loads. Microgrids are a type of electricity system that is expected to play an important role in the future. A microgrid performs all the functions performed by a central electrical system, ie manages the flow of power (via smart meters) between consumers and producers, where in most cases they are RES producers or prosumers where are both producers and consumers, the storage of excess energy (in batteries), the recording of energy exchange in the network and its management. They are divided into two categories, those that are not connected to the rest of the ES (off-grid microgrid) and those that are connected (microgrid with utility interconnection) where these are the most common ones. The first category is found mainly in areas where there is a high percentage of energy poverty and the creation of isolated networks is required.

A key feature of microgrids is their coordinated control, so that they eventually appear for the grid as a single entity with its own decentralized control system which does not burden the network control systems with the control of each unit separately.[6] Another equally basic, as well as innovative, feature of microgrids is their ability to operate not only interconnected with the upstream medium voltage network, which is their normal operation, but also isolated (or islanded) when the connection to the main grid is interrupted, it continues functioning in an organized and controlled manner providing consumers with increased reliability and improved power quality levels. This feature of course requires sophisticated protection, control and telecommunications infrastructure in order to be able to isolate the microgrid and provide stable, autonomous operation. However, the constant progress in the field of telecommunications and controllers of sources of dispersed production helps to make such operation more and more easy to achieve both technically and economically.

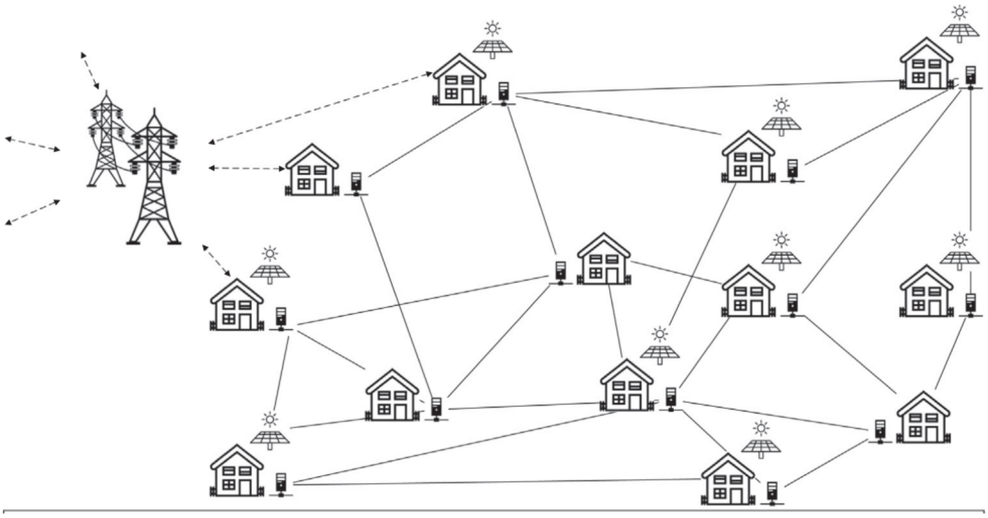


Illustration 1: An example of a microgrid

In Illustration 1 it is demonstrated an example microgrid where there is a connection to the network, PV systems in some of the houses and energy management systems in each house . One such network is that of Brooklyn Microgrid [7] . They trade (locally produced) peer-to-peer energy with their neighbors. The project consists of two main elements:

1. The virtual community platform for the energy market: This platform provides the technical infrastructure for the local electricity market. It is based on a private blockchain using the Tendermint[8] protocol. The TransActive Grid[9] blockchain architecture and the TransActive Grid smart meter are implemented. Note that the TransActive Grid meter is installed in addition to the analog meter. Thus, the TransActive Grid meter measurements can be verified by the corresponding meter during the initial stages of the project.
2. The physical microgrid: A microgrid was built in addition to the existing distribution network. The physical microgrid acts as a backup to prevent power outages. By disconnecting from the main grid, it can operate in off-grid mode. Critical facilities (eg hospitals) then receive energy at constant prices. Homes and businesses must bid for the rest of the network. The natural microgrid currently includes 10 homes and will be expanded.

An example of a microgrid in Greece

The researchers M.; Argyropoulou, Violeta M. [3] from NTUA offers us an example of decentralized production in Greece: “Unfortunately, there are many problems associated with the penetration of RES and other small units in the domestic system of production and distribution of electricity and consequently in the creation of microgrids. A key factor is the different philosophy on which the Greek electrical system was built. A system that today relies on the concentrated generation of electricity from large thermal power plants and radial transmission to one-way power consumption, encounters a number of obstacles related to control, stability, protection and reliability in its conversion in a distributed production network. In addition, significant interventions are required in the distribution and control network, so that they can manage the distributed production both from the renewable energy units and from the other small units. Issues that also need to be studied are the contribution of the microgrids that are interconnected with the central network of medium or low voltage, as well as their behavior in errors or general interruptions.

Despite the difficulties, efforts are being made in Greece for the integration of microgrids in the electricity system. One of them is the pilot microgrid in Kythnos. It is located in the area of Gaidouromantra of Kythnos and is a single-phase microgrid. It electrifies twelve houses in a small valley of Kythnos. The microgrid meets the security requirements set by National Grid for the connection to the houses. The reason for this is because in the future the microgrid can be connected to the rest of the island. The power in each home powered by the mains is controlled by a 6 Ampere fuse. The settlement is located about 4 km away from the nearest point of the medium voltage line of the island. A twenty-square-meter building was constructed in the middle of the settlement to house the batteries and their inverters, the diesel generator as well as the control computer and communication equipment.

Each battery inverter has a maximum output power of 3.6 kW. They are connected in parallel allowing the use of one or more depending on the needs of consumers. There are also load control switches used to keep the batteries from overcharging or overcharging. The system consists of 10 kWp of photovoltaics divided into smaller subsystems, a battery with a nominal capacity of 53 kWh and a diesel generator with a nominal output of 5 kVA. A second system with about 2 kWp is located on the roof of the building where the equipment is housed and is connected to an inverter and a 32 kWh battery. This second system provides the power needed to control and communicate the system". The project is currently called WiseGRID and it implements a Distributed Multi-agent System for load power control [10].

4. Autonomous Electrical Systems

According to researchers[11] autonomous electrical systems are divided in these categories: According to the space to which we refer, we have:
- Global autonomy, which refers to the entire planet, and the approach is similar to the concept of Sustainable Development of Energy
- Continental autonomy, in our case being Europe or, more constrained, by the European Union;
- National autonomy, refers only to a country;
- Local autonomy refers to a locality;
- Neighborhood autonomy, refers to parts of a locality;
- The autonomy of a building, refers to a building that houses several families or an institution;
- The autonomy of a home.

In our case we will be looking into home autonomous electrical systems and community/neighborhood autonomous systems.

The technical compartments of an autonomous electrical system are explained below. A typical Autonomous Power System (APS) consists of several basic elements conceptually shown in Illustration 2 [12]. They are divided into basic modules, i.e. the primary source of power, backup power supply, uninterruptible power supply, control system and energy storage.

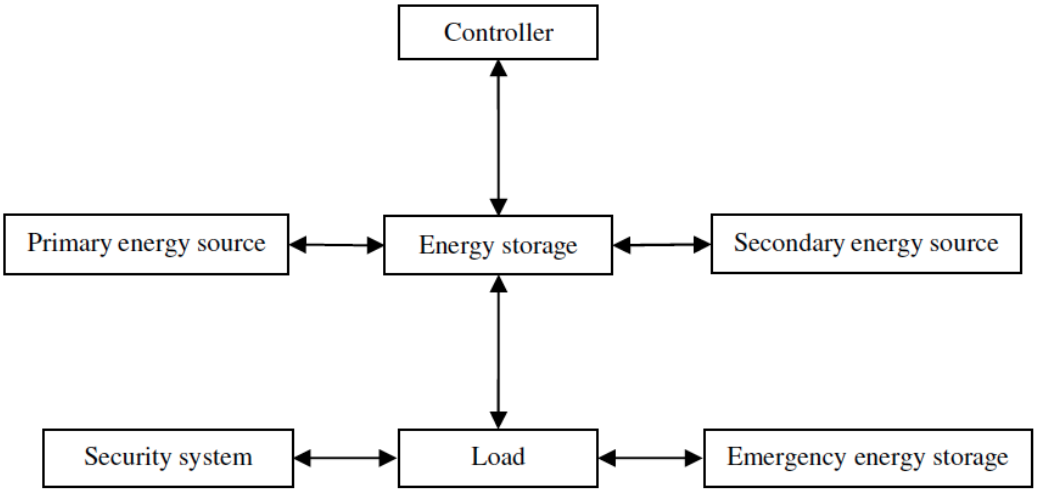


Illustration 2: A typical Autonomous Power System block diagram

However, autonomy expands in the sector of governance and control over the microgrid as it is stated by REScoop work. During its analysis about energy communities, it is mentioned that: *The recast of the EMD includes a definition of "control" referring to the possibility of "exercising decisive influence on an undertaking, in particular by (a) ownership or the right to use all or part of the assets of an undertaking; (b) rights or contracts which confer decisive influence on the composition, voting or decisions of the organs of an undertaking". The effective control of Collective Energy Communities is explicitly limited to natural persons, small and micro enterprises, as well as local authorities for which "the energy sector does not constitute a primary area of economic activity" (the latter limitation refers to "decision-making powers"). For Renewable Energy Communities, the exclusion of large enterprises as shareholders or members equally implies exclusion from the effective control. In addition, the majority of voting rights should be held by "shareholders or members that are located in the proximity of the renewable energy projects".*

Furthermore, RECs are required to be autonomous. As described in the recitals of the REDII, this means that RECs "should be capable of remaining autonomous from individual members and […] traditional market actors that participate in the *community as members or shareholders, or who cooperate through other means such as investment." The concepts of proximity and autonomy are interrelated as both address different aspects of power distribution. The openness of these concepts allows member states to consider national circumstances and existing approaches and to fit them into their national legal systems.* Such organizations work as an example and an inspiration for this study's design.

Solar Home System

Going deeper into autonomous home systems we present the concept of a Solar Home System. An SHS, according to A.K. Podder [13] , is an interconnected system for converting solar irradiance directly into electricity and generally consists of the PV array, battery bank, charge controller, an inverter, protection devices and the system's load. Since the aggregate sun oriented irradiance that achieves the surface of the earth differs with the time of day, season, area and climate conditions, a maximum power point tracker (MPPT) device is used for off-grid applications between the array and load to trace maximum power output of the PV array and also for matching the impedance of the electrical load. A buck converter is utilized here in order to provide a constant dc voltage. The stand-alone PV needs batteries as energy sources in case of stormy weather conditions and at night as they supply energy to the load. To prevent overcharging and deep discharge of the batteries, a charge controller is added in the system. These systems generally include an inverter, which converts the DC voltage of PV modules into AC voltage for direct use with the appliances.

Here is the example circuit diagram of an SHS:

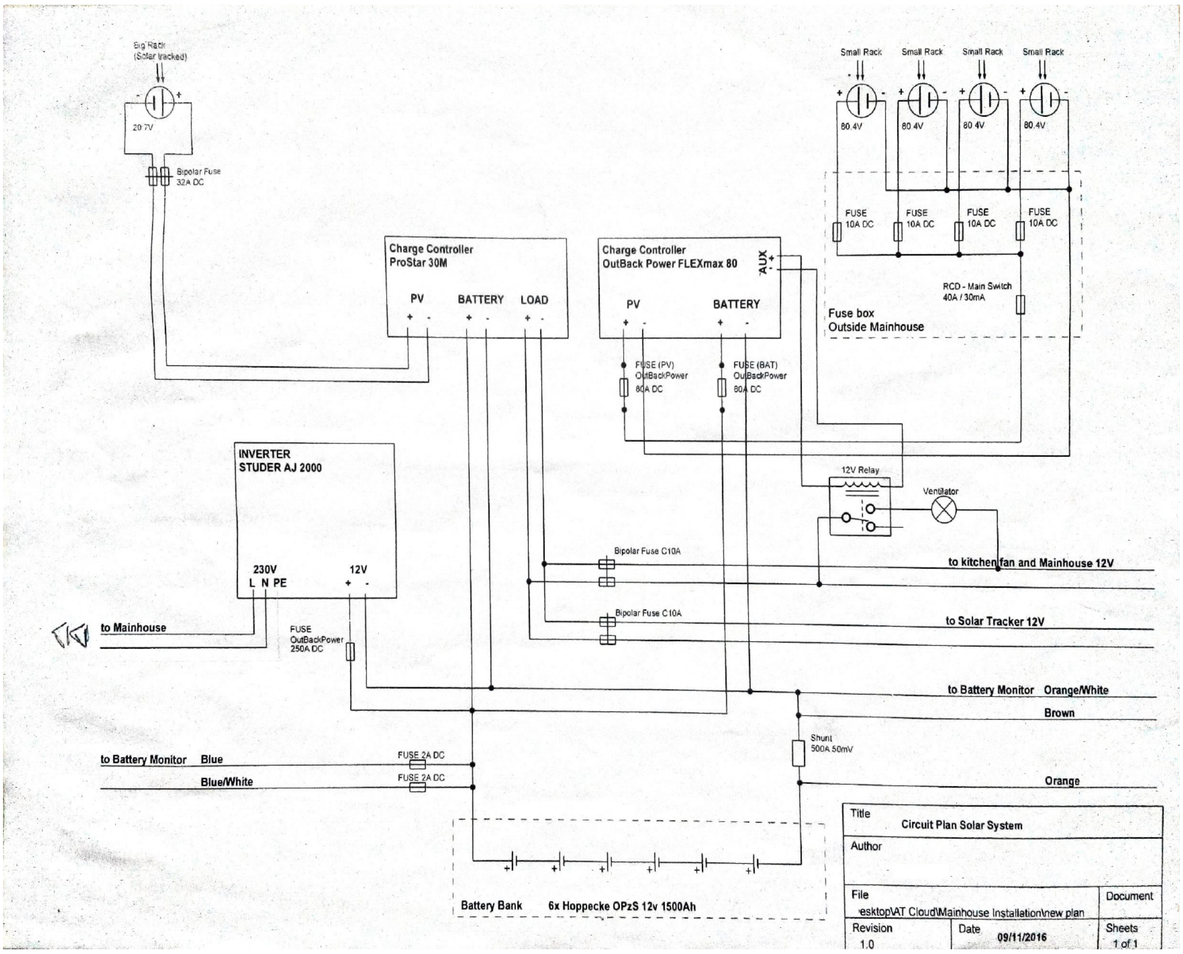


Illustration 3: Solar Home System of House 3&4 in LMRA, (source: personal archives)

This is a SHS with two separate battery chargers, two separate arrays of PV panels which charge the same 12 V batteries, an inverter for AC loads and multiple fuses for short-circuit protection. The use of different battery chargers in this case serves so that the different types of PV panels (Voltage and Watts) can offer the maximum power they can.

5.The branches of decentralized production & reviews

Illustration 4: Centralized, decentralized and distributed networks.

Decentralized power systems differ in structure in two characteristics from the way the grid was structured until now, The first difference is who manages the power flow. in decentralized power systems the management of power flow is done from computer systems that operate with automated algorithms that do not require strict supervision. Platforms use a language of facilitation but their technologies actively mediate and thus shape exchanges between distributed users [14]. This makes it crucial to understand the algorithmic underpinning of the collectivities and activities that platforms afford. Platforms allow their 'members' to engage in activities that otherwise may not have been accessible to them. The implications of such trends are not yet clear, opening a question of what are the potential consequences for consumers, prosumers and communities . Platforms such as blockchain and can solve bidding problems by users. In this way an optimal power distribution plan (PDP) is found. This type of power management is based on the creation of decentralized electricity markets, where money and power transactions are between all users of a network.

The second feature is the ability of users to get and give power to the network, as prosumers. This means that the grid is dynamic and the power flow is not from the top (from the factories) to the bottom (consumers) but horizontally. Another name of these markets according to the Danish researchers Tiago Sousaa et. al. is the consumer-based electricity market [15]. They state that: More active and democratic cooperation of all energy users is important for consumer-based markets, which includes empowering small consumers in their choice to buy or sell energy. In other words, it is a model of energy exchange between users, peer to peer (P2P), without a central power provider.

A peer to peer energy exchange system is an energy trading system in which energy system operators can exchange power with each other in a peer-to-peer manner without the involvement of a central entity, such as companies. The P2P DET system consists of various entities such as consumers, customers, microgrids and the utility network itself. Consumers are consumers who can also produce their own energy on a small scale. When consumers have surplus energy, they can sell it on the grid.[16] P2P power exchange networks can be divided into three categories, based on the segregation of the same Danish researchers:

a) Full P2P market
A complete P2P market implies that each user (i.e. producers, consumers and customers) interacts directly with other users without intermediaries, such as electricity companies or market operators. An example of this is the LMRA microgrid that we are designing in this dissertation.

b) Community based market
The community-based marketplace is structured on the basis of a third entity between two users (the community), the community manager, to manage transactions between users within the community. This third entity also manages the interaction of the community with the rest of the system.

c) Hybrid market.

In the hybrid P2P markets a hybrid approach is proposed for microgrids under the same distribution network. Each microgrid handles the marketing of its members, as it does for a community. At the higher level, these microgrids can import energy from the main grid or trade with each other.

Anneta Matenli et. al., after modeling two different electricity systems, a decentralized and a centralized power plant, concluded that[17]: Comparing the different market settings, we conclude that decentralized regulation is lower than the producers of the central. This translates into less payment by consumers for the same amount of electricity. (Centralized and Decentralized Electricity Markets: Assessment of Operational and Economic Aspects)

Along with the economic benefits of a decentralized approach, Swiss researchers have shown that a decentralized neighborhood energy system can offer up to 92% energy autonomy for homes and a 50% reduction in CO2 emissions from centralized energy management [17]. One element that increases the energy efficiency of these systems is the combination of many different energy generation and storage methods where possible on the small scale of a neighborhood.

Green and Newman outline how local communities can take on community service tasks due to the growing blockchain support systems that facilitate decentralized markets combined with the increasing availability of distributed photovoltaic production[18]. However, utilities can innovate their business models and support small markets with professional know-how, providing ancillary services and ensuring a balanced energy system.

This is a table that sums up information found about the implementation of decentralized technologies and its effects:

	Sector	**Reasons and results of implementation of technology**		
Before implementation	Technical issues	Technological improvements in RES - failed costs	Better network performance through low-level user networking (low voltage)	Growing need for complex decentralized network management systems
	Social issues	Increasing the competitiveness of the price of RES, such as PV and heat sources,	Influence of the 'neighborhood effect' if dynamic networks become a reality	Opening communication between consumers and service providers through smart technologies
Technology		Decentralized generation	MicroGrid	Smart MicroGrid
After implementation	Social issues	Consumers produce their energy -> increase prosumers	Increasing social and business organization models around community-sized networks	Consumer participation in local energy production - new roles and responsibilities between consumers and energy services
	Technical issues	Non-continuous supply of electricity from RES and two-	Application of new social and commercial organizations	An electrical system model with many microgrids is

		way network (dynamic network)	through smart meters	possible

Table of results of implementation of different technologies

6. Blockchain

In the present dissertation it is investigated blockchain and its multiple functions that every day grow more.However, it will be focused in the exchange of energy peer to peer, and more specifically locally within decentralized electricity systems.In this chapter, it is offered an in depth research of what is blockchain and in its most used-applications.

6.1 Definition

To the author's knowledge, there is no universal definition and translation of the term blockchain.Many use Bitcoin as a springboard to explain the term, from its oldest application, cryptocurrencies. Many definitions have been given in an attempt to fully clarify the terminology. A group of researchers within the ISO organization dealing with the subject describes the blockchain as: *a common, unchanging ledger that can record transactions in various industries, [...]. It is a digital platform that records and verifies transactions in a transparent and secure manner, eliminating the need for intermediaries and increasing trust through its highly transparent nature*. IBM proposes a similar definition, saying that *a blockchain is a common, unchanging database for recording transaction history* '. [19]

To go a little deeper, however, we must analyze its structural elements. Initially, then, a chain of transactions is a network between users. These can be divided into two categories, customers and miners. It is important that this separation is not exclusive, (ie a customer can be a miner and vice versa)

- Client: A user who uses the network trades according to his wishes.

- Miner: A user trying to solve a problem under the form: Given α find β so that Γ (β) = α. If he finds the solution, then it transmits to the whole network the solution together with the immediately created one block containing the transactions he wants to integrate.

Each block of construction shows, in the form of a hash, its immediate predecessor and thus the chain is created. So all users, accepting the solution that is transmitted to them, have a universal view of the transaction chain and agree on its validity.

There is a case, however, that a network node has a different one face of the chain, because at least two of his neighbors sent him different solutions and therefore has a problem deciding which solution to accept. There is a simple rule for resolving these disputes: Each node continues to work on the face of the chain it has, until it receives one which is larger. In this case, he stops working at previous and continues to the last. This confirms that in the long run one and only one chain will prevail if the majority of the miners are honest.

It is of the utmost importance to emphasize that the users of a network end up in the long run in a common chain, means essentially that they end up in one and only one common truth between them, which can not be disputed by anyone within the network. Thus, the protocol of each chain of transactions is, in fact, a protocol of consensus agreement. The most interesting part of this truth is the cruelty of chain reversibility. In order for a malicious user to change one of the blocks, say the k-last block, he has to do all the previous work (finding new solutions k-times) and pull out a brand new (k + 1) block to convince everyone else nodes to accept its own chain as the largest and therefore the true. This possibility becomes negligible as his computing power decreases as deep as he wants to change something in the chain.

Essentially, the mechanism explained above makes it more expensive
counterfeiting of a transaction from potential profit. Without a suitable algorithm to reach consensus for blockchain, there would be no trust in Bitcoin blockchain-system, since anyone with access to the transaction history (all nodes) could rewrite the history and publish it as the real one.

Therefore, the following definition from K. Vlasios seems to cover all of the above, the main aspects of a blockchain. [20]*A blockchain is a distributed ledger where a computer is called a node if it joins the network. Each node has full knowledge of all the transactions that have taken place, the information is shared. Transactions are grouped into blocks that are added sequentially to the distributed database. Only one block at a time can be added and to add a new block it must contain a mathematical proof that it is following a sequence from the previous block. The blocks are connected to each other in chronological order. The above definition is very broad and covers almost all existing implementations of trading chains.*

6.2 ***Blockchain applications***

The exchange of information on the Internet until now was done in the form of sending copies of some data. However, when it comes to some information such as money, assets, etc., it can not be done in this way, because in this way there is no real exchange, as is done with material things (when I give it, I no longer have it). This creates the double spending problem. So there are intermediaries such as visa and banks that guarantee the security of transactions, their registration, their classification. However, they create centralization and exclusion for other users, because they manage the data resulting from the transactions in such a way that the need for intermediaries grows. The blockchain provides possible solutions to this problem. Possible uses of blockchain beyond energy are:

- Protecting one's rights over assets (eg Securities, acquisitions)
- Creating a real sharing economy
- Avoiding mediators by reducing mediation costs
- They protect privacy thus protecting the internet self
- Ensure the remuneration of product creators (value)

The blockchain is an idea on which many different algorithms have been implemented. Starting with bitcoin then expanded to many areas, where in each of them it has some common principles such as distributed ledger, encryption etc. Some researchers or projects use platforms such as bitcoin and ethereum, the two most well-known platforms, and integrate them into the system they propose or build a completely new blockchain platform, ie a new algorithm, where you have your own rules.

Bitcoin

The world's first cryptocurrency, Bitcoin, was created in 2009 after the publication of a document by Nakamoto. He proposed a distributed electronic cash payment that uses P2P communication from anonymous and unknown Internet users. While the idea was initially met with widespread skepticism, the price of bitcoin rose by over 1700% and traded around $ 20,000 at the end of 2017[21]

Each user in the Bitcoin system has a digital wallet, where coins are stored and a private and a public key. The wallet can only be accessed from the user's secret private key. The wallet address or Bitcoin address comes from the address of a user with a public key and is used to identify a user with a nickname. A Bitcoin transaction follows the following procedure : First of all, before a Bitcoin transaction, the parties to the transaction must know each other's public addresses. The sender creates an outgoing transaction if several coins are stored in his wallet. The transaction contains information about the quantity of tradable coins and the addresses of the traded parties. A transaction is encrypted with the recipient's public key, digitally signed by the sender and then transmitted to the Bitcoin network.

Special nodes aggregate all outgoing trades in the last 10 minutes into a single block. These nodes are also responsible for refining the validation process, so that on average a block takes about 10 minutes to validate and be included in the blockchain[22]

Some network users are miners or validators. Miners or validators compete with each other to add a new block to the existing blockchain by solving a cryptographic puzzle that creates a hash output that starts with a number of consecutive zeros in the most important positions. The method used adds a random number, which can only be used once per block, and calculates the hash output of the block header. The block header contains information such as the hash of the previous block validated and a special hash of all transactions contained in the block (Merkle tree). The goal for all miners is to achieve a fragmentation spread that is lower than a set goal. Miners have no way of predicting or influencing the outcome, so the only possible action is trial and error. This process of forced coercion requires a computer dependency that increases exponentially with the number of users. When there is proper fragmentation the output is found, the block is returned to the Bitcoin network and is accepted by other nodes if all transactions are valid, and the successful miner gets a financial reward. This process is called proof of work.

It should be noted here that the expansion of the bitcoin network has brought to the surface the problem of scalability (scalability) and the high cost of mining. The cost of mining is now very high asking questions about the viability of the algorithm used by bitcoin but also about blockchain technology as a whole. Its critics are wondering if blockchain is really a technology that can be widely used, let alone replace the financial system. This is why many different consensus mechanisms have been set up in the last year.

Ethereum

Ethereum is a "global computer", a platform that enables users to run distributed applications in a decentralized manner. Part of ethereum is ether, a cryptocurrency (ether) like bitcoin and ethereum blockchain that includes all applications based on it. One function of the Ethereum blockchain is smart contracts where programs are written in the Solidity language, a language specifically designed for this very function.

Ethereum, unlike bitcoin, prioritizes the service protocol, which means that it is a platform that is quite simple and stable in its basic principles, such as privacy, anonymity and consent. [23] Its innovation Ethereum in relation to Bitcoin, is that Ethereum is a more flexible and customizable platform, on which decentralized applications can be created and run securely, while Bitcoin mainly provides the possibility of (financial) cryptocurrency (Bitcoin) transactions.

Ethereum is in a sense a suite of protocols that define a platform for the development and operation of decentralized applications. The focus is on the Ethereum Virtual Machine ("EVM"), which can execute code of arbitrary algorithmic complexity. EVM is Turing complete. Like other blockchains, Ethereum includes a peer-to-peer network protocol. This protocol is responsible for the coordination of the connected nodes, in order for the smooth operation of the network. Each node "runs" the EVM and executes the same commands. Because of this, Ethereum is often referred to as the "global computer"[24].

The basic unit in Ethereum is the account, unlike the Bitcoin blockchain where the basic unit is the transaction. In the Ethereum blockchain, the status of each account is monitored and all status transfers are transfers of value and information between accounts.

There are two types of accounts:

- Externally Owned Accounts (EOAs), which are controlled by private keys
- Contract accounts, which are controlled by the contract code and can only be activated by an EOA.

EOAs are controlled by the people who own and control the private keys, while contract accounts are controlled by their code. The much-discussed "smart contract" is practically the code of the contract account, i.e. the program that runs when a transaction is sent to this account. Users who own EOAs can create new contracts by posting them on the blockchain. Users (EOA accounts) send transactions to the Ethereum network, signing the transaction data with their private key, using the Elliptic Curve Digital Signature Algorithm (ECDSA). A transaction is valid only if it is signed by the sender (from his private key). As a result, the network is sure that the sender of the transaction is the one claiming and not some malicious user.

For each transaction a small fee must be paid to the network. This protects the network by making frivolous computational commands as well as malicious attacks such as denial of service (DDoS) attacks useless. Payment is made for the calculation and the memory used to make the transaction and is proportional to them. This fee is paid on the Ethereum cryptocurrency, ether.

According to a recent report by Eurelectric[20] , the electricity industry association, more than 1,000 projects are currently using Ethereum. Many start-ups use Ethereum-based currencies and cryptocurrencies for Initial Coin Offerings as a means of increasing funding. A key application of Ethereum is Smart Contracts and Decentralized Applications (DApps). DApps are open source and decentralized applications that can run autonomously and without human intervention. DApps use encryption, run on a computer network, and store outputs on public ledgers.

6.3 Consent algorithms

Reaching consensus on which blocks / transactions are validly accepted in a distributed system is a challenge. Consent algorithms must be resistant to node failures, message delays as well as unreliable, unresponsive or even intentionally malicious nodes. Many approaches to the problem of consensus have been proposed. Some authors such as Merlinda Andonia et. al. [26]widely classify them as Lottery-based and voting-based. Lottery-based approaches include proof of work (PoW) public blockchain (used by most cryptocurrencies, such as Bitcoin or Ethereum). In PoW systems, the algorithm rewards participants who solve cryptographic puzzles in order to validate transactions and create new blocks. Another alternative is proof of stake (PoS), in which the validators are selected either randomly but the weight of the "vote" of each validation depends on the size of its "percentage" in the system - defined, for example, as the amount encryption held in a deposit or other merchandise. Voting-based approaches to validation include those based on the Practical Byzantine Fault Tolerance (PBFT) algorithm. In PBFT, nodes transmit votes to receive squares in a multicenter process, at the end of which the ratifiers agree on consensus strategies and key features based on whether to accept a block as a permanent part of the chain (finality). However, as ballots are transmitted over a potentially unreliable network and some of the validators may be unreliable, the consensus voting process requires careful planning.

Proof of stake seems to be one of the most popular alternatives in PoW. The proof-of-stake (PoS) is the alternative proposal of proof-of-work and according to this the miners are selected for mining blocks according to the cryptocurrency chapter they have. This means that the more bitcoins a miner has on a supposed proof-of-stake Bitcoin, the greater its mining power. The proof-of-stake was created as an alternative to proof-of-work, in order to overcome the inherent problems of the latter (time, power, equipment). The proof-of-stake addresses the issue by attributing the mining power to all the holders of each cryptocurrency, in proportion to their capital. In this way, instead of spending energy to find solutions to proof-of-work puzzles, a miner is limited to mining the percentage of trades set on the basis of his capital. If, for example, a miner owns 2% of the total Bitcoins, he can theoretically mine 2% of the blocks. The way in which the defense against malicious miners is secured is the penalty of capital loss for any user who publishes a block with falsified data. An additional advantage of proof-of-stake is the greater security against the 51% attack.

6.4 **Architecture of blockchain network**

A blockchain network or system can follow different system rules and architectures depending on the desired function and usage. Blockchain systems usually consist of network users and validators / miners. User nodes can start or receive transactions and keep a copy of the ledger. In addition to read access rights, validators are responsible for approving book modifications and reaching a network-wide consensus on the valid status of the ledger. Depending on the configuration of the system, there may be some or universal access rights and validation rights. All Internet users can join a public blockchain system. In contrast, access to private blockchains is restricted to authorized participants. Unauthorized (public) blockchains are fully distributed and resistant to censorship as any member of the network can contribute to the validation of transactions. In contrast, in those licensed (privately) only those validation nodes retain write access rights to modify the blockchain.

In the public and unblocked blockchain, users and validators are completely unknown to each other, so the collective effort and trust required to manage the blockchain is caused by the theoretical balances of game theory and rewards (incentives). Incentives usually include resources such as computer work, electricity, or punishment to prevent selfish behavior. Validation nodes are known and believed to behave honestly, therefore no artificial incentives are required for the system to work. As a result, private and authorized accounts can become faster, more flexible and more efficient, however, this comes at the expense of their inability to change and censorship. In addition, some book architectures can be classified as consortium blockchains, ie Hybrids that have both public and private blockchain features.

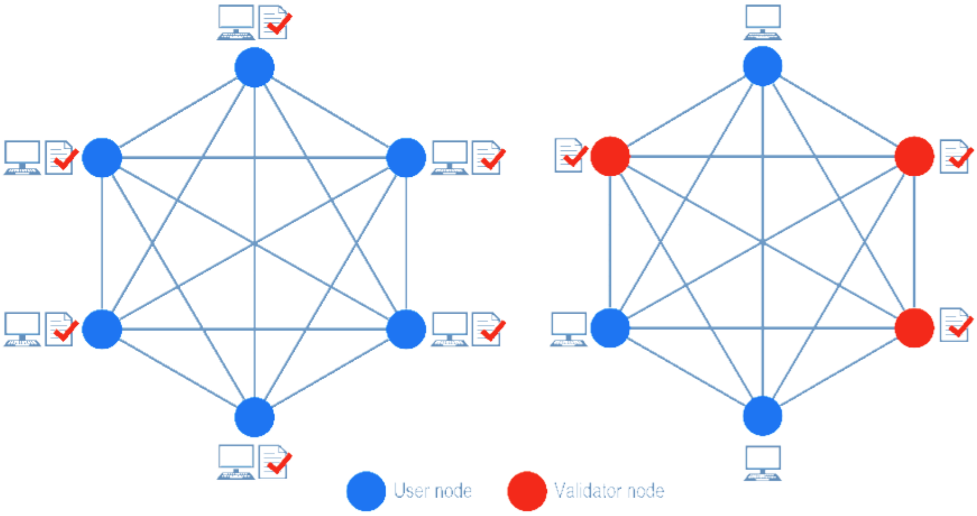


Illustration 5: Differences between a public unlicensed blockchain on the left and a private licensed blockchain on the right.

The blockchain uses distributed ledger technology, a technology that had already been used before the creation of bitcoin. The distributed ledger is a database that exists in different locations or between many participants. A distributed directory is a directory of digital data distributed to many different users where it operates on a consensus basis and is synchronized and shared at the same time. In contrast, most companies currently use a central database stored on a fixed location. All files on a distributed ledger are then registered and bear a unique cryptographic signature. All participants in the distributed ledger can view all of these files. The technology provides a verifiable and verifiable history of all the information stored in this particular data set.

There are more applications than blockchain on distributed ledger technology. Another example is Directed Acyclic Graphs (DAG). Unlike blockchain, a DAG structure stores transactions on nodes, where each node maintains a single transaction [27]. In Nano platform, each account is linked to own account chain in a structure called block-grid equivalent to the account's transaction / balance history. Each account is assigned a chain of accounts. Nodes are attached to an account chain, where each node represents a single transaction in the account chain. Similar to block genesis in blockchain, a DAG holds a genesis transaction. The genesis transaction defines the initial state.

In the literature we have encountered many times, the two technologies of blockchain and distributed ledger as identical. Nevertheless, their separation is important. The blockchain is in a way a subset of distributed ledger technology since there are many applications that use it, but at the same time something very special if it has a character of its own. The difference also lies in whether or not some researchers emphasize trust in existing institutions or not. Proponents of institutional trust support the use of distributed ledger technology but not bitcoin.

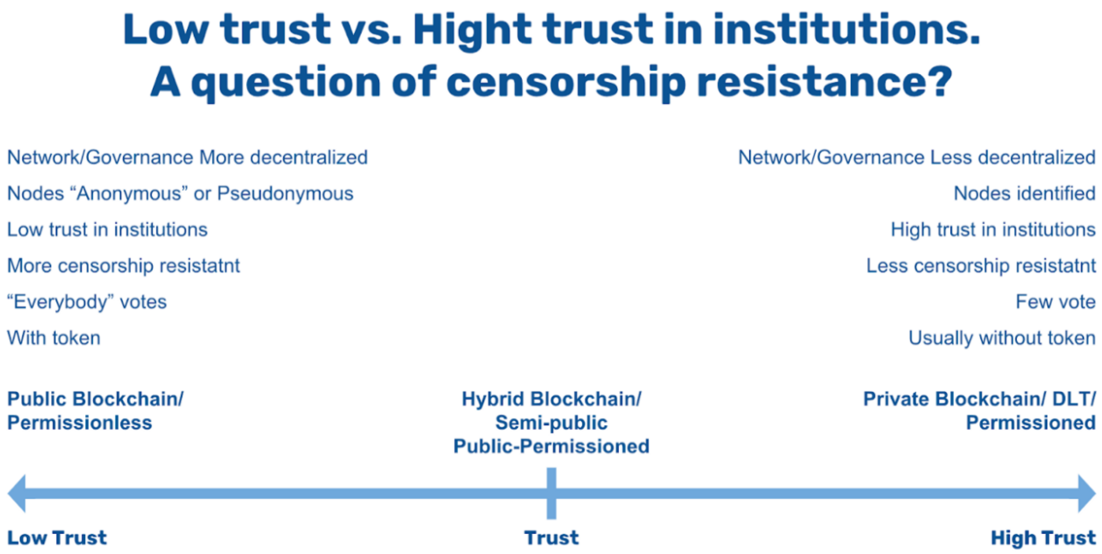


Illustration 6: The spectrum of trust in institutions in relation to the use of blockchain / distributed ledger

As a result of the research that is demonstrated above in the illustration [28] the confidence in the institutions about ledger technologies splits into 3 categories:

- DLT: Confidence in participating nodes in this model is high and can make sense when a large company wants to set up its own blockchain or when a company / government / industry wants to set up a consortium where all participants trust each other. Censorship resistance in this model is low, as it is not a basic requirement.

- Blockchain Hybrids: Trust in a Blockchain hybrid is lower than in a DLT, but that trust is passed on to recognized nodes. The censorship resistance in this model depends on the geographical and participatory distribution of the nodes and the risk of active attacks against the recognized nodes.

- Blockchain: Bitcoin censorship resistance was considered very strong with one vote per computer. However, the progressive concentration of mining with increased fragmentation power in the hands of fewer decision makers or technologies, such as ASICBoost, has cast doubt on the real resistance of public Blockchains to some people.

6.5 Blockchain energy sustainability

Recent research highlights a link between blockchain and sustainability. The study by Harald Vranken [29] shows that the consent algorithm used by bitcoin, proof of work, is so energy-intensive in a large network where the energy viability of a blockchain is questioned.

Bitcoin mining is attractive as it offers a strong financial incentive. For each block mining, the miner receives a block reward as well as the transaction fees of the block transactions. After bitcoin gained popularity, an arms race broke out between the miners. Bitcoin miners initially used general-purpose computers, but quickly switched to more specialized hardware that offered higher performance (in terms of hash rate R, measured in hashes (h) calculated per second) at lower energy costs (in terms of energy efficiency E, measured in the number of hashes calculated per Joule). This specialized material for bitcoin mining has been remarkably developed.

In addition to the capital expenditure on bitcoin mining material, the main cost of bitcoin mining is the operating cost of the hardware, which is mainly the energy cost. There has been a lot of discussion about the total energy consumption of bitcoin mining, not only in internet forums but also in the scientific literature. Estimates vary considerably, ranging from energy consumption equivalent to electricity generated by a small power plant (of the order of 10 MW) to electricity consumption from small to medium-sized countries such as Denmark, Ireland or Bangladesh. (in the range of 3-6 GW).

To put things in perspective, McCook [29] also compares the viability of bitcoin mining with the viability of gold mining and the banking system. The energy consumed annually for gold mining and recycling is estimated at 500 PJ, for printing banknotes and coins at 40 PJ and for the banking system, taking into account ATMs and bank branches at 2340 PJ. Compared to these numbers, the energy used to mine bitcoin in the 3-16 PJ range is relatively small. However, the proportion of bitcoin in the current financial system is relatively small and when bitcoin escalates, more effort will be made to mine bitcoin.

This leads us to the conclusion that blockchain viability is not a given for default and should be considered every time it is used. This is especially true for applications that suggest its application for large networks. Using the right consent algorithm can play a key role in blockchain energy efficiency. It seems that the proof of work algorithm, although it offers absolute network horizontality, is not energy efficient for large networks. That's why ethereum developers use different solutions.

6.6 The social aspect of blockchain

The blockchain was created together with bitcoin to solve some problems that exist in the way money transactions are done so far as stated by the founder of Bitcoin Satoshi Nakamoto . Some of them were the way the intermediaries manage the resulting data and the commission for the provision of their services. The blockchain has some features that solve these problems and at the same time democratize the way the network is managed. O.I. Konashevych in his work [30], making an introspection on how blockchain works, such as bitcoin, i.e. a permissionless blockchain with proof of work, highlights some features listed in the table below. For other blockchain categories, not all of these features apply.

Self-organized	There are no central authorities, shareholders or other persons who have external privileges compared to the other members of the network. However, there are some co-founders who provide the vision, software development, first server and network / project startup. These founders have no privilege and remain ordinary. There are no specific formal rules or requirements for new members to join such a network. All he has to do is install the original software and connect his computer to the existing network.
Autonomous	The members of the network act according to the algorithms (rules) of the program. No one can configure their own algorithms. The system algorithms cannot be changed by anyone or by certain users or members. The ability to provide updates to the system can be initially defined by such algorithms. Algorithms cannot be influenced by the will of any legislation or any other external regulation (such as laws, official laws) as they are executed as machine code.

Rules of cryptography	Some parts of social rules are passed to program algorithms as machine code. Therefore, there is no subjective influence on the system when performing actions. The freedom of certain specific actions is also subject to algorithms. For example, any Bitcoin user can send any available amount from their wallet to any other wallet on the system, but algorithms prevent the user from making double transaction costs or doing the same encryption with another transaction. "Crypto" means that data processing is secure with encryption algorithms.
Open ledger	The transaction data is stored in the sequential chain of blocks and a copy of the entire chain and each new block is stored locally on each user's computer.
Public P2P computer network	The basis of the network on which the blockchain operates is the participation of an unlimited number of people without an accession rule. Some members of the network offer their computing power to the network so that it confirms the validity of the transactions. However, it is not necessary for every user to provide a lot of computing power to participate in such a network.
Distributed cooperation without intermediaries	The network does not have a hierarchy, but a horizontal structure, which connects all the elements of the peer-to-peer network. No member has privileges or additional rights to the network.

	Similarly, there are no intermediaries, managers or coordinators who provide the interaction within the system. People make direct transactions with each other. Miners receive their reward in the form of an internal reward.
Open source	The network software is open and based on open licenses.

Table of social aspect of blockchain

An important point emphasized by Burgwinkel [31] in his conclusions is that the potential of the blockchain in the field of electricity should not be overestimated. Many blockchain companies are marketing a radical vision for the future in which central utilities are being replaced by peer-to-peer power grids. For the foreseeable future, these radical applications are unlikely to substantially change the electricity sector. Instead, initiatives that seek to work together, rather than replace established companies and bring about improvements to the existing electricity system model, are more likely to gain commercial appeal. Policymakers need to pay attention to the application of blockchain in the field of electricity. They should make efforts to understand technology, support the development of blockchain standards in the field of electricity, and allow innovation to flourish by creating regulatory sandboxes that allow demonstration projects. Blockchain does not address the various challenges facing the electricity sector individually, but it should be one of the portfolios of technology options to address these challenges. And its potential as a platform technology can be transformative.

7. Relevant literature on the existing reviews on the energy blockchain

In this investigation it will be examined blockchain applications in energy exchange so an in depth review of the existing blockchain applications is done in order to distinguish the way it is used and which of the applications, according to the researchers, works better in the energy sector. The current literature of blockchain and energy was investigated and a review report was produced that sums up the research that has been done until now. In the research, many papers were discarded as they were only mentioning the possibility of using blockchain but not really referring to an application of blockchain that has been investigated.

The present literature on applications of blockchain technology in the field of energy is structured according to the field of energy where it is examined. The steps of the process followed to create the following categories were as follows:

1. Search the internet for relevant literature on the subject
2. The review of the existing literature and the highlighting of common points between the papers
3. The review of similar literature researches on the subject (surveys, reviews)
4. The collection of all the data and the creation of categories
5. In-depth study of papers and their categorization into categories
6. Adjust the categories and create subcategories according to the literature
7. Creating final categories-subcategories and creating a tree and map of Energy Blockchain

7.1 Categories

The categories into which applications are divided based on the literature are the following:

- **Markets, Trading and Platforms**
  Applications that, based on blockchain technology, create new electricity markets, platforms where prosumers can exchange power

without a central administrator, platforms using the existing network for p2p exchanges and use blockchain-based cryptocurrencies for payment

- **Billing Charges**
  Application of blockchain technology for faster and more efficient billing of customers of an electricity company or payment of micro-producers of RES usually through the technology smart contracts

- **Grid management**
  Blockchain-based applications for managing smart grids, microgrids, networks equipped with smart meters. Three major categories are network loss management, automation and power demand management.

- **Data management**
  Blockchain-based applications for managing data from energy exchanges, usually from smart meters in a smart grid.

- **Security and identity management**
  Blockchain-based applications that emphasize and use cryptography and blockchain features to securely store consumption data, money transactions resulting from energy exchange.

- **Sharing of resources**
  Blockchain-based applications for sharing resources, such as community batteries or charging stations for electric cars.

7.2 Markets, Trading and Platforms

This category of papers focuses mostly on the feature of blockchain technology (a) the decentralized management of a network and (b) the use of blockchain to encrypt encrypted exchanges using cryptocurrencies and smart contracts. Energy exchanges in a decentralized electricity exchange network seem technically impossible without the existence of a mechanism that guarantees the attachment of the necessary energy exchanges, their realization at the right time and safely. The blockchain is suggested by researchers as the means that can fill this gap from a financial and organizational point of view.

Park, et. al. on their platform [32] suggest: based on the need to buy or sell energy, a label is created, which is then sent to all participants in the proposed energy trading platform. The tag is confirmed by a participant who wishes to make a transaction with the original seller / consumer. The tag is then assigned to a block, which is created when the transaction becomes valid. Creating a block activates a contract between the two participants that carries out the direct energy exchange and is stored in a payment list. Finally, the ledger is sent to all participants in the energy trading platform. This process is the process usually followed on the proposed platforms.

In this paper the platform consists of peers-nodes of a smart city, such as a conventional production company, RES production company (PV and wind), electric cars and smart homes. Energy transactions can be made to and from different energy markets. It also proposes the structure of microgrids where P2P energy exchanges will take place and then they will communicate with the main network as a prosumer (consumer and producer). The proposed blockchain structure works together with an algorithm that calculates which blockchain user can currently meet the demand and corresponds to the two nodes. Similar Lei Xue et. al. suggest [33] using blockchain to manage a microgrid in a similar way.

The paper [34]by Chao Liu et. al. proposes a blockchain-based platform so that electric cars stay on grid when not in use, so that unloading them helps stabilize the network while creating a peer market. to peer, electric car owners. This is achieved through an algorithm implemented in the solidarity programming language of the ethereum platform that prioritizes the commands for power demand so that they are covered locally by another user and after the main network always in relation to the user's selling price (peer) and its price network. This proposal covers a problem of the grid today (overload) but also a way to focus control on a part of the grid.

Tianyu Yang et. al. propose [35] building the energy internet on the blockchain with dominant elements prosumers, an energy management system (EMS) in the cloud and multiple forms of energy (electric, thermal, etc.)

Following this, Zhetao Li and Jiawen Kang propose[36] to take advantage of the security of a blockchain consortium on which they build a financial system of energy coins to serve the energy exchange, extending the energy internet to the industrial internet of things. The IoT effect only occurs when two or more objects are connected to each other on a network such as the Internet. In addition to this type of connection, an object could also be indirectly connected to an individual, thus creating a network of objects between objects and people. An example is a network that could connect a person to one or more objects (clock, chair, lamp, etc.) equipped with a specific technological system. The Crypto-trading project proposes an energy blockchain platform consisting of three main sub-platforms, the prosumers platform, a blockchain consisting of smart contracts (Ethereum) for demand management and an online application where prosumers have access to services exchange (transactions) under the guidance of computer systems (robot-advised).

Jiawen Kang and Rong Yu are researching[37] p2p networks based on a blockchain consortium for EV's. They introduce the 'energy coin' as the basis of the new grid micro market and use a double auction algorithm to determine which two nodes will exchange energy. The network operates based on proof of work and possible nodes can be parked in a city.

Se-Chang Oh and Min-Soo Kim write[38] about blockchain as the mechanism that can host a decentralized electricity market that uses 'ecoin' as cryptocurrencies.

The management steps of such a network are modeled through the CLI command platform provided by Multichain and its simulation becomes a Python-based JsonRPC module called Savoir.

Subhasis Thakur and John G. Breslin investigate[39] the optimization of p2p networks using blockchain and introduce the multiple coalition formation algorithm. This blockchain uses a data structure known as UTXO (unspent transaction output), proof of work as a way of validation and smart contracts to carry out transactions. An interesting parameter that the authors introduce as a possible problem is the irreversibility of a blockchain transaction.

Adam Hahn and Sijie Chen document[40] a project implemented at Washington State University, a blockchain consisting of PV's and campus building loads. The blockchain is private and based on ethereum, using smart contracts where they implement the Vickrey algorithm to 'decide' who producer will sell his energy. The simulation platform is VOLTTRON installed on Beaglebone Black devices.

F. Imbault et. al. consider[41] the use of blockchain to produce and store green certificates in the Rueil-Malmaison eco-region in France. The blockchain is hosted by the Predix platform and uses the proof of concept mechanism. This blockchain can be used to generate and store similar certificates and CO2 emissions.

M. Sabounchi and J.Wei simulated[42] the use of ethereum blockchain along with an auction algorithm for power exchange in p2p microgrids using Simulink, the blockchain TestRPC and the interactive Truffle API platform. The principles of the model based on smart contracts are identical to those of the free market (maximization of individual profit and incentives to participate).

Finally, Andrew Seelaus proposes[43] a business model for creating improvised microgrids using blockchain in Africa to bridge the gap between off grid communities and the existing Central Grid.

Jianchao Hou et. al. suggest [44]the use of blockchain in an existing distributed RES production system from PV. They anticipate that this will affect the following sectors: industry standards, the financial sector, the electricity management / metering sector, the energy exchange sector and the RES operating sector, and that it will give positive characteristics to all of them.

Christian Lazariou and Maria Cristina Roscia suggest[45] combining the Internet of Things with the blockchain for smart city design. The blockchain will act as the smart grid topology, where larger blockchains will contain smaller local blockchains and so on. Characteristically, it is emphasized that in this way small producers can participate in the big markets of a smart city.

7.3 Billing

Matevž Pustišek et. Al. investigate[46] the relationship of blockchain with the internet of things and e-vehicles. More specifically, it proposes the attachment of smart contracts (ethereum blockchain) between driver and charging station, to find the best, based on price and distance, e-vehicles charging center. Money transactions are then automatically executed encrypted.

Aysajan Abidin et. al. compare[47] blockchain to multiparty-computation, arguing that blockchain is a safer method of exchanging RES by prosumers and charging consumers. This billing tool uses a private data aggregation technique to calculate users' monthly bills locally and allows vendors to calculate only the monthly bill per customer, but not the individual metrics per time period.

7.4 Data management

Li Jun Wu and Kun Meng are researching[48] how grid agencies with high authority can use the blockchain to store data from energy exchanges. More specifically, they propose a block static storage, a data structure consisting of a public blockchain to confirm the validity and storage of data and a private blockchain to confirm the accuracy of the data and its retransmission. The public blockchain consists of all consumers and providers and represents a digitized PC and the private are the administrators of this PC.

Kenji Tanaka et. al. are introducing[49] the digital router as an integral part of exchanging information on a p2p, blockchain-based network. The digital router consists of back-to-back two-way digital AC-DC-AC converters and divides a grid into mini grids at their own frequency. The information from the router is then sent to the blockchain where it attaches smart contracts to users who have excess energy.

Yu Nandar Aung and Thitinan Tantidham investigate[50] the use of ethereum smart contracts to control device access, storage and data flow management in a smart home (SHS) system. to manage data flow through cloud storage. The proposed system consists of smart home miner (SH miner), private blockchain and local storage connected to SH sensors and actuators. SH miner handles a private Blockchain. The function of the private blockchain is to store policies for data flow or transaction management.

Researchers from the Thapar Institute of Engineering and Technology et. al. are introducing[51] Energychain: a blockchain-based SHS energy exchange system within a smart grid. The proposed model operates in three phases: 1) a miner node selected based on the power capacity of the various SHs, 2) the secure storage of SH’s data 3) the calculation and comparison with other models of the necessary computing power of the blockchain. The proposed blockchain uses PoW.

Ali Dorri et. al. from Australian universities propose[52] a local private blockchain to every smart home that maintains its trading sequence and enforces inbound and outbound trading policies. As in the previous proposed model, there is a miner computer and each smart home device participates in the blockchain with a unique ID. The blockchain manages the exchange of information and exchanges bitcoin as a means of recording energy exchange between devices.

7.5 **Security and ID management**

Kamanashis Biswas and Vallipuram Muthukkumarasamy propose[53] a security framework that integrates blockchain technology with smart devices to provide a secure communication platform in a smart city. More specifically, it proposes the combination of smart phones, p2p technologies such as bitTorrent, private blockchain and smart applications such as Android applications.

Khaled Shuaib et. al. explain[3] in detail the mechanism of smart contracts and how they can be used in two cases: a) For prosumers b) For charging EV’s. Next, they look at a real-world scenario and study the security of transactions that a proof of work blockchain guarantees.

Michael Mylrea and Sri Nikhil Gupta Gourisetti suggest[54] a way to test blockchain-based networks for their cyber attack vulnerability. They use PNNL's testbed B2G and built-in Transactive Campus to provide a unique combination of live telemetry and real-time data to simulate the grid and improve blockchain security technology.

Gaoqi Liang et. al. compare[55] the security of a public or private blockchain-based power exchange network through simulation experiments on the IEEE-118 reporting system. More specifically, they consider two scenarios of malicious attacks and through SCADA that prove the protection of private blockchain against them.

Nicola Fabiano researches[56] the legal issues arising from the implementation of the blockchain and proposes the formulation of a legal framework that will include it. Stresses that the dissemination of personal data to distributed ledgers is not 100% compatible with the newly introduced GDPR legislation for their protection, in the areas of adequate information to users and in the identification of users due to their anonymity. In order for blockchain to be more accessible in practical and professional applications, it is necessary to design a system that protects privacy from its design (by-design-privacy) and a Privacy Management System that will be globally compatible.

Andreas Unterweger et. al. are trying to implement a protocol[57] for deciding the price of tariffs on smart grids via smart contract in Ethereum. They emphasize, like N. Fabiano, the absence of privacy-by-design in ethereum and that the cost to the miners for the development and execution of the implemented smart contract is at least twice as high as what would be acceptable for its use largely.

7.6 Sharing of resources

Ioannis Kounelis et. al. proposed, designed and implemented[58] an ethereum blockchain tailored for micro-producers to promote small-scale RES production. The model envisions the existence of a local microgrid where prosumers are able to store excess energy in a private battery or in a community battery or give energy back to the grid and be rewarded with a Helios Coin cryptocurrency. Also each time a user sends power to the grid, the smart contract will issue a Helios Coin corresponding to the energy generated and will automatically transfer them to the power generator.

7.7 Grid management

7.7.1Demand side management

Xigao Wu et. Al. use[59] blockchain technology to record data from the power flow calculation model and adjust the price of electricity and use a smart contract to store transaction data. By calculating the power flow, a microgrid generator operation plan is created and the power management system automatically generates smart contracts. In the end the two interested parties complete the transaction and thus the load on the microgrid is adjusted. The authors choose to use MultiChain to build a private blockchain to implement the above.

Charilaos Akasiadis and Georgios Chalkiadakis introduce[60] the concept of co-operative prosumers where blockchain functions as a tool for decision making and profit sharing. In order to achieve the effective rearrangement of consumption and to reward the members of the cooperative according to their behavior, they propose the introduction of the COOPcoin cryptocurrency. Instead of PoW they use "proof of-physical-action": the reward in a cryptocurrency for the mining is after its use in the natural world (such as the shift of electricity production from a prosumer).

David Vangulick et. al. document[61] the E-cloud project's attempt to bridge energy communities in France with blockchain. The tokens exchanged are kWh. Demand is managed by a Merkle tree algorithm. This exchange creates a local market. It also solves internal security issues as long as there is a daily physical presence that helps build trust between users while its structure due to the Proof of Stake mechanism shields the community from outside attacks.

7.7.2 Loss management & Automation

E. Riva Sanseverino et. al. investigate[62] the application of blockchain on the off-grid systems to compensate for the energy losses caused by energy transactions, in order to achieve a more realistic correspondence between the physical condition of the energy grid and the consequent costs incurred by users. The blockchain functions as a means of storing energy losses and their equal performance to the users of a microgrid,

The same researchers, in a more extensive report[63], suggest that the distribution of losses should be done in real time and for each transaction that includes a generator and a loading node, appropriate indicators should be defined. The simulations show that the losses are more properly distributed using the blockchain.

Eric Munsing et. al. focus[64] more on solving power flow problems in microgrids through blockchain-based Alternating Direction Method of Multipliers (ADMM) algorithms. The proposed algorithm can be used to predict load for the next day, the optimal load flow plan is stored in the blockchain and payments can be made via smart contracts.

7.8 Graphs

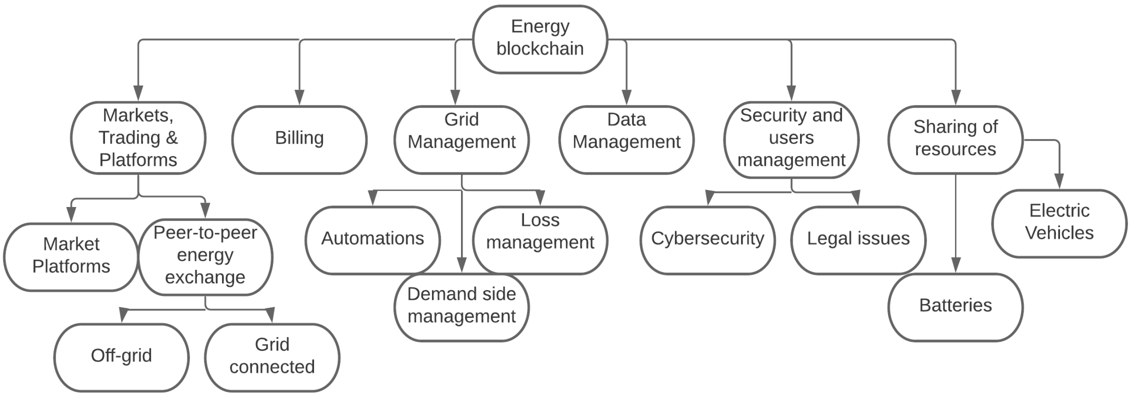


Illustration 7: Categories of Energy Blockchain in a flowchart

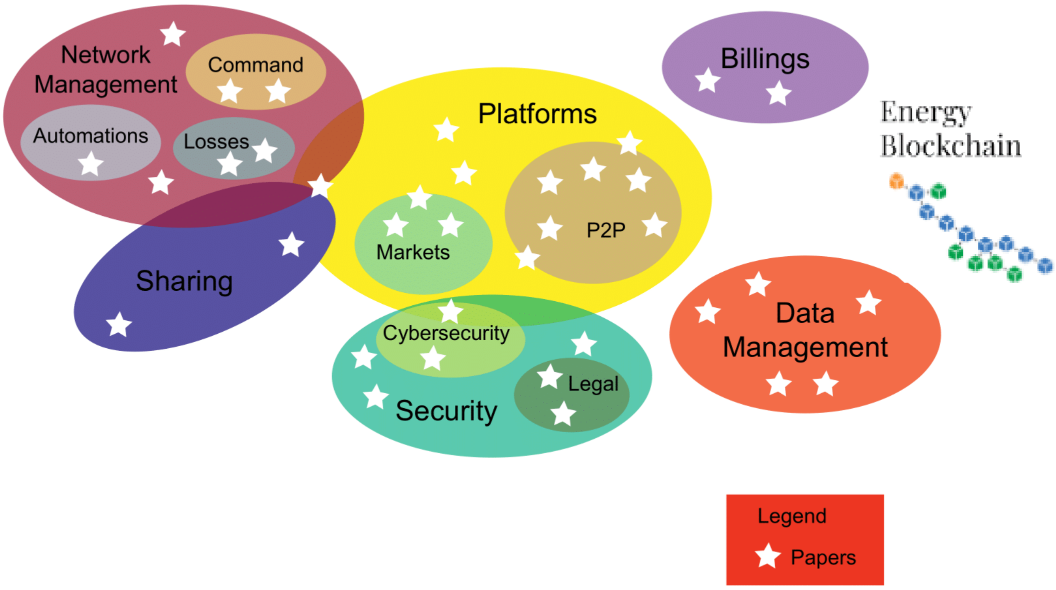


Illustration 8: Maping of the categories of energy blockchain

Second Part. Case study: Los Molinos del Río Aguas Microgrid

A.Los Molinos del Río Aguas (LMRA)

A.1 Reasons for choosing LMRA

In this study, it is selected to study the creation of a microgrid and an embedded blockchain-based market in a village called Los Molinos del Río Aguas (LMRA), belonging in the province of Almeria in the south of Spain.

Illustration 9: Satellite Photo of Los Molinos del Río Aguas (LMRA)

Illustration 10: Satellite photo of South of Spain, with red the position of LMRA

The reasons why this position was chosen are explained below:

1. **The special energy infrastructure of the village,** which consists of 14 autonomous solar house systems, not interconnected and off-grid.
2. **Personal working experience on site,** which consisted of working on one of the SHS and living on site, experiencing the problems of an off-grid and not interconnected electrical system.
3. **The possibility of implementation of my study case,** from the side of the community of users in LMRA because of the existence of a technological investigation center in the location, Sunseed Desert Technology.

A.2 Information and important social factors

Los Molinos del Río Aguas is part of the Krast de Yesos Natural Park, protected by NATURA 2000 network, situated in a deserted area with few vegetation and few water resources. The village was built on the riverbed of the river Rio Aguas as a fountain of energy for the mills of grains of wheat, reason which explains the origin of the name of the village [65] . Los Molinos del Rio Aguas is a village that was abandoned by its original habitants around 1960s and was repopulated in the year 1980 by people having a vision to repopulate the village with a low impact on the environment lifestyle.

The ecological principles and the principles of self-governance led to certain choices from the new habitats of the village. As the population grew in a chaotic and not structured way, the need of systematic process of electrification of the houses was not followed and together with the existent legal obstacles, the village was not connected with the grid which reaches its nearest town, Sorbas. This way, a previously not electrified village was populated by new habitants which chose to electrify their houses in an ecological way by putting solar panels and creating autonomous systems.

Reasons that led in this choice is that:

1. LMRD is situated in one of the sunniest areas of Europe with an average direct beam nominal radiance of 800 W/m^2 [66]. Apart from the sun, the wind average in the area is not sufficient for an effective small scale wind turbine and the solution of small scale water turbines lacked in security and production-cost criteria.
2. In the village is operating since 1980, Sunseed Desert Technology Center which promotes the deployment of renewable energy and specifically solar power [67]
3. Motives for self-consumption and self-production of electrical energy as part of the self-governance strategy introduced by the new habitants of the village
4. Cost-efficiency criteria. The cost of the interconnection to the grid was bigger than the set up of a small solar home system.
5. Legal obstacles. The legal status of the reconstructed buildings in LMRD has had many complications and it is lacking proper urban planning.

A.3 Sunseed Desert Technology Center

Sunseed Desert Technology is a technology training center for sustainability. It is an international community of volunteers and coordinators working and learning together to develop, research and communicate alternatives to reduce the ecological footprint of human activities. Its goal is self-sufficiency and living with a low environmental impact. It is an internationally established multicultural community that collaborates with other programs and local, national and international organizations, such as schools, universities and environmental associations. Develops informal ways of education such as workshops, seminars, tours and formal ways such as university internships. It also welcomes volunteers from all over the world throughout the year to learn in its various sections, which are: appropriate technologies, ecological construction, sustainable living, organic gardening, dry soil management, communication and education. As a technology education project, Sunseed activities are designed to facilitate the teaching and learning of skills and tools for sustainable living and environmental protection while developing innovative solutions to technological problems. [67]

Sunseed since its foundation was investigating appropriate technologies for the environment of deserted areas, like the one of Almeria, so the appropriate technology department was created in order to continue this mission. The use of solar power for producing electricity and for producing heat to cook was the areas that have been kept alive as practice and technique since its start. The Department of Appropriate Technology (AT) which I was coordinating during 2018-2019, was responsible for the electrification of the facilities of the center, the maintenance of its SHS and its improvement. Part of the responsibilities of the AT department was also the maintenance and the management of the water supply system of the village LMRD, a service provided to the community in exchange for a yearly contribution. This was one of the communal agreements and functions between the residents of LMRD.

Here it is useful to give some more information about appropriate technology as it is connected to the topic of our research. Appropriate Technology is an approach to technology and how it should be developed. It has been historically approached by many scientists such as Lewis Mumford and Ivan Illich and nonscientists, such as E. F. Schumacher, Ernst Friedrich "Fritz" economist Mahatma Gandhi. It is based on the following key pillars:

- Small scale
- Decentralized
- Designed by users and the local community
- Designed according to the prevailing environmental conditions of the place to be implemented
- Sustainable for the environment and energy efficient

This event introduced the communal management of one basic good of the community, leaving open the possibility for further possible management of more goods. This projects’ study case is based on the willingness of the residents to accept further proposals on communal management of goods, this time the communal management of an electricity grid. The existence of Sunseed Desert Technology and the AT department is a foundation on which an electricity grid could prosper, because the possibility of contracting a technician for maintenance of the grid seems possible. This means that the community could potentially have an internal operator for the management of communal aspects and the billing perspective. We will develop further in our study case proposal.

A.4 Common goods/ communitarian management

LMRD has a history of managing in a communitarian way one of the basic goods of the village which is the water coming from the river. The water from the river is used for two reasons: 1) For irrigation 2) For domestic use. The first one is based on the ancient way of “acequia”, which is a cannal that traspasses everybody’s properties and has outputs for irrigation for each field. The second one is pumped through a pump into a tube that manually the users can open and close their outlets for filling up their personal water tanks. Both of them are managed in a rotative way based on an agreed schedule, an agreement that was done in a villagers’ meeting. Sunseed Desert Technology was defined as the responsible to maintain the both of these canals and make sure the schedule is followed, a service which is communally paid by each resident.

This is a sign of communitarian management of a common good which is an important social factor that affects our design of the proposed microgrid. This shows to the investigator that electricity could potentially work as a common good and be of communitarian management with a unity of the village as a grid manager. This type of communitarian property is an important factor in our design and possible implementation as it opens up the responsibility of an autonomous self-managed microgrid without the need of an external factor. However we realise the technical obstacles that exist in this task and we implement it into the design with a lot of autonomaticated control of both the grid and the market. Parallely, the communitarian management of the grid does not mean the homogenization of the property of the assets of each individual in the community but the unification of the variety of different assets into a grid commonly managed.

Signs of commonly shared electricity are also evident already in LMRD as there are two houses (House 11 & House 15) that already are connected on the AC side with House 16 . This is part of a private agreement between the owners of House 11 and House 15 that did not own means of electricity production and instead of being converted in another two SHSs they chose to buy electricity from the excess of the House 16. This relation between different individuals inside the investigated grid also is an important factor to design the appropriate market for the design microgrid.

B. Existing electrical facilities of LMRD

B.1 Houses and electrical assets

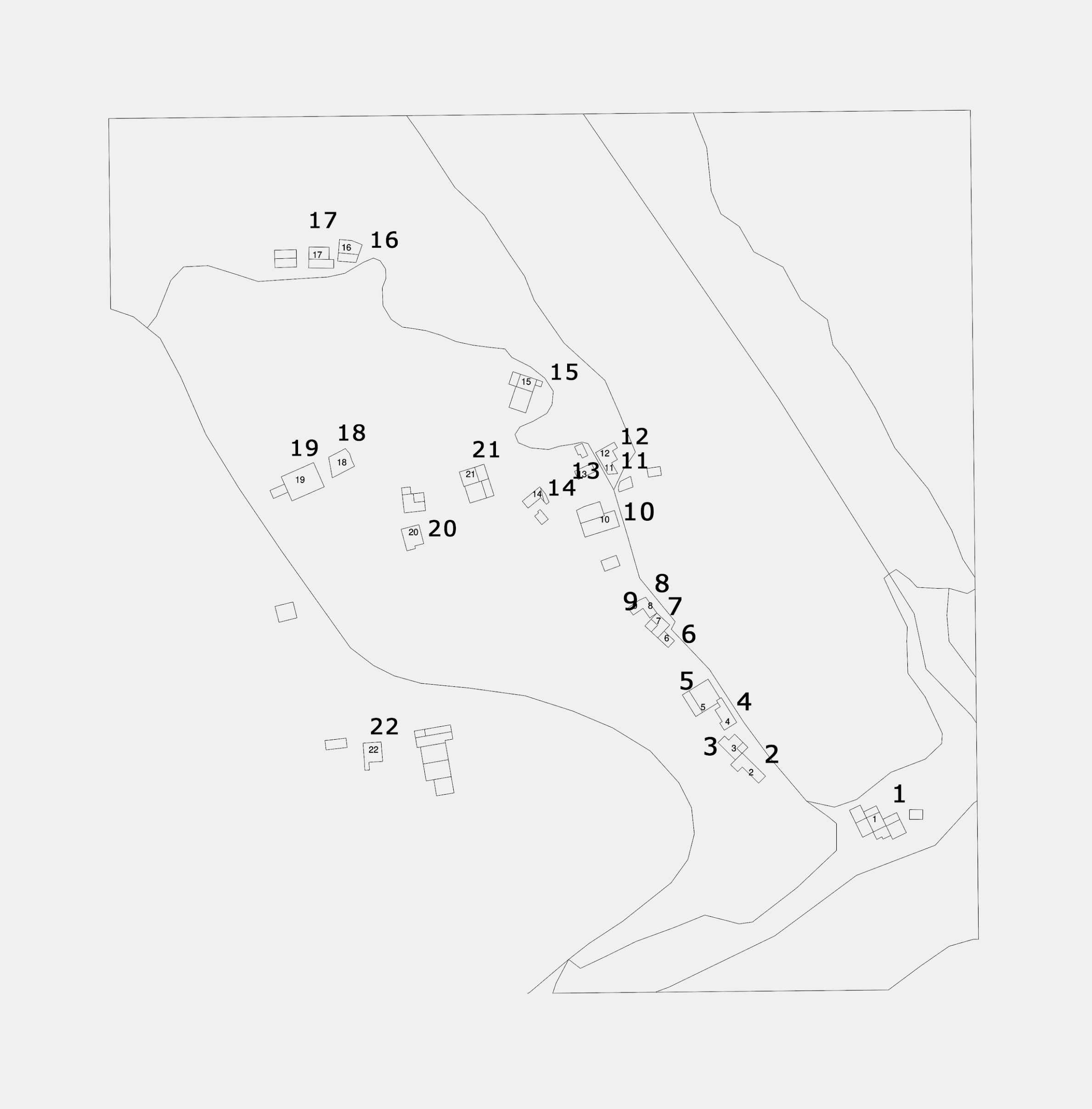


Illustration 11: Urbanistic plan of LMRD with numbered houses

The data below are results of personal research: LMRD consists of 21 inhabited and uninhabited houses. There are 18 houses that are inhabited at least one month per year and 3 that are currently uninhabited (House 3&4 are considered united because of their unified electrical system) . 10 of the houses are habited during the whole year while the rest 8 are partly inhabited, mainly the summer months. All the 18 houses are considered to have a consumer load profile which reflects their average electrical consumption and the factor “months of use” that reflects the time that the load is active. A table of the electrical assets of each house is demonstrated:

House	**Batteries Capacity (kWh)**	**Usable* battery capacity (kWh)**	**PV (kWatts)**	**Average prod. day (kWh)**	**Average prod. year(kWh)**	**Diesel generator (kW)**	**Consumer profile**	**Avg. cons./ year (kWh)**	**Months of year use(%)**	**Actual Avg. cons./year** (kWh)**
House 1	5.40	2.70	0.50	2.32	847.82	0.50	Medium	1,910.88	1.00	1,910.88
House 2	5.40	2.70	0.40	1.86	678.26	0.00	Medium	1,910.88	0.40	764.35
House 3&4	18.00	9.00	1.40	6.50	2,373.90	0.50	Low	990.51	1.00	990.51
House 5	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00
House 6	36.00	18.00	2.88	13.38	4,883.44	1.00	High	3,079.72	1.00	3,079.72
House 7	5.40	2.70	0.30	1.39	508.69	0.00	Low	990.51	1.00	990.51
House 8	24.00	12.00	1.00	4.65	1,695.64	0.00	High	3,079.72	1.00	3,079.72
House 9	24.00	12.00	1.00	4.65	1,695.64	0.50	High	3,079.72	1.00	3,079.72
House 10	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00
House 11	0.00	0.00	0.00	0.00	0.00	0.00	Medium	1,910.88	1.00	1,910.88
House 12	0.00	0.00	0.00	0.00	0.00	0.00	Medium	1,910.88	0.40	764.35
House 13	6.00	3.00	0.50	2.32	847.82	0.00	Medium	1,910.88	0.40	764.35
House 14	18.00	9.00	0.00	0.00	0.00	0.50	High	3,079.72	1.00	3,079.72
House 15	0.00	0.00	0.00	0.00	0.00	0.00	Low	990.51	1.00	990.51
House 16	52.80	26.40	3.00	13.94	5,086.92	2.00	High	3,079.72	1.00	3,079.72
House 17	10.08	5.04	0.45	2.08	759.65	0.00	Low	990.51	1.00	990.51
House 18	18.00	9.00	1.50	6.97	2,543.46	0.50	Medium	1,910.88	0.75	1,433.16
House	18.00	9.00	1.50	6.97	2,543.46	0.00	Medium	1,910.88	1.00	1,910.88

19										
House 20	0.00	0.00	0.00	0.00	0.00	0.00	Medium	1,910.88	0.40	764.35
House 21	0.00	0.00	0.00	0.00	0.00	0.00	-		0.00	0.00
House 22	18.00	9.00	0.50	2.32	847.82	0.50	Medium	1,910.88	0.40	764.35
SUM	259.08	**129.54**	**14.93**	69.35	**25,312.51**	**6.00**				**30,348.23**

Table of existing electrical assets of LMRD

//The houses that are uninhabited are marked with 0 consumption.//

*Usable battery capacity= 0,5*Batteries Capacity

**Actual Avg. cons./year= Avg. cons./ year * Months of year use

A summary of statistics of LMRD existing electrical assets is demonstrated:

Autonomous systems: **14**

Number of AC loads: **18**

Number of high consumer profile: 5 (**28%**)

Number of medium consumer profile: 3 (**17%**) whole year, 6 (**33%**) some months

Number of low consumer profile: 4 (**22%**)

Number of potential new connections: **3**

And some interesting information about the table above:

Consumption not covered by PV production	5,035.71 kWh/year
Hours of diesel generators production needed (if all generators are used)	839.29 h/year
Hours of diesel generators production needed (if one generator of 1kW is used)	5,035.71 h/year

B.2 PV production and data

Each house is considered a Solar Home System, with an energy storage of batteries, an inverter DC/AC, PV panels of various power capacity, battery chargers, a backup diesel generator (in some cases), a consumer profile and their average consumption per year. The data given for the PV panels are data given by the owners at their nominal power. The average production for every year of the PV panels are measured according the meteorological data given in the platform Photovoltaic Geographical Information System [66] for the year 2016, where its houses' production is multiplied by the average production of 1 kW PV. The power of the diesel generator is nominal and the capacity of the batteries are calculated approximately in order to create homogenous battery profiles. The usable battery capacity is the 50% of the nominal capacity of the batteries, following a healthy strategy for the use of the batteries, a strategy widely followed in LMRD. Some users use a limit of higher percentage (80%) and other users use lower, so an average of both was used as a general rule for all cases. The factor month of year use represents: when it is 1 equals the 12 months, when it is 0.25 equals 3 months per year, etc.

The meteorological and production data are also demonstrated below :
Localization [Lat / Lon]: 37.090, -2.077
Horizon: Calculated Database: PVGIS-SARAH
PV Technology: Crystalline Silicon Installed PV [kWp]: 1
System losses [%]: 14
Simulation results: Tilt angle [°]: 40
Azimuth angle [°]: 0
Annual PV production [kWh]: 1695.64
Annual irradiation [kWh / m2]: 2154.91
Year-on-year change [kWh]: 44.97
Changes in production due to: Incidence angle [%]: -2.44
Spectral Effects [%]: 0.44
Temperature and low irradiance [%]: -6.63
Total losses [%]: -21.31

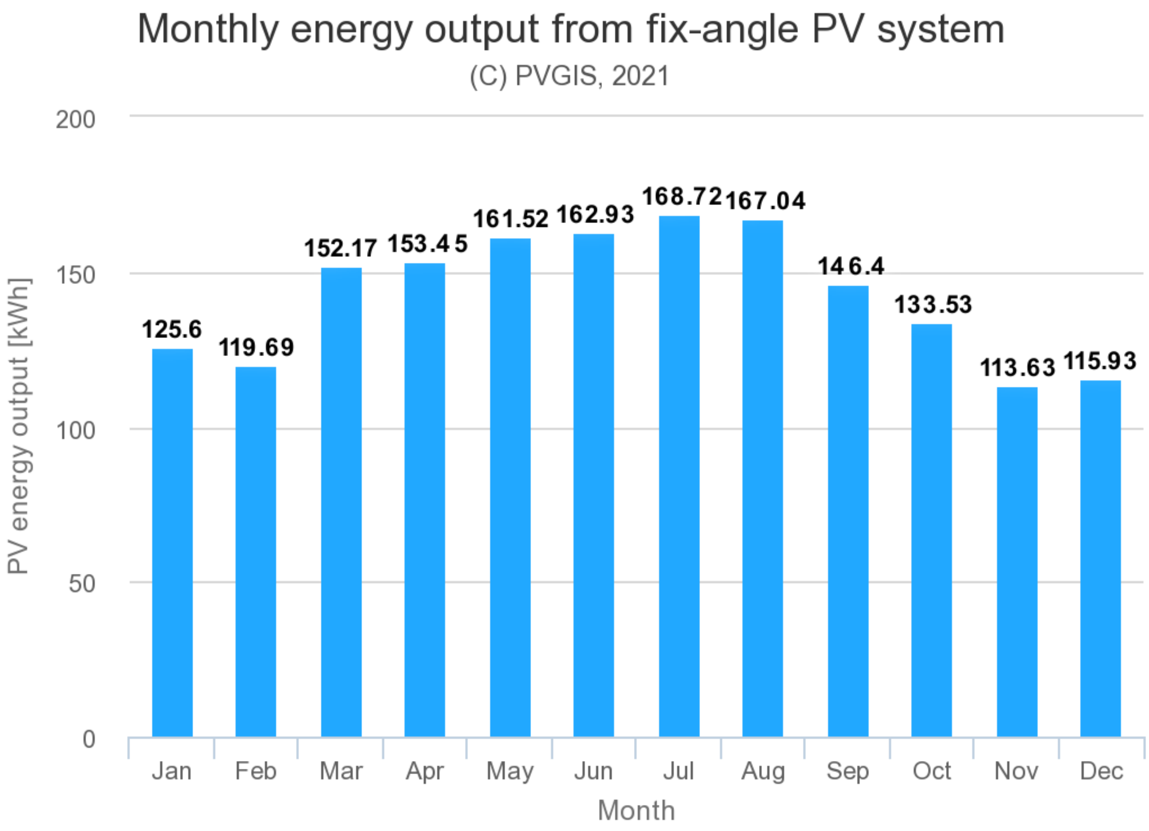


Illustration 12: Production of one PV panel of 1 kW in LMRD during one year

The production of the PVs was considered the one given from the platform as most of the installations of LMRD are well installed, looking at the south and in an angle appropriate for the trajectory of the sun of the area. Any effects on the aging of the different PV panels will be taken into account in the study case. According to the table, the nominal sum of the PV installed in LMRD is 14.93 kW and the average total production in one year is 25,312 kWh which is less than the 30,348.23 kWh needed for the average yearly load. The **5,035.71 kWh** of difference is assumed to derive from diesel generators production which in total in LMRD exists diesel generators of 6 kW, which is a percentage of **16 %** of the total electricity production. This is a percentage which raises in the winter months and drops in the summer months. Diesel generators are used to charge the batteries and provide AC consumption when it is needed.

B.3 Consumption profiles

The consumption profiles were calculated through the adaptation of the tool “Rural African Load Profile tool” developed by NREL. The load profiles are divided in 3 categories: High Consumption Profile, Medium Consumption Profile and Low Consumption Profile. In these 3 categories different numbers of devices were attached and according to an approximate daily time of usage a daily and yearly load profile was created.

	All Households	**High Income Household**	**Medium Income Household**	**Low Income Household**
	Appliance Wattage (W)	**Appliance Count**	**Appliance Count**	**Appliance Count**
LOW WATTAGE APPLIANCES				
Lights	9	20	20	15
Mobile Phone/Charger	8	5	4	4
Radio	15	1	1	0
HIGH WATTAGE APPLIANCES				
Laptop Charger	60	5	4	4
Washing machine	1400	1	1	0
Power Tools	1200	4	3	3
Refrigerator **1**	50	1	1	0

Table of devices used for calculation of load profile

Here it is noted that many devices of a “normal” household are missing. This is because in the SHSs that are investigated a minimum of electrical consumption is needed in order to keep the size and the cost of the system low. For example, water heaters are solar and kitchens use gas bottles to cook. Also a percentage of ownership depending on the different consumption profile is added in order to better approximate the real number of devices existent among all the houses.

	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00
LOW WATTAGE APPLIANCES													
Lights	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	48.6	32.4	16.2	64.8	32.4
Mobile Phone/Charger	0.0	0.0	0.0	0.0	0.0	0.0	3.2	3.2	3.2	3.2	3.2	8.0	8.0
Radio	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	2.6	2.6	2.6	5.3
HIGH WATTAGE APPLIANCES													
Television	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	150.0	150.0	150.0	150.0
DVD Player	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Iron	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	240.0	240.0	240.0	240.0	480.0
Refrigerator	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Total High Income	**50.0**	**50.0**	**50.0**	**50.0**	**50.0**	**50.0**	**53.2**	**53.2**	**344.4**	**478.2**	**462.0**	**515.4**	**725.7**

13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	13:00	14:00	15:00	16:00
16.2	0.0	0.0	40.5	81.0	40.5	121.5	121.5	81.0	81.0	16.2	0.0	0.0	40.5
8.0	8.0	0.0	0.0	16.0	16.0	16.0	16.0	16.0	0.0	8.0	8.0	0.0	0.0
5.3	5.3	2.6	2.6	0.0	0.0	0.0	0.0	0.0	0.0	5.3	5.3	2.6	2.6
150.0	0.0	0.0	150.0	30.0	45.0	90.0	180.0	180.0	75.0	150.0	0.0	0.0	150.0
0.0	0.0	0.0	0.0	0.0	140.0	280.0	280.0	420.0	280.0	0.0	0.0	0.0	0.0
16.2	0.0	0.0	40.5	81.0	40.5	121.5	121.5	81.0	81.0	16.2	0.0	0.0	40.5

Tables of calculation of hourly load profile of a high consumption house

	High Income Household	Medium Income Household	Low Income Household	All Households Assuming Varying % High, Medium, and Low Income
0:00	50.0	30.0	0.0	28.3
1:00	50.0	30.0	0.0	28.3
2:00	50.0	30.0	0.0	28.3
3:00	50.0	30.0	0.0	28.3
4:00	50.0	30.0	0.0	28.3
5:00	50.0	30.0	0.0	28.3
6:00	53.2	32.2	2.6	31.0
7:00	53.2	32.2	2.6	31.0
8:00	344.4	221.3	122.9	235.0
9:00	478.2	260.9	196.8	315.5
10:00	462.0	246.5	186.7	301.7
11:00	515.4	293.1	220.9	347.1
12:00	725.7	410.2	290.7	482.0
13:00	709.5	395.8	280.5	468.2
14:00	543.3	327.4	186.4	360.1
15:00	52.6	31.9	0.0	29.9
16:00	243.1	121.9	109.3	158.8
17:00	177.0	124.0	80.2	129.5
18:00	291.5	205.4	63.3	194.6
19:00	1037.5	693.6	319.1	704.1
20:00	1127.5	726.0	369.5	760.7
21:00	747.0	514.0	164.2	494.4
22:00	486.0	353.0	92.6	325.0
23:00	90.5	66.0	25.3	62.9
Total Wh/day/household:	**8437.6**	**5235.3**	**2713.7**	**5601.3**
Total kWh/year/household:	**3,080**	**1911**	**991**	**2044**

Table of current households' hourly load profile

Note: The last column is measured with a coincidence factor of 80%.

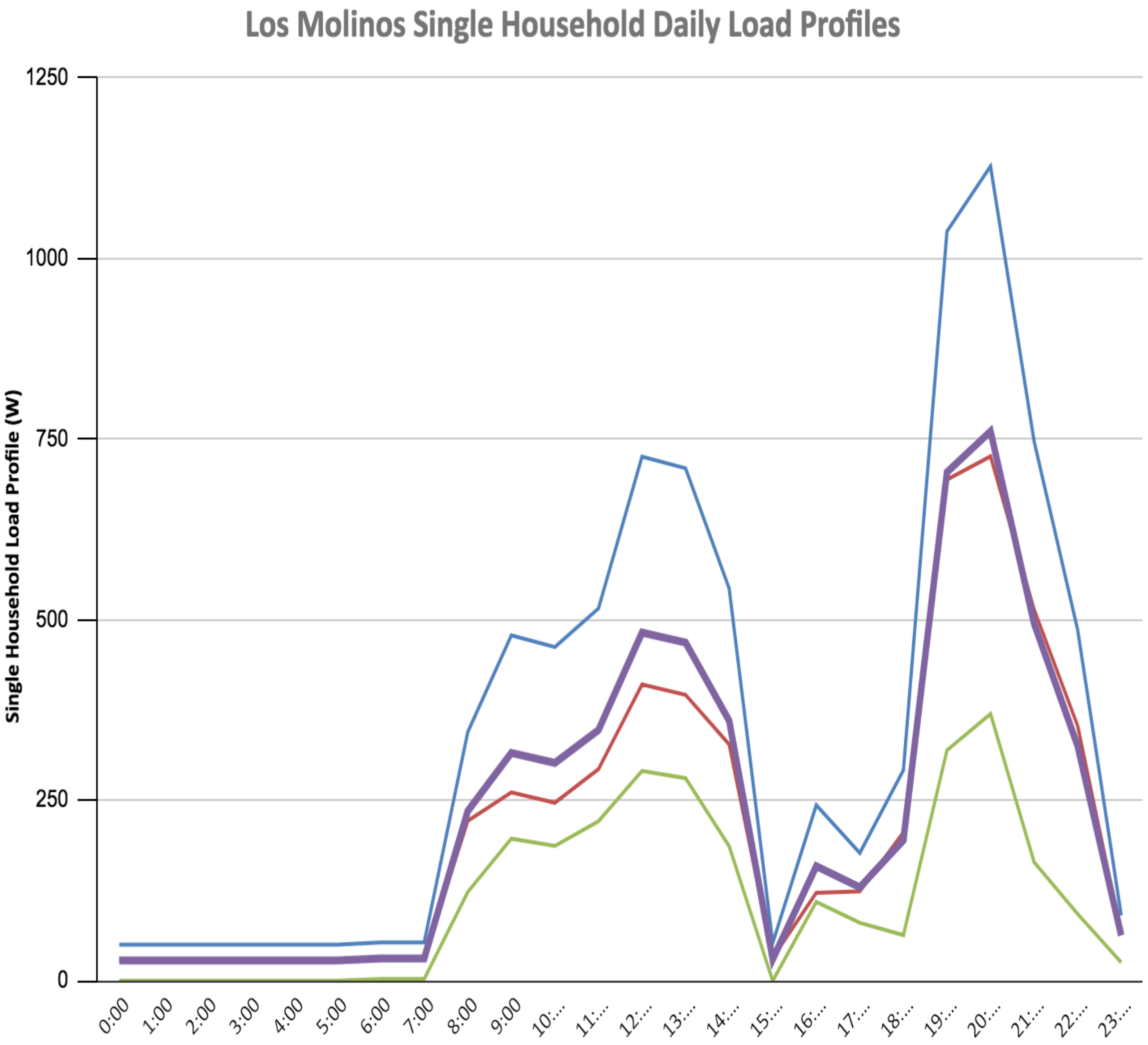


Illustration 13: Load profiles of low (green), medium(red) and high (blue) consumption profile and combined consumption profile(purple) with 0,8 coincidence factor

After having the load profile of single households in LMRD, the following results show the load profile the total load as if the loads were interconnected with a coincidence factor of 80%.

	Total Household Load (kWh)
0:00	1.25
1:00	0.81
2:00	0.60
3:00	0.51
4:00	0.55
5:00	0.66
6:00	0.87
7:00	1.45
8:00	3.33
9:00	4.51
10:00	4.91
11:00	5.56
12:00	6.62
13:00	6.43
14:00	5.02
15:00	2.65
16:00	3.03
17:00	3.29
18:00	4.76
19:00	8.68
20:00	9.52
21:00	7.33
22:00	4.95
23:00	2.34
Total kWh/day	90
Total kWh/year	32,712
Max kW/day	9.52
Min kW/day	0.51

Table of total LMRD current Load profile

In the Table of total LMRD current Load profile it is observed that there are two peaks of the load: a) at 12:00 of 6.5 kW b) at 20:00 of 9.5 kW. In total in one day there is an average of 90 kWh of load and in the year 32.712 kWh. This number differs from the one given in the table of existing assets of LMRD (30,348.23kWh) because in the table the coincidence factor is not taken into account. In the investigation,the number provided by the “Table of total LMRD current Load profile” is used as a more reliable choice, so the current average load for one year in LMRD is considered 32.712 kWh.

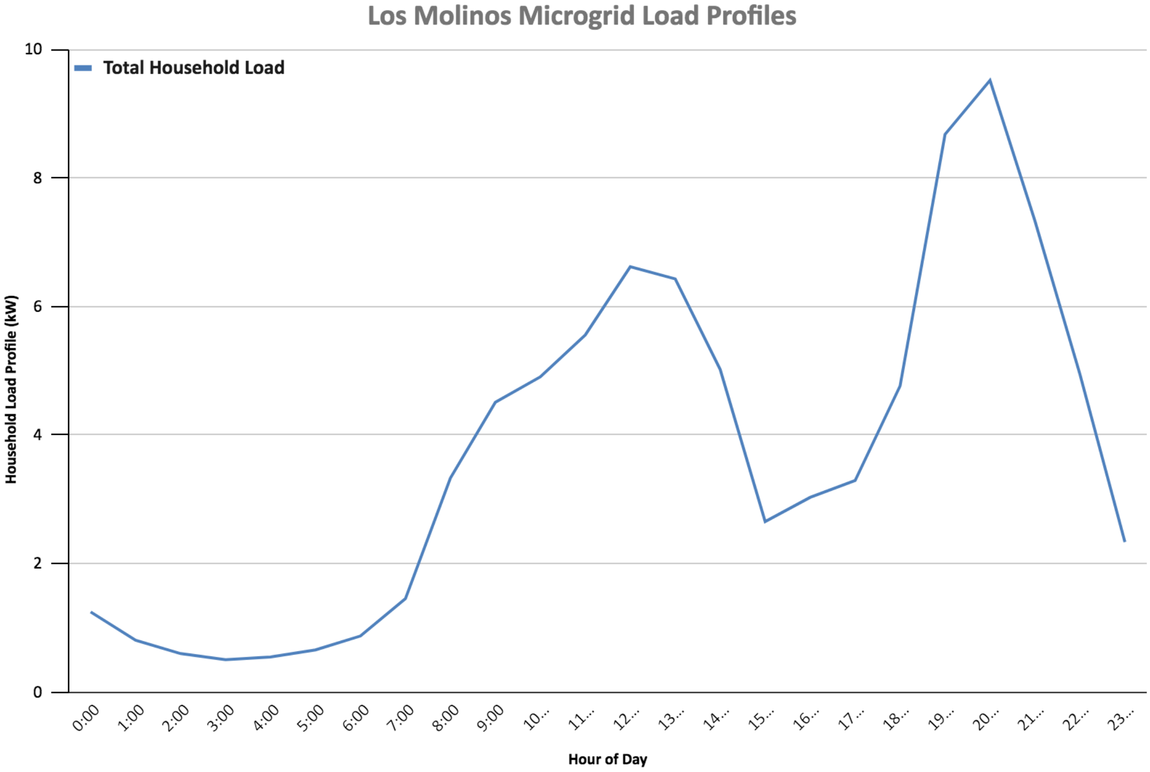


Illustration 14: Total LMRD existing Load profile

SImulations in Homer

For using a base case for our case, we used Homer PRO microgrid software in order to simulate the existing function of the investigated SHSs. Different microgrid simulation programs were taken into account such as DERCARM, Homer, Hybrid2 and !Hoga and the choice was HOMER Pro because it is simple and appropriate for our study case (of an off grid microgrid). It combines simulation,optimization and sensitivity analysis. Homer is described as: "*The HOMER Pro® microgrid software by HOMER Energy is the global standard for optimizing microgrid design in all sectors, from village power and island utilities to grid-connected campuses and military bases. Originally developed at the National Renewable Energy Laboratory, and enhanced and distributed by HOMER Energy, HOMER (Hybrid Optimization Model for Multiple Energy Resources) nests three powerful tools in one software product, so that engineering and economics work side by side*" [68]

C. The microgrid

C.1 Design objectives & future scenario

The case study is focused on creating an off grid microgrid in LMRDA with communal assets of production and storage and based on that an internal market for the compensation of the costs of the investment. The LMRD microgrid will consist of the existing houses, the possible new residents of the 3 houses that are now not inhabited and a communal set of PV panels (communal PV) and batteries (communal batteries) stored in a communal building. The design is focused on including as much as possible the existent infrastructure and adding any assets needed to meet the need of the grid.

Objective of the design is to create a more sustainable and stable way to electrify the village of LMRD in a cost-efficient way. The aim is through the interconnection of the existing autonomous SHSs to take advantage of the maximum production from renewable resources. As well in this way the “new” houses/clients will also avoid the purchase of individual assets but the microgrid will provide them electricity through the excess of individual houses and communal production. Through this design many issues that concern sustainability of microgrids are challenged: a) private or communal property of production assets b) decentralized control over a commonly owned grid c) improving cost efficiency of off-grid electrical systems.

The study case investigates the development of the case for 20 years. The design is taking into consideration a realistic assumption of rising need of electricity in the modern houses for the following years, in contrast for the need of reducing individual electricity consumption proposed. Although the community investigated is governed by the principles of sustainability and ecology, the inevitable electrification of more daily needs is a certain fact. Reports[69] show that an average 10-15% percent rise of electricity demand will be noted in the next 20 years. In this study case it is selected a 10 % expected rise of electricity which is added in the “future” case. Here is the table that includes a 10% increase of consumption to each house and 3 new houses with partial load throughout the year.

House	Batteries Capacity (kWh)	Usable* battery capacity (kWh)	PV (kWatts)	Average prod. day (kWh)	Average prod. year(kWh)	Diesel generator (kW)	Consumer profile	Avg. cons./ year (kWh)	Months of year use(%)	Actual Avg. cons./year **(kWh)
House 1	5.40	2.70	0.50	2.32	847.82	0.50	Medium	2,156.16	1.00	2,156.16
House 2	5.40	2.70	0.40	1.86	678.26	0.00	Medium	2,156.16	0.40	862.47
House 3&4	18.00	9.00	1.40	6.50	2,373.90	0.50	Low	1,067.16	1.00	1,067.16
House 5	0.00	0.00	0.00	0.00	0.00	0.00	Low	1,067.16	0.50	533.58
House 6	36.00	18.00	2.88	13.38	4,883.44	1.00	High	3,517.72	1.00	3,517.72
House 7	5.40	2.70	0.30	1.39	508.69	0.00	Low	1,067.16	1.00	1,067.16
House 8	24.00	12.00	1.00	4.65	1,695.64	0.00	High	3,517.72	1.00	3,517.72
House 9	24.00	12.00	1.00	4.65	1,695.64	0.50	High	3,517.72	1.00	3,517.72
House 10	0.00	0.00	0.00	0.00	0.00	0.00	High	3,517.72	1.00	3,517.72
House 11	0.00	0.00	0.00	0.00	0.00	0.00	High	3,517.72	1.00	3,517.72
House 12	0.00	0.00	0.00	0.00	0.00	0.00	Medium	2,156.16	0.40	862.47
House 13	6.00	3.00	0.50	2.32	847.82	0.00	Medium	2,156.16	0.40	862.47
House 14	18.00	9.00	0.00	0.00	0.00	0.50	High	3,517.72	1.00	3,517.72
House 15	0.00	0.00	0.00	0.00	0.00	0.00	Low	1,067.16	0.70	747.01
House 16	52.80	26.40	3.00	13.94	5,086.92	2.00	High	3,517.72	1.00	3,517.72
House 17	10.08	5.04	0.45	2.08	759.65	0.00	Low	1,067.16	1.00	1,067.16
House 18	18.00	9.00	1.50	6.97	2,543.46	0.50	Medium	2,156.16	0.75	1,617.12
House 19	18.00	9.00	1.50	6.97	2,543.46	0.00	Medium	2,156.16	1.00	2,156.16
House 20	0.00	0.00	0.00	0.00	0.00	0.00	Medium	2,156.16	0.40	862.47
House 21	0.00	0.00	0.00	0.00	0.00	0.00	Medium	2,156.16	1.00	2,156.16
House 22	18.00	9.00	0.50	2.32	847.82	0.50	Medium	2,156.16	0.40	862.47
SUM	259.08	129.54	14.93	69.35	25,312.51	6.00				41,504.07

Table of “future” electrical assets of houses of LMRD

Usable battery capacity**= 0,5Batteries Capacity**

****Actual Avg. cons./year= Avg. cons./ year * Months of year use**

And according to the algorithm based on the residential appliances and coincidence factor of 0,8 the following results are demonstrated:

	High Income Household	**Medium Income Household**	**Low Income Household**	**All Households Assuming Varying % High, Medium, and Low Income**
0:00	100.0	30.0	0.0	36.7
1:00	100.0	30.0	0.0	36.7
2:00	100.0	30.0	0.0	36.7
3:00	100.0	30.0	0.0	36.7
4:00	100.0	30.0	0.0	36.7
5:00	100.0	30.0	0.0	36.7
6:00	103.2	32.2	2.6	39.2
7:00	103.2	32.2	2.6	39.2
8:00	394.4	269.3	122.9	250.3
9:00	528.2	308.9	217.8	330.7
10:00	512.0	294.5	207.7	317.3
11:00	565.4	341.1	241.9	361.4
12:00	775.7	506.2	311.7	505.4
13:00	759.5	491.8	301.5	492.0
14:00	593.3	423.4	186.4	384.8
15:00	102.6	31.9	0.0	38.1
16:00	293.1	121.9	130.3	165.4
17:00	227.0	124.0	84.4	135.3
18:00	341.5	205.4	69.6	192.5
19:00	1087.5	789.6	331.7	707.8
20:00	1177.5	822.0	394.7	764.2
21:00	797.0	514.0	189.4	473.2
22:00	536.0	353.0	103.1	313.3
23:00	140.5	66.0	25.3	70.2
Total Wh/day/household:	**9637.6**	**5907.3**	**2923.7**	**5800.5**
Total kWh/year/household:	**3,518**	**2156**	**1067**	**2117**

Table of future households' hourly load profile

In the future case scenario there are 3 houses added, one low, one medium and one high profile consumption and low, medium and high consumption profile load was raised 10%. The results of the two tables differ because the “months of the year use” of each house is not taken into account in the second calculation and the coincidence factor is not taken into account in the first calculation. In this investigation, it is used the number provided by the “Table of total LMRD future LMRD microgrid Load profile” as more reliable, so the current average load for one year in LMRD is considered 44.461 kWh.

	Total Real Household Load
0:00	1.77
1:00	1.21
2:00	0.95
3:00	0.84
4:00	0.90
5:00	1.05
6:00	1.34
7:00	2.12
8:00	4.66
9:00	6.23
10:00	6.77
11:00	7.64
12:00	9.12
13:00	8.89
14:00	7.00
15:00	3.72
16:00	4.14
17:00	4.43
18:00	6.27
19:00	11.43
20:00	12.48
21:00	9.39
22:00	6.35
23:00	3.13
Total kWh/day	122
Total kWh/year	44,461
Max kW/day	12.48
Min kW/day	0.84

Table of “future” LMRD microgrid load profile

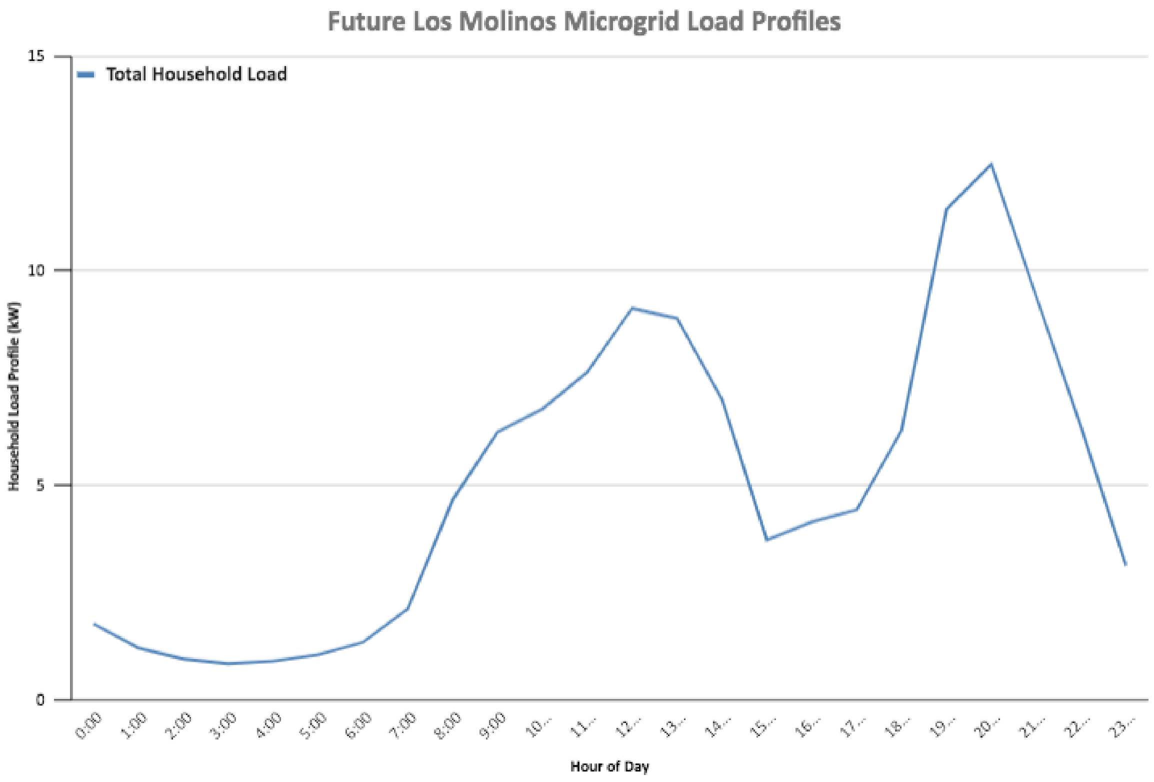


Illustration 15: Future LMRD Microgrid load profile

Having this as a base scenario, then future communal loads were investigated.
An important factor of the design is the social factor of acceptance of specific proposals. The village of LMRD is under protection as it belongs to a NATURA 2000 site and big interventions would not be allowed aesthetically and by the law. The residents would not invest a big amount in an uncertain project so the investment was kept low and the possibility of the return of investment is in a short time. The study was adapted to the financial capacity of the residents, the capacity of ownership and management of the grid and limitation of interventions in the community. So the only asset which was examined as a possible addition to the grid was the replacement of the existing mechanical pump with an electric one. The data that occurred are the following:

Commercial Entity Type	Operating Hours (Hours/Month)	Per Unit Wattage (Watts)	Montly Electricity Consumption (kWh/Month)
Water Pumping	217	985	214

Table of info about communal load

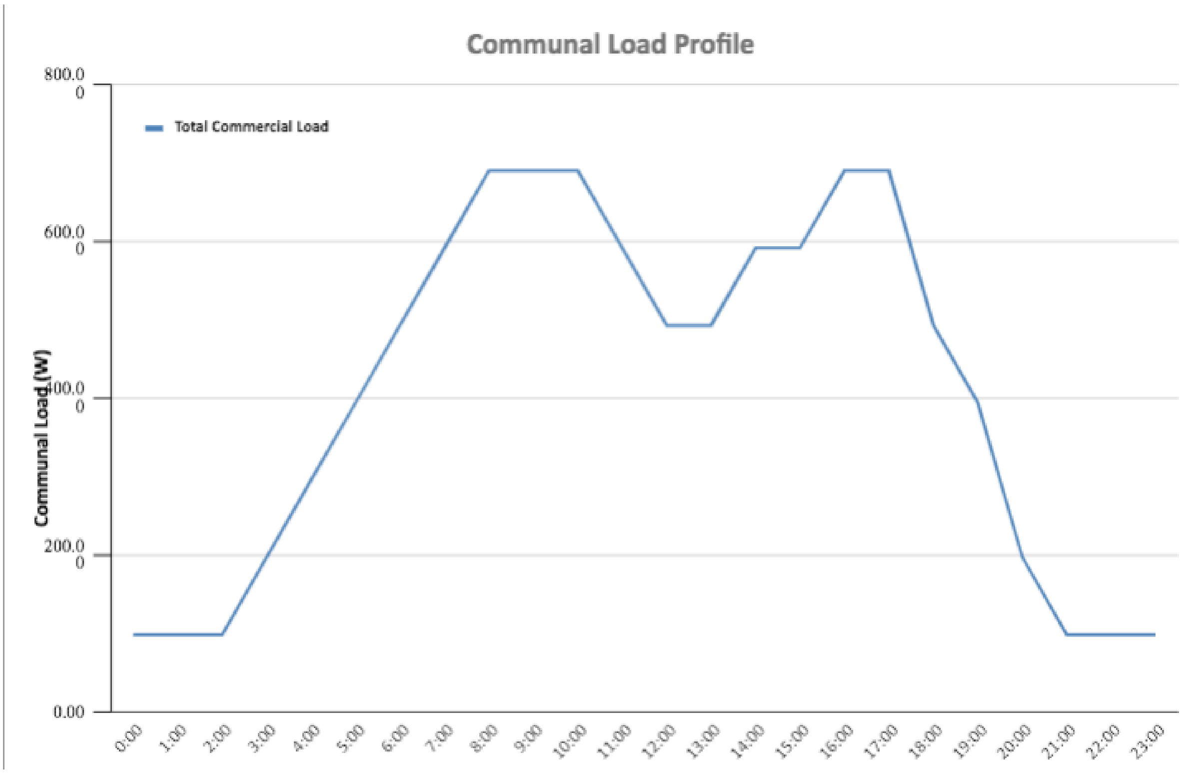


Illustration 16: Communal Load profile

	Total Household Load	Total Communal Load	Total Household + Communal Load
0:00	1.77	0.10	1.87
1:00	1.21	0.10	1.31
2:00	0.95	0.10	1.05
3:00	0.84	0.20	1.03
4:00	0.90	0.30	1.19
5:00	1.05	0.39	1.44
6:00	1.34	0.49	1.83
7:00	2.12	0.59	2.71
8:00	4.66	0.69	5.35
9:00	6.23	0.69	6.92

10:00	6.77	0.69	7.46
11:00	7.64	0.59	8.23
12:00	9.12	0.49	9.61
13:00	8.89	0.49	9.38
14:00	7.00	0.59	7.59
15:00	3.72	0.59	4.31
16:00	4.14	0.69	4.83
17:00	4.43	0.69	5.12
18:00	6.27	0.49	6.77
19:00	11.43	0.39	11.82
20:00	12.48	0.20	12.67
21:00	9.39	0.10	9.49
22:00	6.35	0.10	6.45
23:00	3.13	0.10	3.23
Total kWh/day	122	0.01	**132**
Total kWh/year	44,461	3.60	**48,056**
Max kW/day	12.48	0.00	**12.67**
Min kW/day	0.84	0.00	**1.03**

Table of future LMRD microgrid load profile with communal load

The electrification of the water pumping activity could provide a flexible load to the microgrid, which can help the reliable operation of the system by quickly lowering demand to balance the grid and minimizing the power curtailed by the Pvs. Alternatives to this could be solar pumps that work only throughout the day and they are autonomous. This could be an appropriate solution of LMRA as each individual has a private tank and there is already a shared schedule for filling up the tanks. The option of adding a pump in the microgrid is not taken into account in the design but the study is done in order to provide the data needed for a future addition in the grid.

C.2 Modeling the scenario

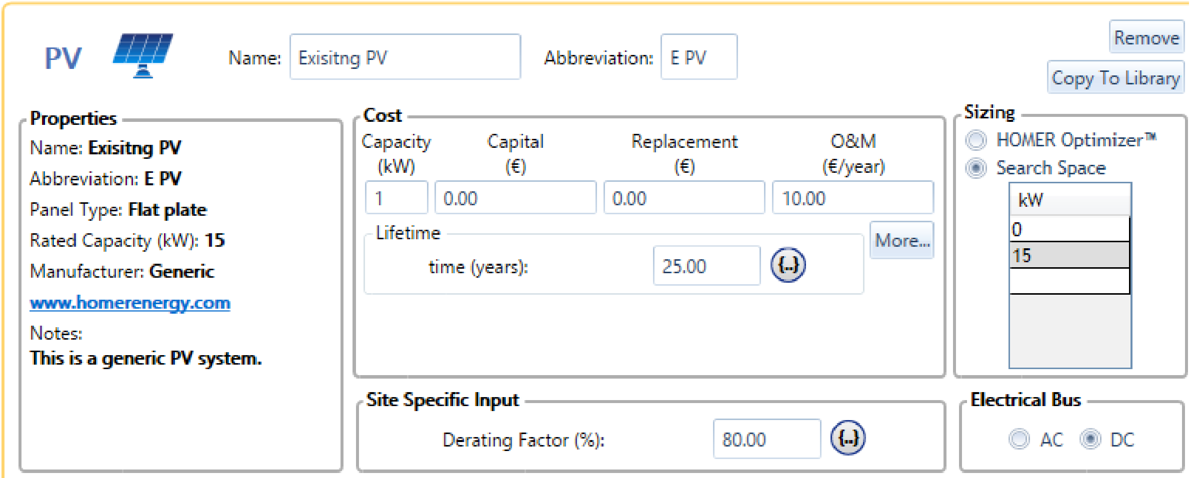
The method of designing the microgrid that was used was inspired by the paper [70] by Juan M. Rey et. al. and adapted in order to match the Homer simulation platform . The investigation examines at the energy potential and the meteorological data of LMRD choosing the appropriate means of renewable production, second the energy capacity needed for the microgrid and third defining and modeling the topology and the load of the grid. This work provides a less complex and more appropriate model for the simulation platform of Homer program.

1) Renewable & Generators Production

By observing at the existent and future case that, there is a need of adding more production units in the microgrid apart from incorporating the already existent ones.In the first place it is investigated the Energy Potential and Meteorological Data of the LMRA microgrid. It is taken into consideration the data given in the section B.2 about the PV production and meteorological data. The total already installed PV panels have 14.93 kWp of nominal power. The meteorological data provided for LMRD position also offer 1695.64 kWh/kWp annually which means 25,312.5 kWh annually. In order to cover the whole load with new PV panels this would mean 44.461- 25.312= 19.149 kWh more solar power, which means a minimum of more 11.5 kWp of solar power. The solar power that the system can absorb depends on the load and battery capacity of the moment that is being produced so the exact size of new PVs is provided in the Homer simulation because it optimizes the size in this way in contradiction to our data which provides only with the kWp that is needed for the whole year.

In the second place, it is investigated the potential of other small scale production units such as pico-hydro units and small wind turbines. The first option was discarded because an intervention in the flow of the river which flows nearby is highly prohibited and socially not approved. The second option was investigated more in depth. In LMRD there is already installed a small wind-turbine of 350 W that is left abandoned and now it is not functioning. The main reason why the solution of the wind turbine was abandoned was the cost of the maintenance of the wind turbine was higher than the production of electricity. New small wind turbines prototypes were investigated but the mean wind speed of the area does not overcome 5m/s [71] so the option of the replacement of the existing one was also discarded.

Finally, PV panels were selected as the production unit that will be added to the grid. The existing PV panels are considered one cluster of 14.9 kW nominal power and the new PV panels another cluster which is bound to be optimized with economical and functional criteria.



Name: Exisitng PV
Abbreviation: E PV

Properties
Name: **Exisitng PV**
Abbreviation: **E PV**
Panel Type: **Flat plate**
Rated Capacity (kW): **15**
Manufacturer: **Generic**
www.homerenergy.com
Notes:
This is a generic PV system.

Cost

Capacity (kW)	Capital (€)	Replacement (€)	O&M (€/year)
1	0.00	0.00	10.00

Lifetime
time (years): 25.00

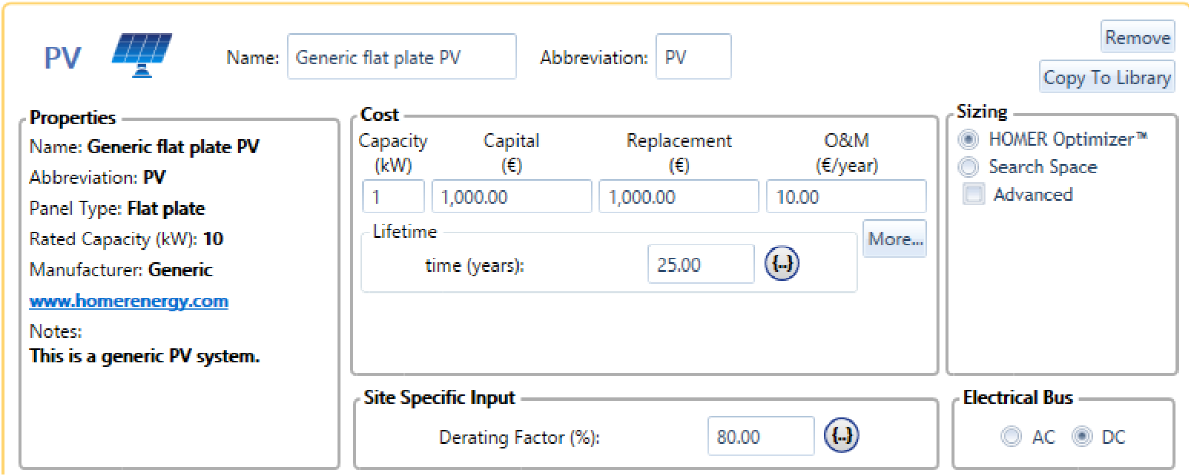
Sizing
○ HOMER Optimizer™
● Search Space

kW
0
15

Site Specific Input
Derating Factor (%): 80.00

Electrical Bus
○ AC ● DC

Illustration 17: Existing Pv modeling



Name: Generic flat plate PV
Abbreviation: PV

Properties
Name: **Generic flat plate PV**
Abbreviation: **PV**
Panel Type: **Flat plate**
Rated Capacity (kW): **10**
Manufacturer: **Generic**
www.homerenergy.com
Notes:
This is a generic PV system.

Cost

Capacity (kW)	Capital (€)	Replacement (€)	O&M (€/year)
1	1,000.00	1,000.00	10.00

Lifetime
time (years): 25.00

Sizing
● HOMER Optimizer™
○ Search Space
☐ Advanced

Site Specific Input
Derating Factor (%): 80.00

Electrical Bus
○ AC ● DC

Illustration 18: Communal PV modeling

HOMER uses the following equation to calculate the output of the PV array:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right)$$

Y_{PV} = the rated capacity of the PV array, meaning its power output under standard test conditions [kW]

f_{PV} = the PV derating factor [%]

$\overline{G}_T$ = the solar radiation incident on the PV array in the current time step [kW/m^2]

$\overline{G}_{T,STC}$ = the incident radiation at standard test conditions [1 kW/m^2]

In the investigation, it is considered that:

a) The existing infrastructure will remain as it is. There will be no upgrades by individuals and repairs to individual property is calculated inside the capital of inversion for the grid. The replacement of it is covered by the individual so it is not calculated as part of the cost of the investment for the grid.

b) The new PV panels are property of the community but managed by the grid manager. They are installed on a communal land or building. The material and installation cost of the PV panels is calculated according to the average prices of 2020, which was close to 1000 euros per kW with an average lifetime of 25 years
and connected the DC bus as their primary function is to charge batteries.

c) Purpose of the extension of the production units is not to promote extensive use of more electricity but to provide electricity security and economical solutions to the rise of demand for the next 20 years.

Generators

In the microgrid, the diesel generators contribute to the total production by connecting to the AC side. The management of each diesel generator is a responsibility of each house and they are used only in the case that they charge batteries that cannot offer more energy, they reached 50%. In the existing infrastructure, there are 8 generators of varying nominal power. In the future scenario, all of them are deployed as an integral part of the grid.

In Homer simulation, the existing generators were grouped together in a group of generators of 6 kW in total called Gen6. The generators are given third priority, after

PV panels and batteries. The cost of the fuel is set to 1 dollar per litre with a high inflation rate for the future. The costs of maintenance and fuel of the diesel generators are included into the total inversion.

2) Energy storage & inverters

In the investigation, it is assumed that the existing infrastructure of batteries can be part of the microgrid. The batteries will work with two way inverters that can control the State of Charge (SoC) of the batteries and accordingly demand power or discharge excess electricity. State of charge (SoC) is the level of charge of an electric battery relative to its capacity. The units of SoC are percentage points (0% = empty; 100% = full). The minimum SoC is set at 50% as a minimum battery health policy and that the battery can discharge to the microgrid above a preselected percentage, chosen by the microgrid manager.

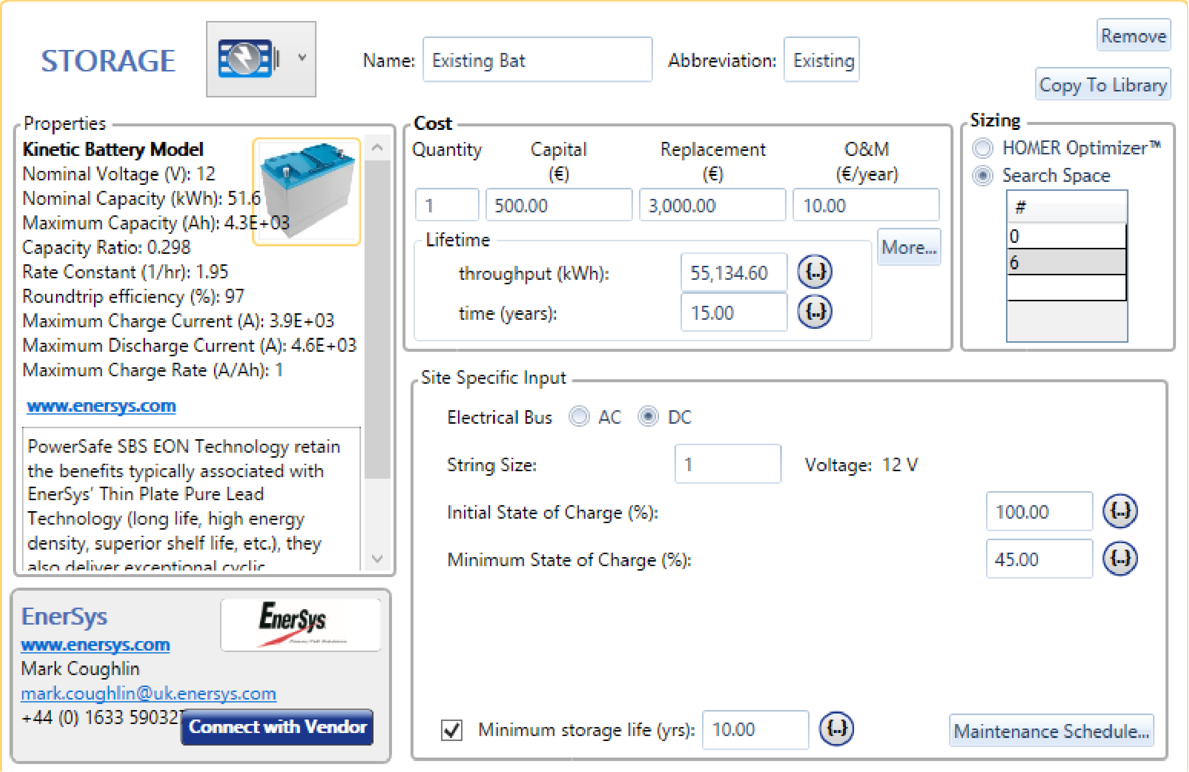
In our investigation, we consider that:

a) The existing infrastructure will remain as it is. There will be no upgrades by individuals and repairs to individual property is calculated inside the capital of inversion for the grid.
b) New batteries are property of the community but managed by the grid manager. They are installed on a communal land or building.
c) Purpose of the extension of the energy storage units is not to promote extensive use of more electricity but to provide electricity security and economical solutions to the rise of demand for the next 20 years.

By the future case, it is assumed that also an addition of energy storage & replacement of the existing inverters is needed in the grid. The addition of energy storage will be a pack of batteries connected with the communal PV panels and together provide the additional kWh that is needed to cover the demand. Of course, the use of diesel generators is not expected to be eliminated because of weather and grid reliability factors. The exact percentage that the communal assets contribute is calculated in Homer simulation and optimization. However, the real energy exchange will be automaticated by the market and a blockchain algorithm, so it will differ from the simulation given by Homer.

The modeling of the batteries aligned with the platform of Homer followed these steps:

a) The existing batteries were modeled according to their capacity in kWh and then grouped together in one cluster with total capacity the sum of all batteries. This cluster has zero capital cost but has replacement cost.
b) A cluster of new batteries unit was created with unknown size bound to Homer Optimizer algorithm
c) The optimizer was run only with the new cluster in order to determine the appropriate size of batteries needed in total in the microgrid. Appropriate size was determined
d) Then the two clusters were unified, reducing the cost of the existing batteries in order to determine the real cost of the new batteries and sum it to the total cost of the investment.



Name: Existing Bat

Abbreviation: Existing

Properties

Kinetic Battery Model
Nominal Voltage (V): 12
Nominal Capacity (kWh): 51.6
Maximum Capacity (Ah): 4.3E+03
Capacity Ratio: 0.298
Rate Constant (1/hr): 1.95
Roundtrip efficiency (%): 97
Maximum Charge Current (A): 3.9E+03
Maximum Discharge Current (A): 4.6E+03
Maximum Charge Rate (A/Ah): 1

www.enersys.com

PowerSafe SBS EON Technology retain the benefits typically associated with EnerSys' Thin Plate Pure Lead Technology (long life, high energy density, superior shelf life, etc.), they also deliver exceptional cyclic

EnerSys
www.enersys.com
Mark Coughlin
mark.coughlin@uk.enersys.com
+44 (0) 1633 59032

Cost

Quantity	Capital (€)	Replacement (€)	O&M (€/year)
1	500.00	3,000.00	10.00

Lifetime

throughput (kWh): 55,134.60

time (years): 15.00

Sizing

○ HOMER Optimizer™
● Search Space

#
0
6

Site Specific Input

Electrical Bus ○ AC ● DC

String Size: 1

Voltage: 12 V

Initial State of Charge (%): 100.00

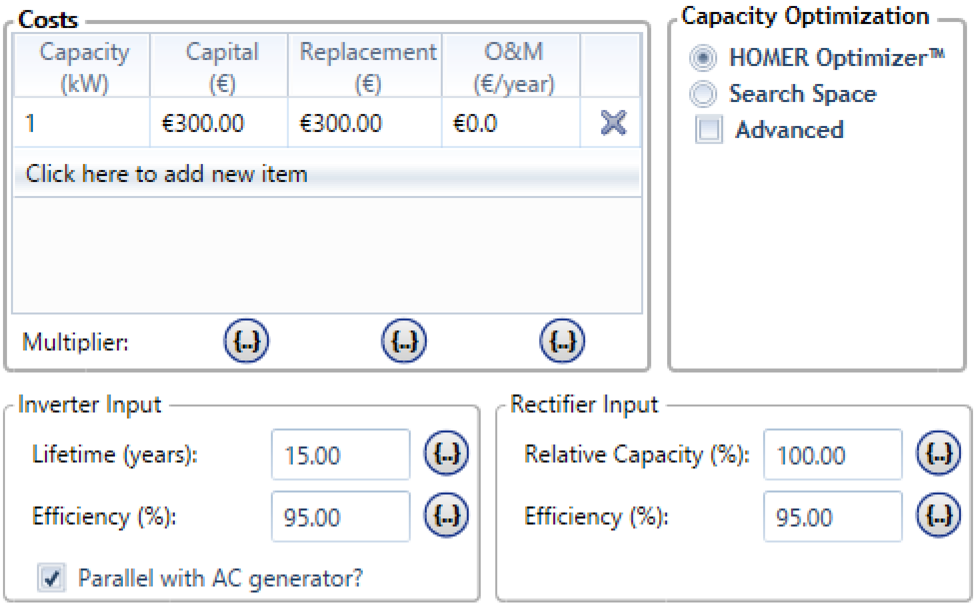
Minimum State of Charge (%): 45.00

☑ Minimum storage life (yrs): 10.00

Illustration 19: Batteries modeling

The simulation is concentrated on finding the kWh of capacity needed by the microgrid and not for determining the battery model appropriate for this application.

The inverter needed for the microgrid was not calculated in separate clusters because there is the need of replacement of the existing ones in order to be able to work in parallel. The lifetime assigned was 15 years with efficiency of 95% and capital and investment cost of 300 euros per kW. The sizing of each individual inverter is not part of this investigation and the actual total size of the sum of all inverters may differ from the total power capacity of the simulation. However, the simulation provides us with the capacity needed in order all the energy is able to exchange in between the elements and takes into consideration the peak of the load which is 12.5 kW.


Costs

Capacity (kW)	Capital (€)	Replacement (€)	O&M (€/year)
1	€300.00	€300.00	€0.0

Click here to add new item

Multiplier: {..} {..} {..}

Capacity Optimization

● HOMER Optimizer™
○ Search Space
☐ Advanced

Inverter Input

Lifetime (years): 15.00 {..}
Efficiency (%): 95.00 {..}
☑ Parallel with AC generator?

Rectifier Input

Relative Capacity (%): 100.00 {..}
Efficiency (%): 95.00 {..}

Illustration 20: Inverter modeling

3) Distribution network & Load

The grid will be connected on the AC side. DC solutions with dual-loop control were investigated [72] as demonstrated in illustration below:

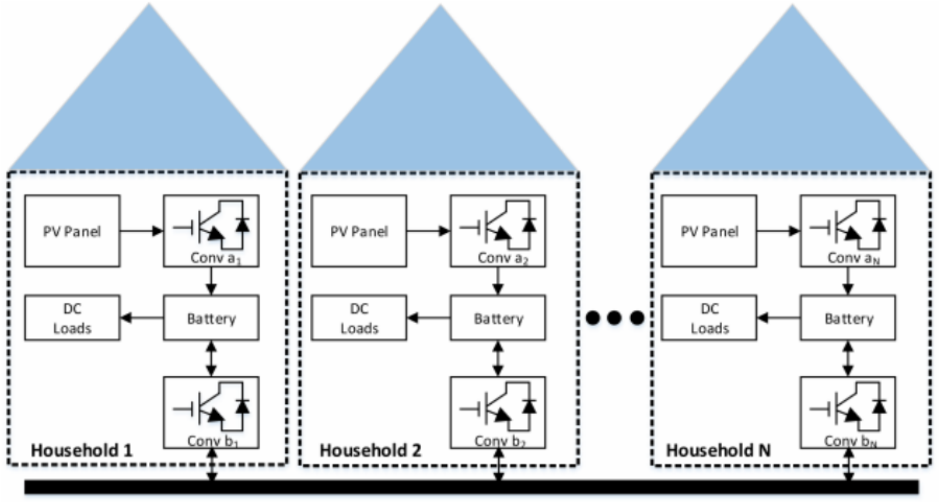


Illustration 21: Scheme proposed by the paper "Dual-loop control strategy applied to PV/battery-based islanded DC microgrids for swarm electrification of developing regions

However they were discarded because of non-industrial applications and devices that can support our study case. On the other hand, inverters found from SMA or Victron Energy companies can provide solutions to an off-grid AC system such as paralleling inverters, two way management and SoC management.

The topology of the AC grid was designed on a scaled map in order to calculate the wiring distances. The topology of the grid was decided to be a C-shape topology with the community building in the middle with two different wirings for interconnection with it. Both connecting lines are connected with a relay that allows either the line "Communal Building- house 21" to work or line "Communal building-House 11" to work. In this way the total wiring is constructed in a radial way. The topology took into consideration reliability criteria and shortest distance criteria. In the future, wiring could be deployed in between house 22 and house 1 with a relay that will enable electricity to pass through in case of breakdown in another part of the microgrid. The total wiring was measured and it resulted in 0,9 km of overground wiring which resulted in a maximum of 5% power losses for the maximum distance and a cabling of 6 AWG which could cost at least 2500€.

Every house is a prosumer with the possibility of producing and selling to the grid extra energy and consume its own energy or buy from the grid except from the communal building which works only as a producer. Houses can have energy exchanges in between them and each one with the communal building. For the Homer simulation, there is no priority in between these exchanges. However, with the integration of the energy market the price will be a regulating factor that will create priority in between the two options. Illustration 22 demonstrates the designed connections between the houses and the communal building.

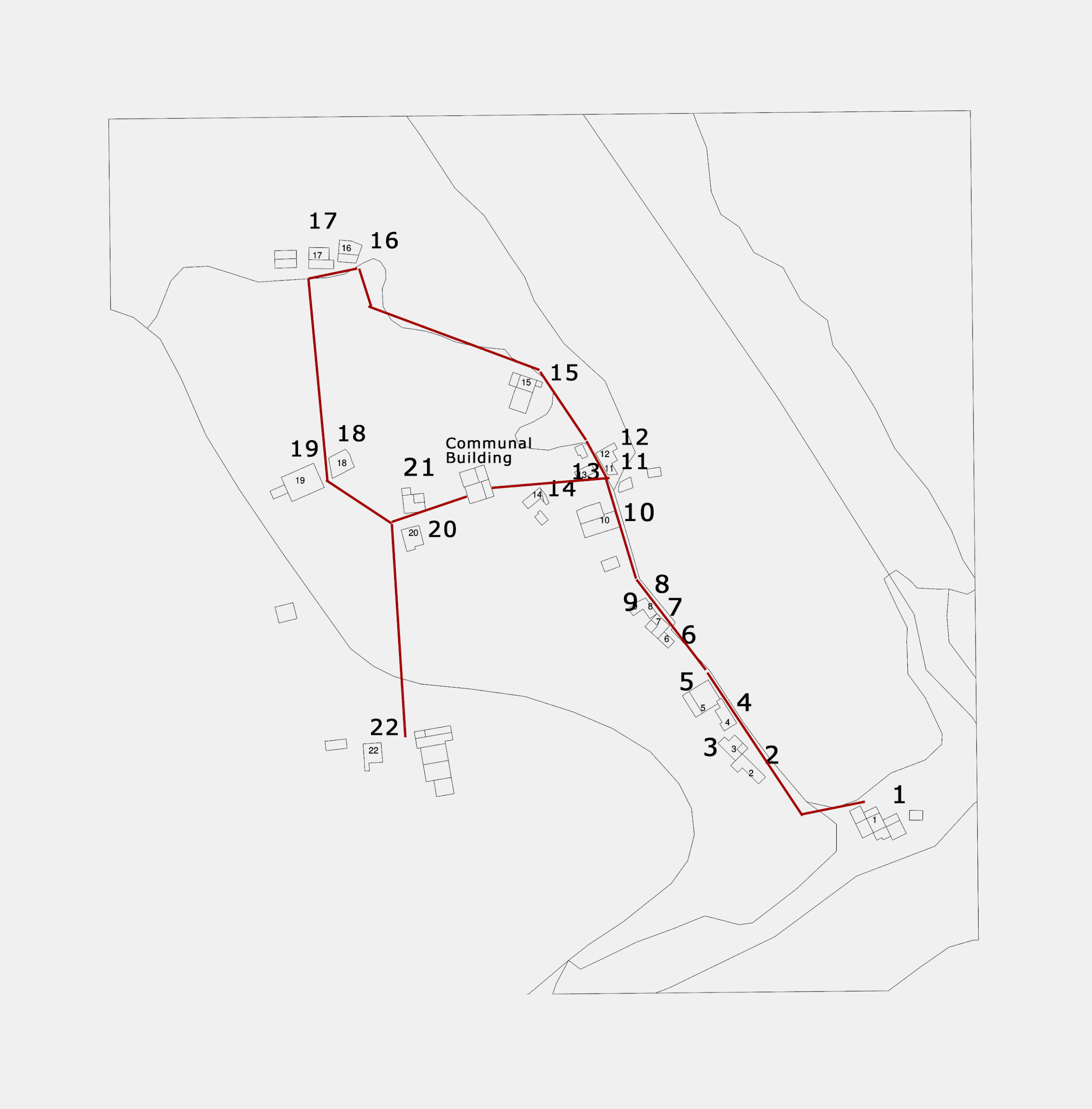
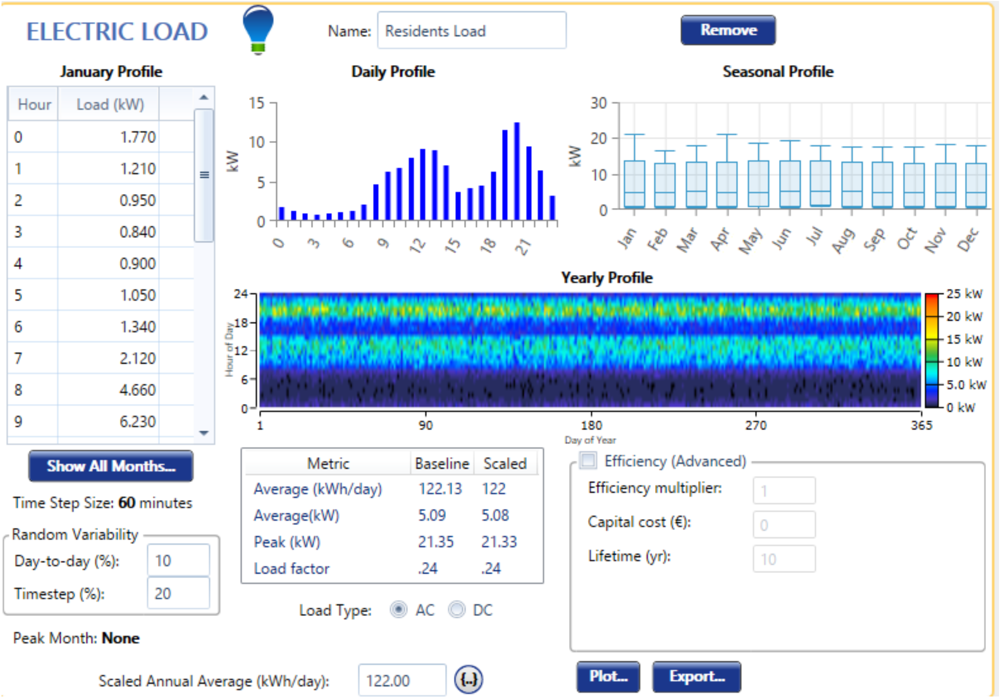


Illustration 22: Map of AC microgrid topology

The load of LMRD is considered the load profile of each house according to their consumption profile combined with a coincidence factor of 0.8. An average load for the whole year is considered for reasons of simplicity however in Homer simulation peak months selected are the ones of summer when it is more populated as demonstrated in illustration 23. So in the simulation the grid is considered a single load with the load profile of the total load. A 10% day to day variability is considered for the simulation.



Name: Residents Load

January Profile

Hour	Load (kW)
0	1.770
1	1.210
2	0.950
3	0.840
4	0.900
5	1.050
6	1.340
7	2.120
8	4.660
9	6.230

Time Step Size: **60** minutes

Random Variability

Day-to-day (%): 10

Timestep (%): 20

Peak Month: **None**

Metric	Baseline	Scaled
Average (kWh/day)	122.13	122
Average(kW)	5.09	5.08
Peak (kW)	21.35	21.33
Load factor	.24	.24

Load Type: ● AC ○ DC

☐ Efficiency (Advanced)

Efficiency multiplier: 1

Capital cost (€): 0

Lifetime (yr): 10

Scaled Annual Average (kWh/day): 122.00

Illustration 23: Homer simulations’ load

The mechanism for adding day-to-day and time-step-to-time-step variability is simple. First, HOMER assembles the year-long array of load data from the daily profiles you specify. Then, it steps through that time series, and, in each time step, it multiplies the value in that time step by a perturbation factor α:

$$\alpha = 1 + \delta_d + \delta_{ts}$$

where:

δ_d = daily perturbation value

δ_{ts} = time step perturbation value

HOMER randomly draws the daily perturbation value once per day from a normal distribution with a mean of zero and a standard deviation equal to the daily variability (Day-to-day) input. It randomly draws the time step perturbation value every time step from a normal distribution with a mean of zero and a standard deviation equal to the time-step-to-time-step variability (Timestep) input value. The varying load between months it is demonstrated in illustration 24.

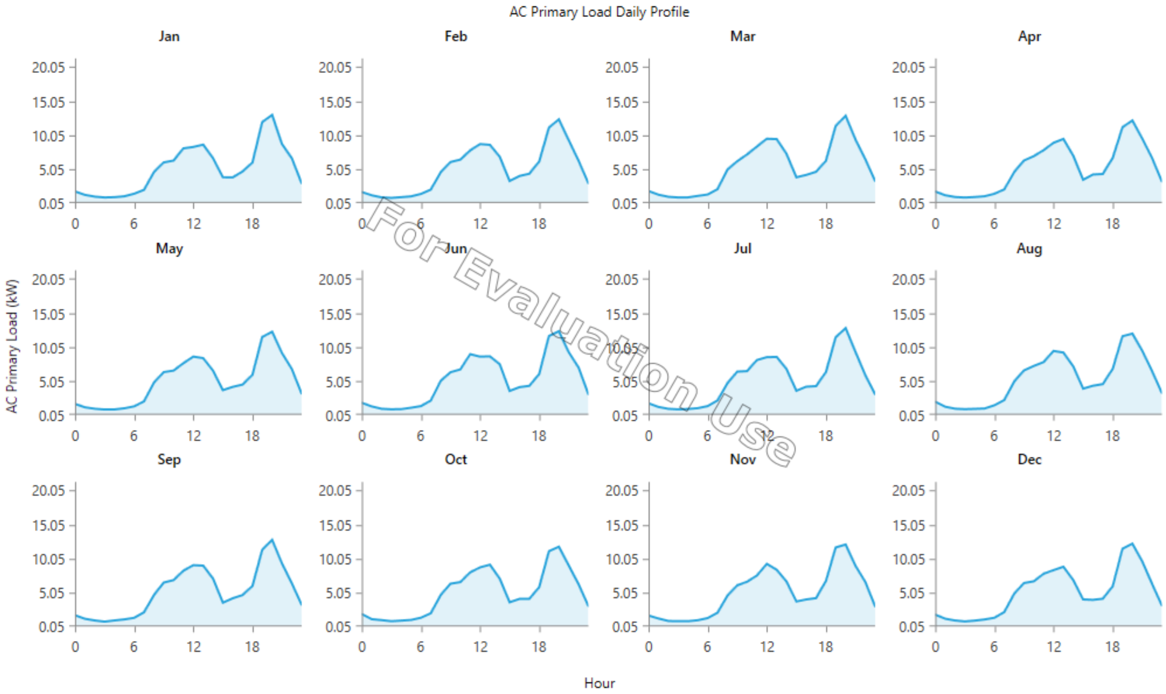


Illustration 24: Homer simulations' average load per month

Real consumption data were provided by Sunseed Desert technology but they were less than the amount needed and unreliable, so the option of using real consumption data to calculate the load profile of the houses was discarded.

C.3 Simulation & Optimization

In Homer platform the grid was modeled the way it is presented in the schematic above. There are two buses:

a) the DC bus in which the two clusters of PV are connected and the batteries (the two unified clusters).
b) The AC bus in which the generators and the load is connected.
c) The inverter which interconnects the two buses.

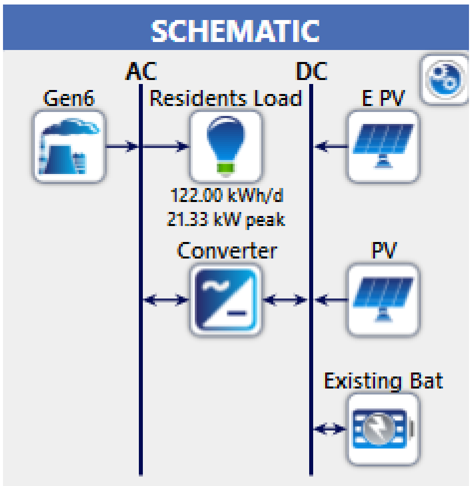


Illustration 25: Simulations' grid schematic

The simulation optimized the size of the inverter, of the new PV and of the new batteries and at the same time running all reliability tests of the grid. This is how Homer works according to the developers of the program:

"HOMER simulates energy systems, shows system configurations optimized by cost, and provides sensitivity analyses.[68]

Simulation

HOMER simulates the operation of a system by making energy balance calculations in each time step (interval) of the year. For each time step, HOMER compares the electric and thermal demand in that time step to the energy that the system can supply in that time step, and calculates the flow of energy to and from each component of the system. For systems that include batteries or fuel-powered generators, HOMER also decides in each time step how to operate the generators and whether to charge or discharge the batteries.

HOMER performs these energy balance calculations for each system configuration that you want to consider. It then determines whether a configuration is feasible, (i.e., whether it can meet the electric demand under the conditions that you specify), and estimates the cost of installing and operating the system over the lifetime of the project. The system cost calculations account for costs such as capital, replacement, operation and maintenance, fuel, and interest.

Optimization

HOMER Pro has two optimization algorithms. The original grid search algorithm simulates all of the feasible system configurations defined by the Search Space. The new HOMER Optimizer uses a proprietary derivative-free algorithm to search for the least-costly system. HOMER then displays a list of configurations, sorted by net present cost (sometimes called life-cycle cost), that you can use to compare system design options.

In our investigation we used both of the optimizing algorithms. From the simulation came up two different cases, which are demonstrated below. Both cases were fully functional for the grid. The differences in between them were a) different size of new PV panels b) different investment cost c) different renewable production percentage/ generators production. These differences are compared in the first place and then the full details of the simulation results are demonstrated.

	Case A	***Case B***
Size of new PV	*15.4 kW*	*10 kW*
Investment cost	*23.767 €*	*20.351 €*

Renewables percentage	*94.5 %*	*90 %*

Here are some calculation which occur from the comparison of the two cases:

Difference of investment cost= 23.767- 20.351= 3.416 €

*For case A: Cost of extra PV power= 5,4 kW * 1.000 €= 5.400 €*

For case B: Cost of extra fuel= 5.400-3.416= 1.984 €

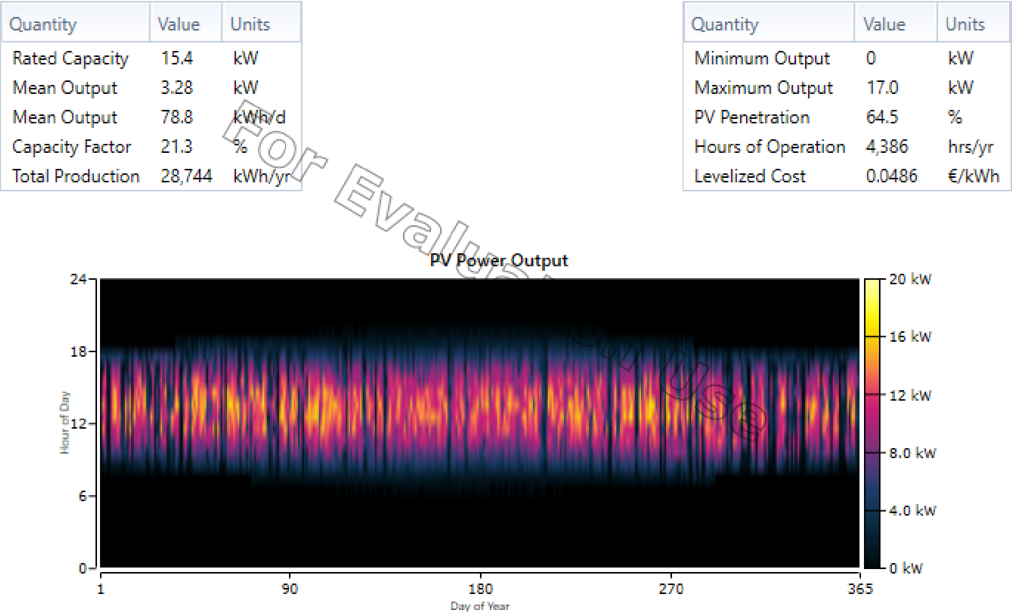
Both cases were valid according to the criteria of the investigation. In Case A, there is higher renewables' penetration to the total production so the fuels' cost is lower in comparison to case B that the investment cost is lower, a fact that has its disadvantage that more money is paid in fuel than in PVs. The decision was to choose Case A, because it is closer to the goals of the investigation, which is to find the most sustainable solution for the electrification of LMRD keeping in mind that the cost is not a lot higher. So the case which is developed further is the case A.

C.4 Simulation results

1) Production

As we mentioned above, the optimized size of the new PV panels is 15.4 kW. Various statistics of the grids' simulation for the next 20 years are demonstrated below:

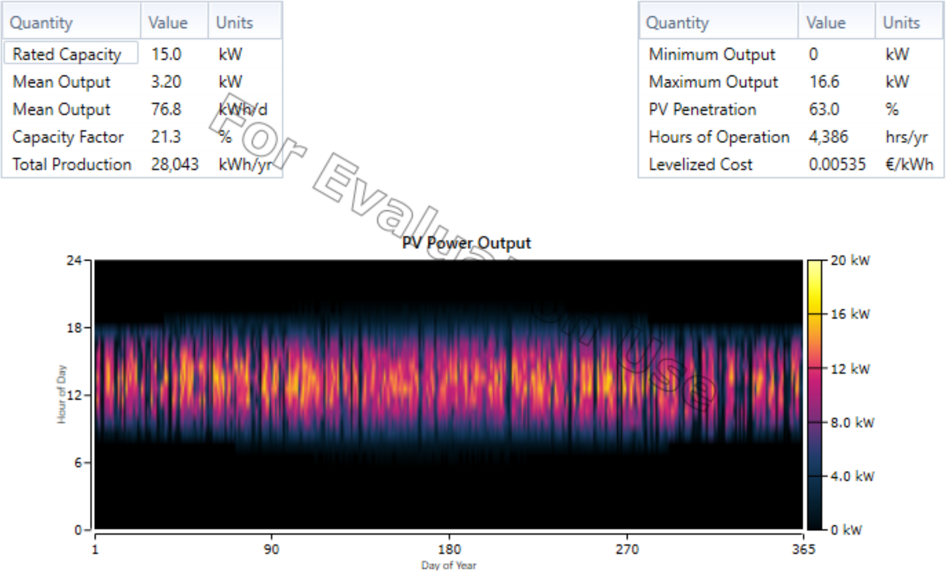
Illustrations 26 & 27 demonstrate the exact days of the year that the PVs produced energy, which time of the day and how many kWs, providing as well some statistics over their period of production.



Quantity	Value	Units
Rated Capacity	15.4	kW
Mean Output	3.28	kW
Mean Output	78.8	kWh/d
Capacity Factor	21.3	%
Total Production	28,744	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	17.0	kW
PV Penetration	64.5	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.0486	€/kWh

Illustration 26: New PV statistics

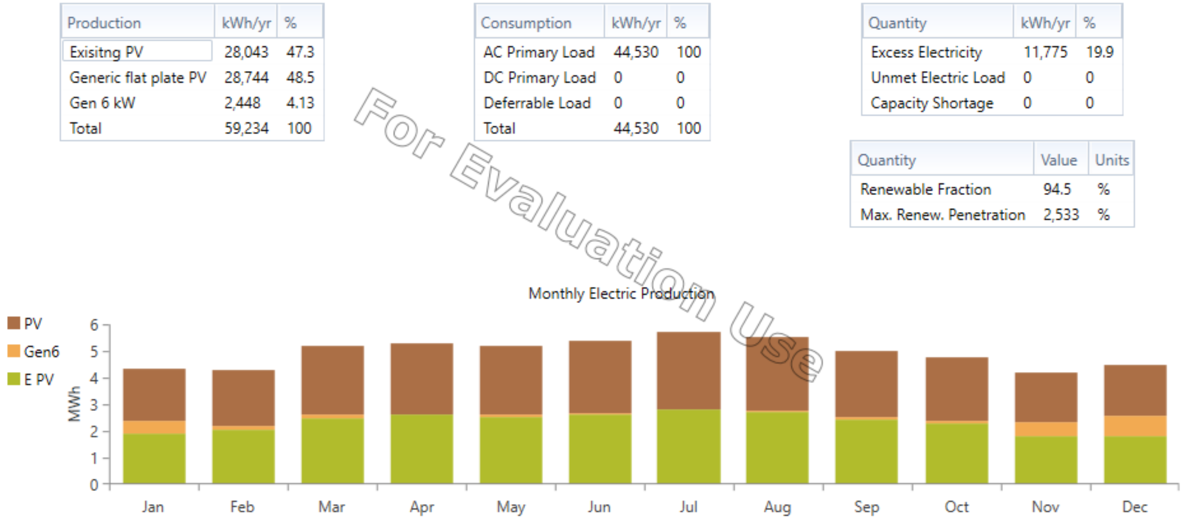


Quantity	Value	Units
Rated Capacity	15.0	kW
Mean Output	3.20	kW
Mean Output	76.8	kWh/d
Capacity Factor	21.3	%
Total Production	28,043	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	16.6	kW
PV Penetration	63.0	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.00535	€/kWh

Illustration 27: Existing PV statistics

Illustration 28 & 29 highlights the fact that the percentage of Total renewable production divided by total generation is 95.9 % and reneable penetration is 94,5 %



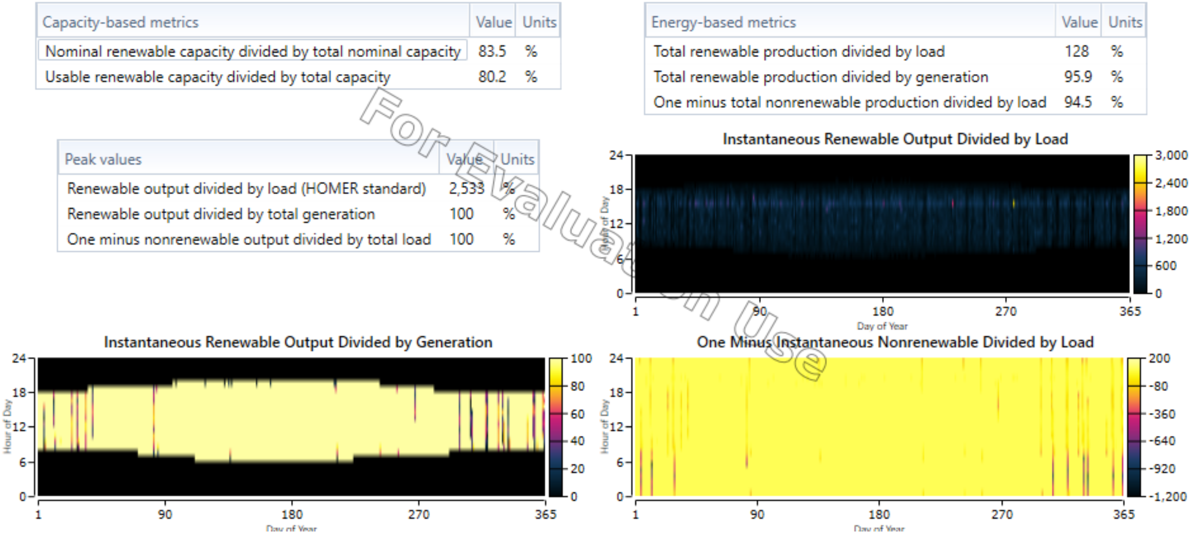
Production	kWh/yr	%
Exisitng PV	28,043	47.3
Generic flat plate PV	28,744	48.5
Gen 6 kW	2,448	4.13
Total	59,234	100

Consumption	kWh/yr	%
AC Primary Load	44,530	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	44,530	100

Quantity	kWh/yr	%
Excess Electricity	11,775	19.9
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	94.5	%
Max. Renew. Penetration	2,533	%

Illustration 28: Monthly Electric Production statistics



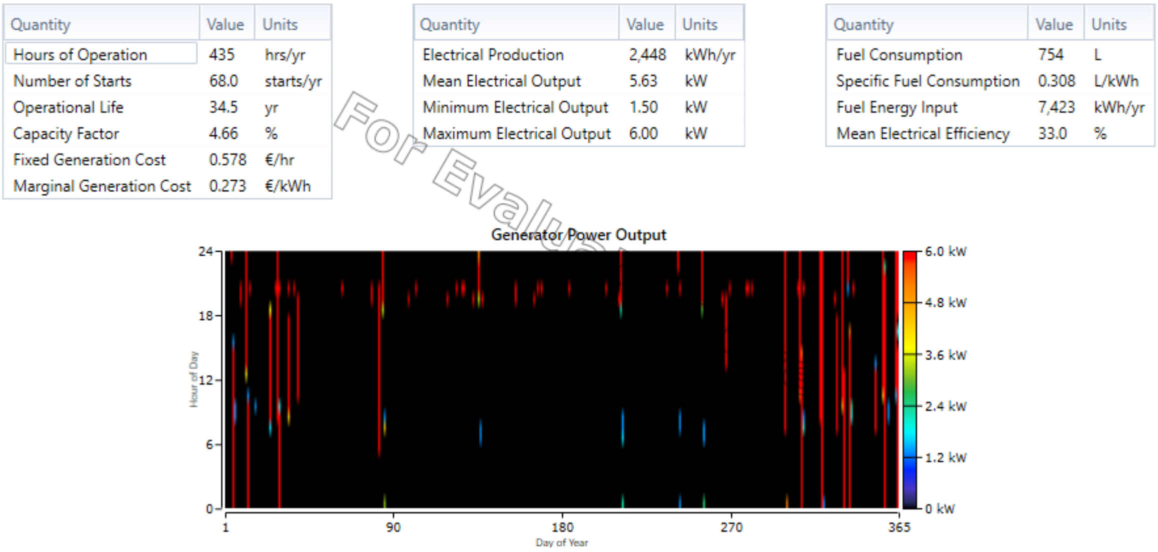
Capacity-based metrics	Value	Units
Nominal renewable capacity divided by total nominal capacity	83.5	%
Usable renewable capacity divided by total capacity	80.2	%

Energy-based metrics	Value	Units
Total renewable production divided by load	128	%
Total renewable production divided by generation	95.9	%
One minus total nonrenewable production divided by load	94.5	%

Peak values	Value	Units
Renewable output divided by load (HOMER standard)	2,533	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

Illustration 29: Renewable Penetration statistics

Illustration 30 demonstrates that the use of generators as a backup generator is not an efficient way to use the generators as their efficiency is pretty low (capacity factor= 4.66 %). This fact increases the cost of the generation is (0,578 €/hr) . The calculated average marginal cost of all generators is 0.273 €



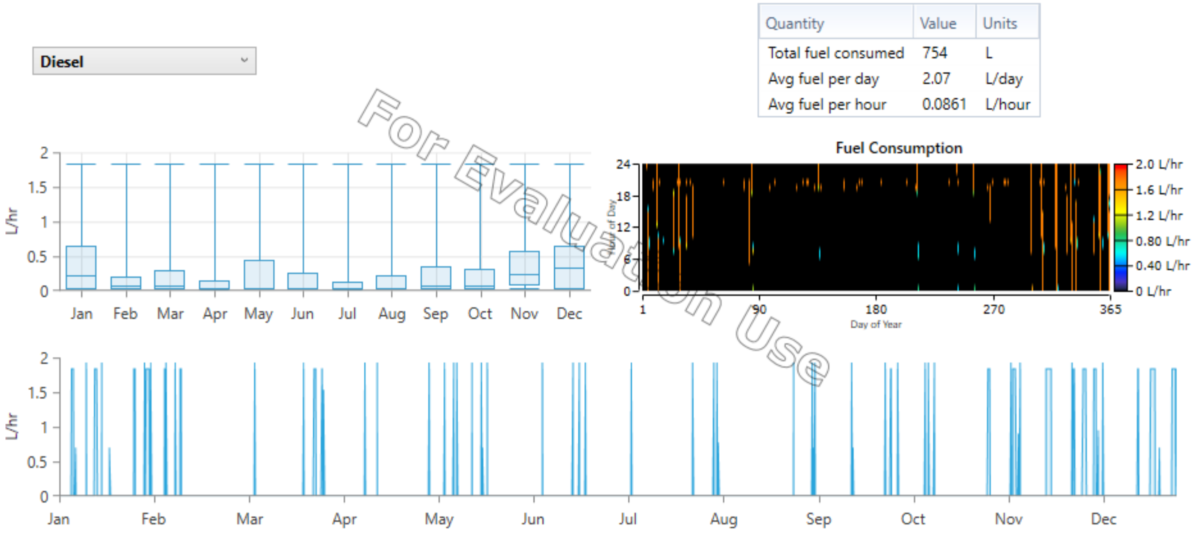
Quantity	Value	Units
Hours of Operation	435	hrs/yr
Number of Starts	68.0	starts/yr
Operational Life	34.5	yr
Capacity Factor	4.66	%
Fixed Generation Cost	0.578	€/hr
Marginal Generation Cost	0.273	€/kWh

Quantity	Value	Units
Electrical Production	2,448	kWh/yr
Mean Electrical Output	5.63	kW
Minimum Electrical Output	1.50	kW
Maximum Electrical Output	6.00	kW

Quantity	Value	Units
Fuel Consumption	754	L
Specific Fuel Consumption	0.308	L/kWh
Fuel Energy Input	7,423	kWh/yr
Mean Electrical Efficiency	33.0	%

Illustration 30: Generators statistics

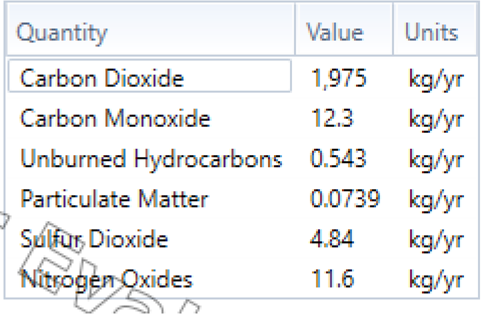
As it was expected, illustration 31 illustrates that the months that fuel was used was the months of November, December and January and the autumn months coming after. However it can observed that during almost all months the generator was used which highlights its function as a backup generator and its importance in the system of the microgrid



Quantity	Value	Units
Total fuel consumed	754	L
Avg fuel per day	2.07	L/day
Avg fuel per hour	0.0861	L/hour

Illustration 31: Fuel statistics

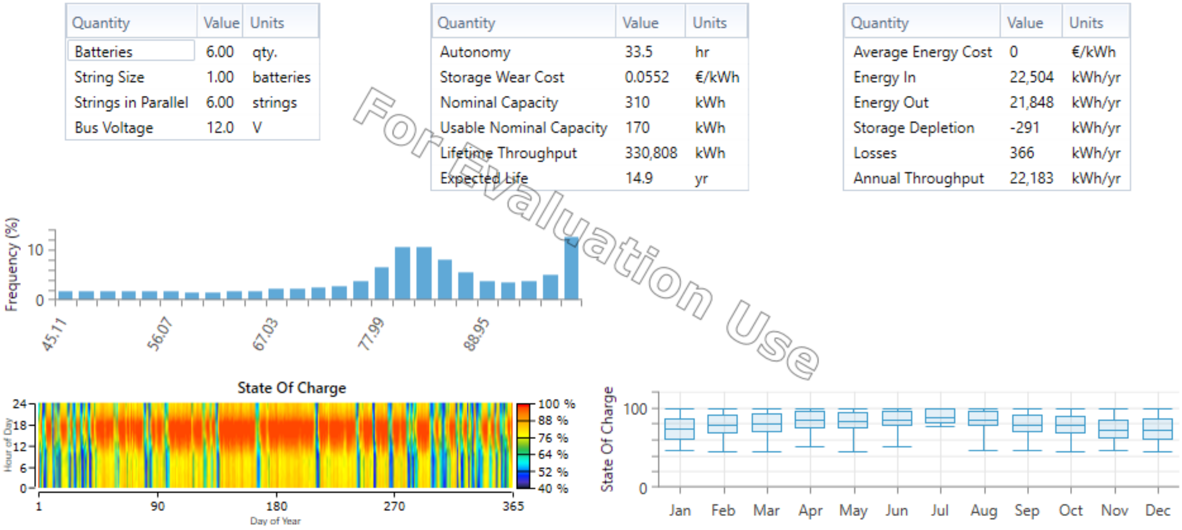
Illustration 32 demonstrates the emissions statistics of energy production in the microgrid. This statistics are important for sustainability criteria.



Quantity	Value	Units
Carbon Dioxide	1,975	kg/yr
Carbon Monoxide	12.3	kg/yr
Unburned Hydrocarbons	0.543	kg/yr
Particulate Matter	0.0739	kg/yr
Sulfur Dioxide	4.84	kg/yr
Nitrogen Oxides	11.6	kg/yr

Illustration 32: Emissions statistics

2) Batteries



Quantity	Value	Units
Batteries	6.00	qty.
String Size	1.00	batteries
Strings in Parallel	6.00	strings
Bus Voltage	12.0	V

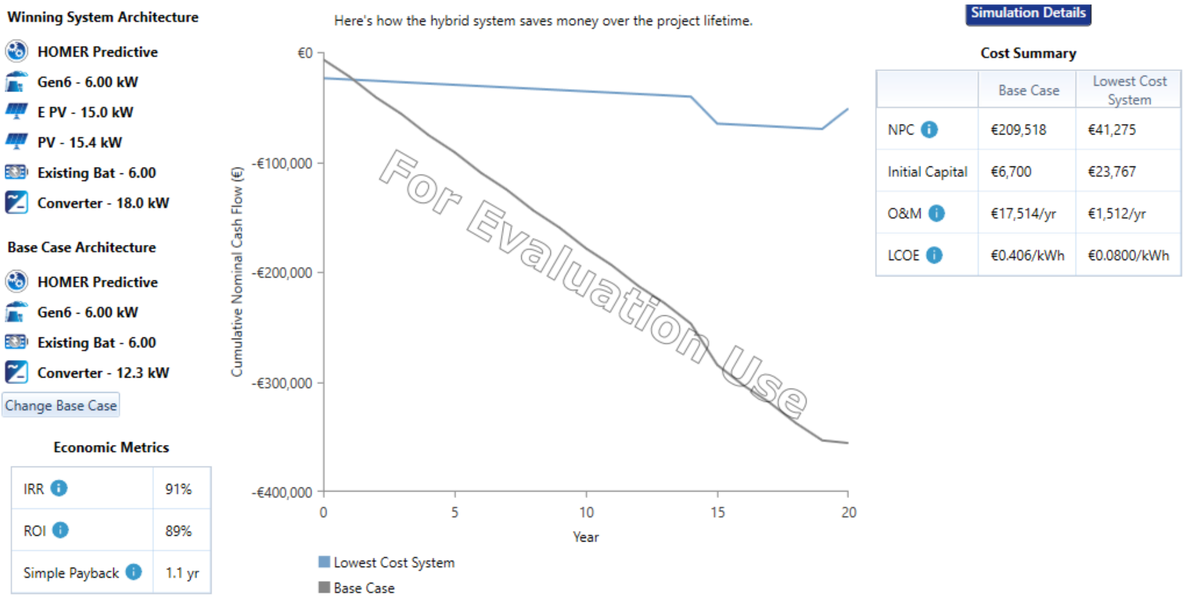
Quantity	Value	Units
Autonomy	33.5	hr
Storage Wear Cost	0.0552	€/kWh
Nominal Capacity	310	kWh
Usable Nominal Capacity	170	kWh
Lifetime Throughput	330,808	kWh
Expected Life	14.9	yr

Quantity	Value	Units
Average Energy Cost	0	€/kWh
Energy In	22,504	kWh/yr
Energy Out	21,848	kWh/yr
Storage Depletion	-291	kWh/yr
Losses	366	kWh/yr
Annual Throughput	22,183	kWh/yr

Illustration 33: Batteries statistics

In illustration 33, the nominal capacity of the existing batteries is 260 kWh, so the new batteries installed are 310-260= 50 kWh. The total autonomy hours offered are 33.5 hours and storage wear cost 0.0552 €/kWh. The estimated life with this kind of use is 15 years time, an excellent estimated life for off-grid appliances. From the frequency and percentage diagram we can notice that the batteries were kept around 80 % and 100 % most of their time of use which follows the battery health policy.

3) Costs



Winning System Architecture

- HOMER Predictive
- Gen6 - 6.00 kW
- E PV - 15.0 kW
- PV - 15.4 kW
- Existing Bat - 6.00
- Converter - 18.0 kW

Base Case Architecture

- HOMER Predictive
- Gen6 - 6.00 kW
- Existing Bat - 6.00
- Converter - 12.3 kW

Economic Metrics

IRR	91%
ROI	89%
Simple Payback	1.1 yr

Cost Summary

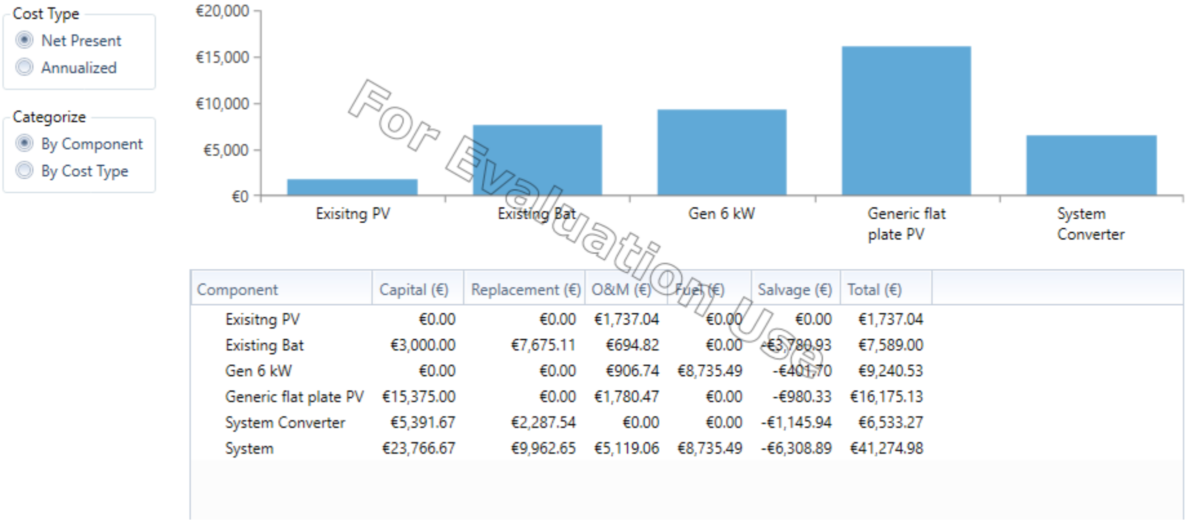
	Base Case	Lowest Cost System
NPC	€209,518	€41,275
Initial Capital	€6,700	€23,767
O&M	€17,514/yr	€1,512/yr
LCOE	€0.406/kWh	€0.0800/kWh

Illustration 34: Overview of costs statistics

In Illustration 34, there are two cases compared: Winning System Architecture of PV- Gen- Batteries and Base case scenario which is Gen-Bat and the economic metrics produced are the result of this comparison. From this image we can detect some important information: the Net Present Cost of the system designed is 41.275 €, the initial capital 23.767 €, the maintenance costs 1.512 €/yr and the Levelized Cost of Energy(LCOE) of the system is 0.08 €/kWh.

The costs are explained in more detailed below:

In illustration 35, It can be observed that the highest costs come from the new PVs, then comes the generators and in the third place comes the new Batteries with the inverters.



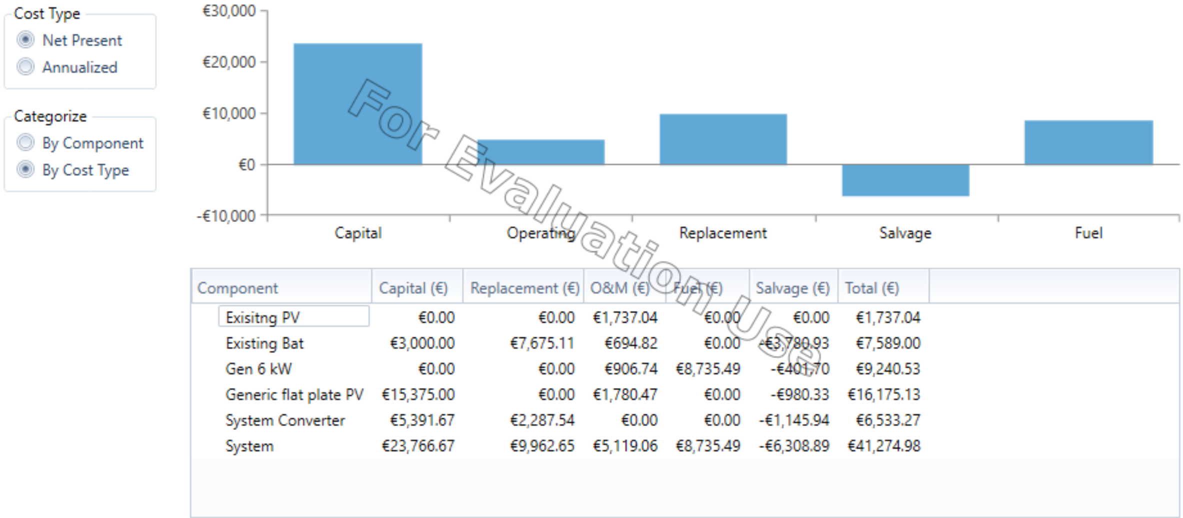
Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Exisitng PV	€0.00	€0.00	€1,737.04	€0.00	€0.00	€1,737.04
Existing Bat	€3,000.00	€7,675.11	€694.82	€0.00	-€3,780.93	€7,589.00
Gen 6 kW	€0.00	€0.00	€906.74	€8,735.49	-€401.70	€9,240.53
Generic flat plate PV	€15,375.00	€0.00	€1,780.47	€0.00	-€980.33	€16,175.13
System Converter	€5,391.67	€2,287.54	€0.00	€0.00	-€1,145.94	€6,533.27
System	€23,766.67	€9,962.65	€5,119.06	€8,735.49	-€6,308.89	€41,274.98

Illustration 35: Costs analysis by component

In illustration 36, It can observed that the highest costs are capital costs of 23.767 € and then comes replacement costs 9.962 €, fuel costs 8.735 € and operating and maintenance costs 5.119 € with a total of 41.274,98 € system costs.



Cost Type
● Net Present
○ Annualized

Categorize
○ By Component
● By Cost Type

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Exisitng PV	€0.00	€0.00	€1,737.04	€0.00	€0.00	€1,737.04
Existing Bat	€3,000.00	€7,675.11	€694.82	€0.00	-€3,780.93	€7,589.00
Gen 6 kW	€0.00	€0.00	€906.74	€8,735.49	-€401.70	€9,240.53
Generic flat plate PV	€15,375.00	€0.00	€1,780.47	€0.00	-€980.33	€16,175.13
System Converter	€5,391.67	€2,287.54	€0.00	€0.00	-€1,145.94	€6,533.27
System	€23,766.67	€9,962.65	€5,119.06	€8,735.49	-€6,308.89	€41,274.98

Illustration 36: Costs analysis by Cost type

4) Overview & comments

The simulation is showing a viable solution for creating a microgrid in LMRA. The microgrid will provide the existing and possible 3 more residents with 95% energy produced from PV panels. The average percentage of renewable production of the houses now is close to 84% (as mentioned in a previous chapter) so the grid helps in raising this percentage 11%. At the same time, provides more electrical security as in case of system failure of an individual house the AC load of one house could have energy either from the communal building or another house if it is possible. It creates the opportunity for more efficient use of the existing infrastructure because a house that is fully charged and has excess of production in a specific moment can directly sell its excess to other users of the grid instead of putting PV panels on open-circuit. It creates an electrical system with less need of intervention and time by the users as there are less cases for the need to turn on diesel generators, an action performed manually.

The grid will work by multiplying the elements that already exist in the infrastructure so the residents will also feel familiar to the new infrastructure and there would not be a big jump in between the technologies used and the future ones that would create alienation from the users to the grid manager. At the same time, the three new houses will be saving a big investment needed to build 3 new autonomous systems, a task much more expensive than the initial capital cost of the grid.

However the project of LMRD microgrid has two important factors-problems: a) a capital cost of 23.000 € covered by the existing community and b) a grid manager with ability and knowledge of the equipment and responsible for the production and storage of the communal building, the transmission of the energy and the management of the controllers that allow energy to be exchanged in between houses. Inside the existent infrastructure there are users that have bigger assets than others so the motives for creating the grid by existing or new residents are different. An internal market that will try to solve the raising problems will be proposed in the following chapter.

D. The market

D.1 Introduction

As the theoretical research showed, electricity markets are already well spread for fostering microgrids and now more and more using blockchain technologies. In this study case, there are private and communal/grid assets in the system which means that there is the need of a mechanism in order to connect these two elements. Houses work as prosumers and communal building as a producer, of which owners are the same houses. The way these economic relationships are regulated will be through an energy market and smart contracts conducted between them.

The designed energy market will cover the need for:

a) Creating contracts of use in between the different users that compensate the different assets that each user is contributing to the grid (e.x. House A uses the power of house B because house B has more PV panels)
b) Regulating the priority of use of energy produced in the grid.
c) Compensating the members of the existing community for the capital investment of creating the grid
d) Compensating the replacement and maintenance costs of the grid
e) Compensating the running costs of the grid management (salaries,equipment etc)

The LMRA energy market could lead to two different cases:

1) Case A: Communal power has priority in being sold which means cheaper prices for it
2) Case B: Houses power has priority in being sold which means cheaper prices for it

These two reflect two different mentalities for the grid. In case A is that the communal power works like the grid provider which provides the extra energy that all the houses need and in case B is that the grid works as a peer to peer energy platform and communal power works as a backup power system. In the first case, communal property owners will receive equally the benefit of the market while in the second case, users with bigger assets will be benefited more creating a producer-consumer relationship between the houses.

D.2 Communal agreements & investment plan

The market must be built upon clear agreements regarding the property. So the investigation goes on specific proposals on how the costs of the grid will be shared among the houses' owners in order to define the communal property. Upon that proposal, then we can define the share of the benefits of the communal property and the way these benefits can compensate the costs and how long will this be by making some future cases.

The proposal of how the communal costs and benefits are gonna be distributed is below:

a) All the existing houses (18) contribute up to a percentage to the capital cost. This could be either equally, so the ownership of the communal property is split equally in between houses (ideal case) In this case it is 23.767/18= 1.320 €/ house. On the other hand, It could be a varying percentage with a minimum and maximum of participation, so the ownership is split accordingly to appropriate percentages (more realistic scenario). In this case a minimum and maximum percentage of participation is needed in order to call the property communal and not private of some houses. At the same time it is guaranteed that all houses take part in the creation of the grid, as all houses will benefit from the interconnection of the infrastructure.

b) A separate entity could be created in order to own and manage the communal property and grid. Communal property is defined as the communal PV panels, communal batteries, their installations and transmission lines. Each house is a stakeholder of the entity according to the percentage of participation.

c) The entity manages the grid. This means that it is responsible for making sure it works according to the agreements and regulates the market parallel of taking care of the technical part of the grid, from construction to the maintenance.

d) This entity receives the benefits of the communal property and distributes to the appropriate services which were:

    i) Compensating the replacement and maintenance costs of the grid

    ii)Compensating the running costs of the grid management (salaries,equipment etc)

    iii) Returning possible benefit to the owners compensating them for their initial investment

e) Once the capital of the investment is refunded to the investors (either by private benefits or communal benefits), the new houses can become part of the entity that owns the communal property and participate in its governanve.

D.3 Market platform

Going through the research of similar projects, it was decided that the market will be based on blockchain to save the data of the transactions and use smart contracts for the energy transactions. Instead of a cryptocurrency, in this case, it is used euros because the target of the market is to compensate for an investment done in euros. Furthermore, it is needed a monthly bill with all energy transactions and the costs. The platform that most met the criteria is D3A (Decentralized Autonomous Area Agent) which is being developed by Grid Singularity as an interface and codebase to model, simulate, optimize a custom energy exchange. The D3A is designed to build “digital twin” representations of physical energy systems and energy markets.[73]

The current implementation of the D3A focuses on the spot & balancing market. Spot market is, typically, 15 minutes agents within the grid that are trading through a one-sided pay-as-offer, double-sided pay-as-bid or double-sided pay-as-clear auction. The duration of the markets can be configured. Currently, three spot market types are implemented:

1. One sided pay-as-offer
2. Two sided pay-as-bid
3. Two sided pay-as-clear

In this case scenario, it isn chose the one side pay-as-offer option which means that the market object collects offers and serves the functionality of accepting and deleting offers as well as dispatching these offer events to its listeners (other areas and their markets). The auction is continuous, meaning that once an offer is posted, it can be accepted right away, even before the end of the slot market. Energy producing agents (or “sellers”) post offers in the market with an energy price determined by the devices' strategy.Consuming agents (or “buyers”) can see the offers available in their local market, filter the affordable offers and then select the cheapest offer among them. The energy rate by which the seller and buyer settle is the price of the offer (pay-as-offer). Consequently, the trade rate may be different than other trades settled in the same slot.

The current basic blockchain integration uses Substrate, which allows modular business logic to be built directly in the blockchain and facilitates a high transaction throughput. Substrate has components called pallets, where each pallet can represent different functionality, such as smart contracts, storage and auctions. Currently, the integration of D3A includes a storage pallet that provides immutable storage of executed transactions, and additional functionalities will continue to be actively developed.Blockchain can optionally be enabled on simulations running locally with the backend code base. This is how D3A smart contracts work:[73]

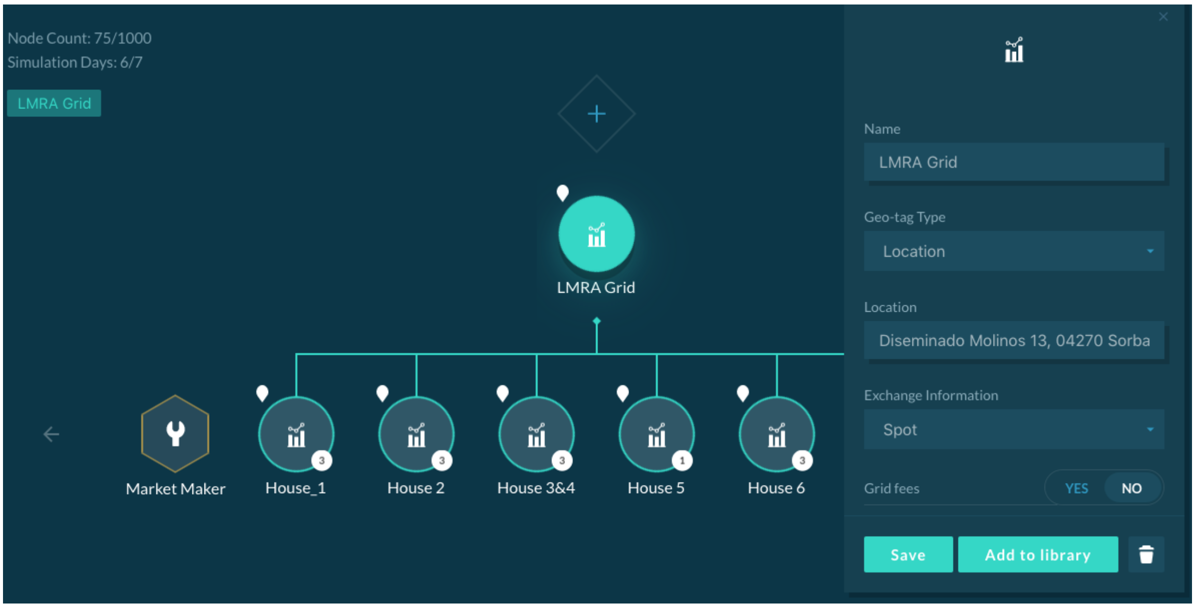
“*There are 3 main non-view functions/transactions on the contract:*

- *offer(): Places an energy offer to the market. Needs the offered energy and the offer price as arguments. The smart contract generates an offer id and stores the offer in its 'offers' mapping, similar to its Python counterpart. Emits a NewOffer event on success, which will notify the listeners of the contract about the new offer that was created.*
- *cancel(): Removes a previously created offer from the market. Needs the offer id in bytes as argument. This function removes the offer id from the 'offers' mapping. Emits a CancelOffer event to notify the listeners about the deleted offer.*
- *trade(): Performs an energy trade. Needs the selected offer id and the desired traded energy as arguments. Similar to the accept_offer Python function, it checks whether the selected offer is eligible for this trade and performs the actual trade. In case the desired energy is less than the offer energy, a partial trade is performed and a new residual offer is generated. The listeners get notified for the offer change by an OfferChanged event that gets emitted, which notifies the listeners about the new and the old offer ids, along with the new offer energy and price. On a successful trade, a NewTrade event is also emitted, which notifies the listeners about the trade that was performed.*

This contract is also responsible for the energy and token balance of the devices registered in it. For the energy balance, it is stored directly on the market contract ('balances' mapping). As for the token balance, a separate smart contract is responsible (ClearingToken) which is invoked via an external function during the trade function, in order to update the price/token balances of the buyer and the seller of the trade.”

The modeling of the infrastructure follows the online platform set up by D3A which can be found in d3a.io . In this platform it is attempted to simulate the microgrid that is set up in the previous chapter and on top of that try to establish the market and check if the results can accomplish our goals. The grid is set up in the final form when all the houses are interconnected including new residents and communal property is installed. In the platform there is no need for clustering as all 21 users can be represented with their assets and each one represents a "market" as it is called by D3A platform.

In the platform there is a main market which is called LMRA grid which is the entity that includes all the rest. The market, as mentioned, is a spot market with 15 minutes intervals and with no grid fees as the system is off-grid. However, in the future grid manager could decide to add grid fees, this option is available. There is the market maker, which in our case of an off-grid system functions in islanded mode setting the higher price of selling energy in the grid.


Node Count: 75/1000
Simulation Days: 6/7

Name: LMRA Grid
Geo-tag Type: Location
Location: Diseminado Molinos 13, 04270 Sorba
Exchange Information: Spot
Grid fees: YES NO

Illustration 37: LMRA market - overview 1

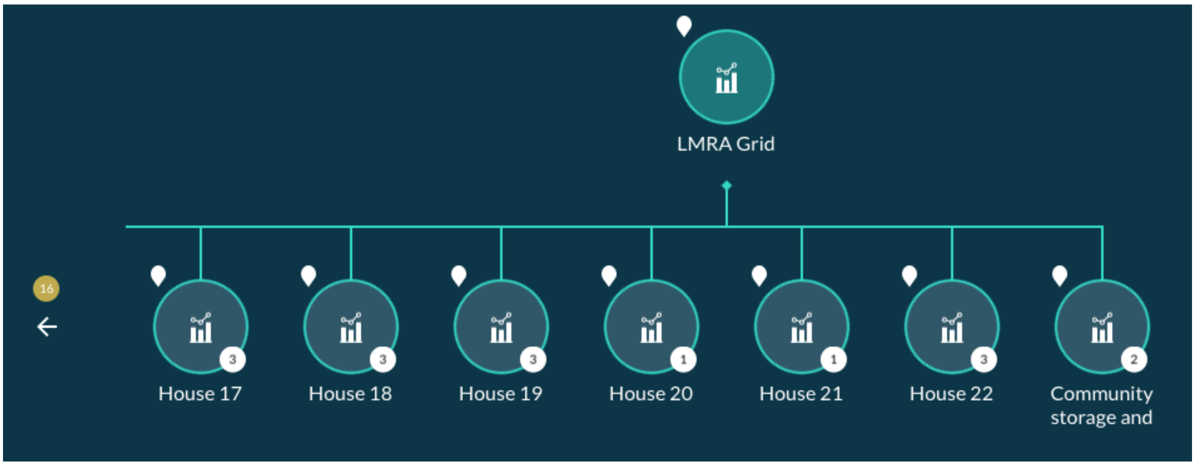


Illustration 38: MRA market - overview 2

The simulation has a maximum of 7 days. Our simulation runs for 6 days for month January of 2021 .Each house is represented as a market with 4 different elements, as illustrated in illustration 39. PV panels and power plants as production units, batteries as storage units and its load. Here it should be noted that the platform offered by D3A is more complex than what the system that we investigate needs. In the case of LMRA, one unique controller for each house would be needed with a buying and selling price for the whole house rather than the system of D3A which implements a controller for every asset of the house.

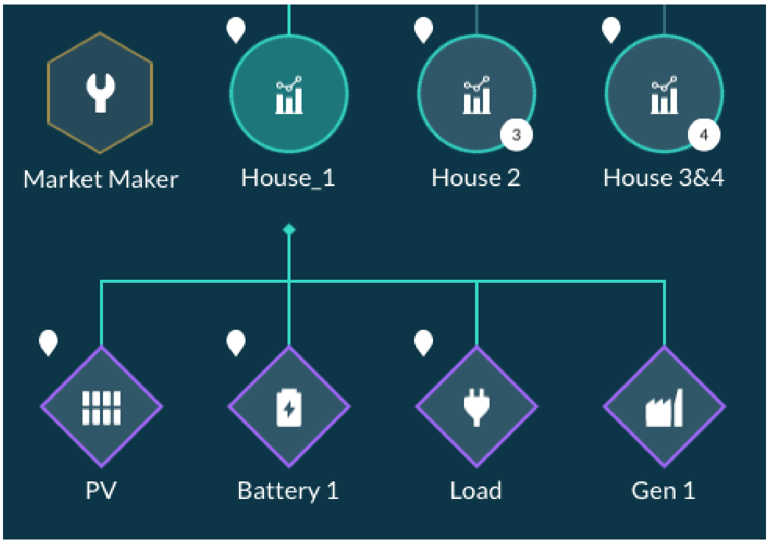


Illustration 39: LMRA house market

1)Production

Every PV unit represents the group of PV panels that each house owns. By changing the number of panel count, which each panel is 200 W, you can adjust the nominal power of the group of the PVs. Here it should noted that because the nominal power of the existing PVs does not correspond to an exact multiple of 200 W the closest price higher than than is selected (e.x. 500 W= 600 W). The solar profile represents the production profile of the PVs which in this case is put as Sunny, as LMRA belongs to the sunniest regions of Europe. Then comes the pricing: a) initial selling rate which will be defined afterwards depending on the case b) final selling rate c) rate decrease rate and d)update interval. For all assets rate decrease is adjusted according to the initial and final selling or buying rate and update interval is always 1 minute.

Every power plant unit, apart from its name has a fixed selling rate which in our case corresponds to the fixed generation cost produced by HOMER simulation, 30 cents/kWh and its nominal power (e.x. Gen1 of House1 is 0.5 kW). The embedded code of D3A incorporates finite power plants with a production strategy that keeps them operating in the background as the basic means of production on top of which function the varying production of PVs. This comes in contradiction to the strategy that is implemented in LMRA grid in the simulation of Homer. The strategy of D3A is reducing the amount of energy PV can sell raising the average price of the electricity. However, generators are included into the simulation in order to meet all the load keeping in mind that the average price with 5 % production by generators would be lower.

2)Batteries

Battery elements include: *battery capacity* and *minimum state of charge*, data given by the table of table of “future” electrical assets of houses of LMRD, initial capacity which for all batteries is set to 100 % for the start of the simulation and max power rating for battery which actually is controlled by the inverter which transforms its DC power to AC. This number varies among houses depending on the inverter model that will be used, we define it between 3 and 5 kW.

Afterwards comes pricing a) initial selling rate which will be defined afterwards depending on the case b) final selling rate and rate decrease for that c) initial buying rate d) final buying rate e) buying decrease rate at 1.5 cent/update and f)1 minute update interval. Also it is chosen the possibility of what is called capacity-based method which is explained below: “This method was created to sell energy at lower prices during high SOC (when the battery has more energy stored) and at higher prices during low SOC (when the battery can afford to sell its stores less).

If the cap_price_strategy is true, the offer price for the ESS is calculated according to:

offer_rate = initial_selling_rate - ((initial_selling_rate - final_selling_rate)*soc/100).

As an example, considering an initial_selling_rate of 30 cents/kWh and a final_selling_rate price of 20 cents/kWh, an ESS with an SOC of 1% would sell its energy at 29.9 cents/kWh, and a battery at 100% SOC would sell its energy at 20 cents/kWh.”[73]

3)Loads

The loads act with a load profile file which is uploaded to the platform. Each house got a different load profile according to each consumer profile. The data for the load profile file were drawn by the *Table of future households’ hourly load profile.* There is also a final buying rate and a decrease rate for the price. An important factor is that the backend code of D3A does not seem to use a coincidence factor, as it occurs from the documentation.

4)Prices

The market is set up in this way:

a) A load can buy power from a PV or a Battery or a Generator element
b) A Battery can buy power from a PV or another Battery or a Generator element and sell power when there is no PV power. If it sells to the owner the benefit and cost cross eliminate. The buying price should be lower than the selling price.
c) A PV always wants to sell its power so the lowest price is 0. If it sells to the owner the benefit and cost cross eliminate. If it sells to other houses, the benefit goes to the owner.
d) A generator is deployed as a backup and sells to the owners of generators.
e) Load elements would always buy in order to meet their load. There is no option of not buying if the price is too high.
f) Selling prices start from top to down and buying prices start from bottom up.

In the market designed there is a price hierarchy which is explained in the table:

Case A	**Price limits for houses with generator**	**Price limits for houses without generator**
Houses' PV selling price	$0<x<8$	$0<x<8$
Communal PVs' selling price	$0<x<7$	
Houses batteries' buying price	$5<x<30$	$5<x<8$
Communal batteries' buying price	$5<x<8$	
Houses batteries' selling price	$30<x<35$	$9<x<20$

Communal batteries' selling price	9<x<18	
Generators selling price	30	-
Load buying price	x<35	

Table of pricing for case A

Case B	**Price limits for houses with generator**	**Price limits for houses without generator**
Houses' PV selling price	0<x<7	0<x<7
Communal PVs' selling price	0<x<8	
Houses batteries' buying price	5<x<30	5<x<8
Communal batteries' buying price	5<x<8	
Houses batteries' selling price	30<x<35	9<x<18
Communal batteries' selling price	9<x<20	
Generators selling price	30	-
Load buying price	x<35	

Table of pricing for case B

Some data that affected my decisions:

PV average generation price= 0,05 €

LCOE= 0,08 €

*Diesel marginal generation cost= 0,275 €/kWh //*The *marginal generation cost* is the *cost* of producing one more kWh, once the generator is already running//

Average current kWh price from the national grid= 0.18 €

D.5 Simulation results

The simulation results for the 4 different dates were identical so one of them is presented as an example for all.These are the results of the simulation for simulating the microgrid with the pricing table of **Case A**: In illustration 40, it can be seen that the load was fully met. The two basic factors of the simulation are self-sufficiency and self consumption. The Self Sufficiency is the self consumed energy divided by the total energy demanded. “Self consumed” means the power that was produced and consumed in the same house. The total energy demanded counts total energy demanded by the loads. . Self Consumption is the self consumed energy divided by the total energy produced. The energy produced includes PV panels which at some times produce more than what it can be consumed or stored so this percentage can also vary depending on the month of simulation.

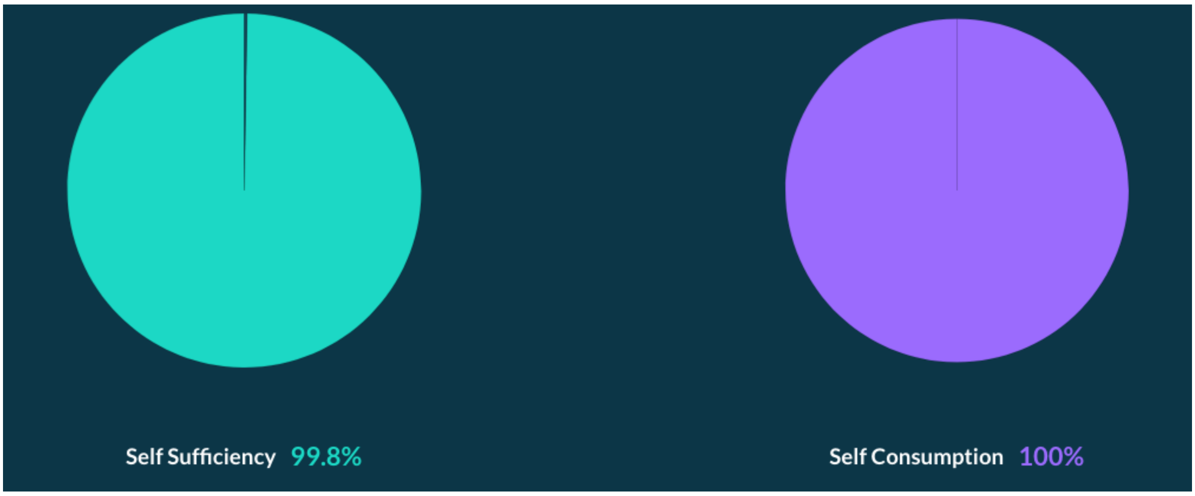


Illustration 40: Market simulation results for self-sufficiency and self-consumption

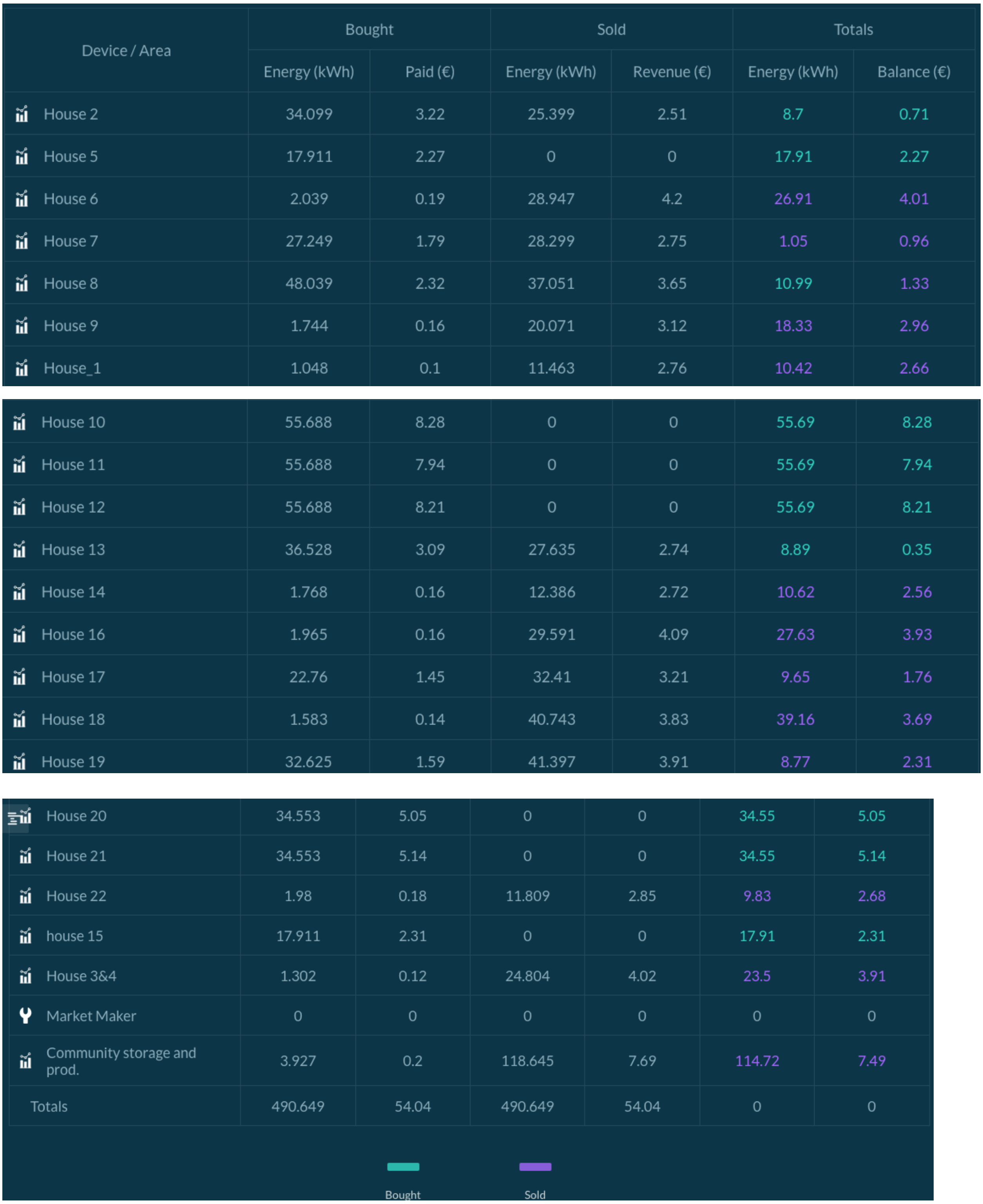
In illustration 41, it can be observed that houses that are not self-sufficient have transactions with a variety of houses and a big percentage from community PVs and storage. As it was expected, the main seller is the community storage and production as it can be seen in the billing table. The energy price costs an average of 0,16 €/kWh for houses that do not have any assets while community storage sells on an average of 0,07 €/kWh. Each house has a benefit or cost in the end of the 6 days (purple and blue colour) which is in connection to their assets, if they have extra battery capacity they probably end up selling to other houses.

House 2

House 2 sold 57.911 kWh
House 2 bought 32.511 kWh from House 2
House 2 bought 2.907 kWh from House 9
House 2 bought 4.939 kWh from House 18
House 2 bought 2.603 kWh from House 3&4
House 2 bought 0.849 kWh from House_1
House 2 bought 12.146 kWh from Community storage and prod.
House 2 bought 0.085 kWh from House 7
House 2 bought 0.224 kWh from House 13
House 2 bought 1.052 kWh from House 22
House 2 bought 0.459 kWh from House 8
House 2 bought 2.631 kWh from House 6
House 2 bought 1.82 kWh from House 19
House 2 bought 1.219 kWh from House 14
House 2 bought 2.877 kWh from House 16
House 2 bought 0.289 kWh from House 17

Illustration 41: Market simulation results for House 2

Illustration 42 is demonstrating the billing format produced by D3A platform for 6 days.



Device / Area	Bought		Sold		Totals	
	Energy (kWh)	Paid (€)	Energy (kWh)	Revenue (€)	Energy (kWh)	Balance (€)
House 2	34.099	3.22	25.399	2.51	8.7	0.71
House 5	17.911	2.27	0	0	17.91	2.27
House 6	2.039	0.19	28.947	4.2	26.91	4.01
House 7	27.249	1.79	28.299	2.75	1.05	0.96
House 8	48.039	2.32	37.051	3.65	10.99	1.33
House 9	1.744	0.16	20.071	3.12	18.33	2.96
House_1	1.048	0.1	11.463	2.76	10.42	2.66
House 10	55.688	8.28	0	0	55.69	8.28
House 11	55.688	7.94	0	0	55.69	7.94
House 12	55.688	8.21	0	0	55.69	8.21
House 13	36.528	3.09	27.635	2.74	8.89	0.35
House 14	1.768	0.16	12.386	2.72	10.62	2.56
House 16	1.965	0.16	29.591	4.09	27.63	3.93
House 17	22.76	1.45	32.41	3.21	9.65	1.76
House 18	1.583	0.14	40.743	3.83	39.16	3.69
House 19	32.625	1.59	41.397	3.91	8.77	2.31
House 20	34.553	5.05	0	0	34.55	5.05
House 21	34.553	5.14	0	0	34.55	5.14
House 22	1.98	0.18	11.809	2.85	9.83	2.68
house 15	17.911	2.31	0	0	17.91	2.31
House 3&4	1.302	0.12	24.804	4.02	23.5	3.91
Market Maker	0	0	0	0	0	0
Community storage and prod.	3.927	0.2	118.645	7.69	114.72	7.49
Totals	490.649	54.04	490.649	54.04	0	0

Illustration 42: Market simulation results for case a billing

Illustration 43 demonstrates the development of price in relation to time. It can be detected that the lowest price is 0,01 €/kWh and the maximum is 0,3 €/kWh.

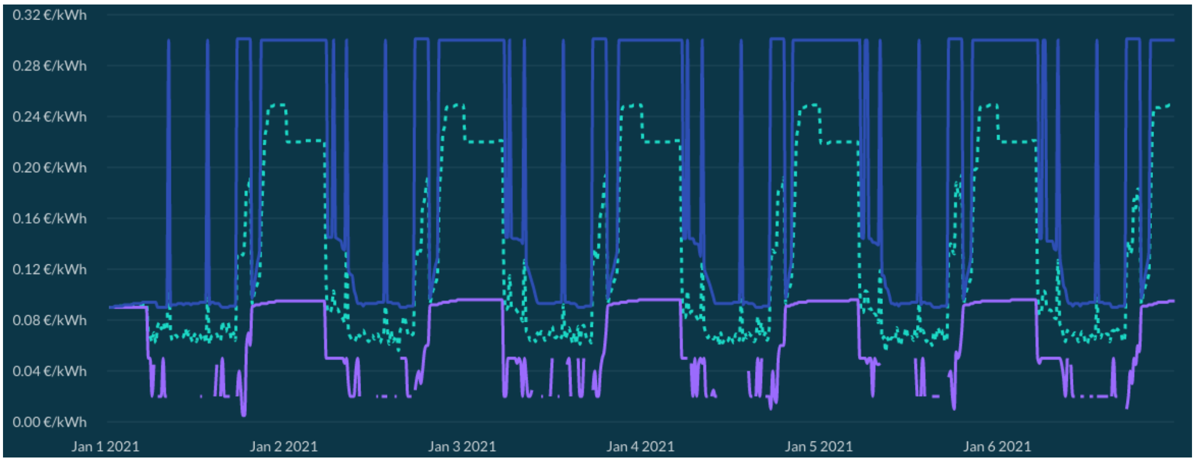
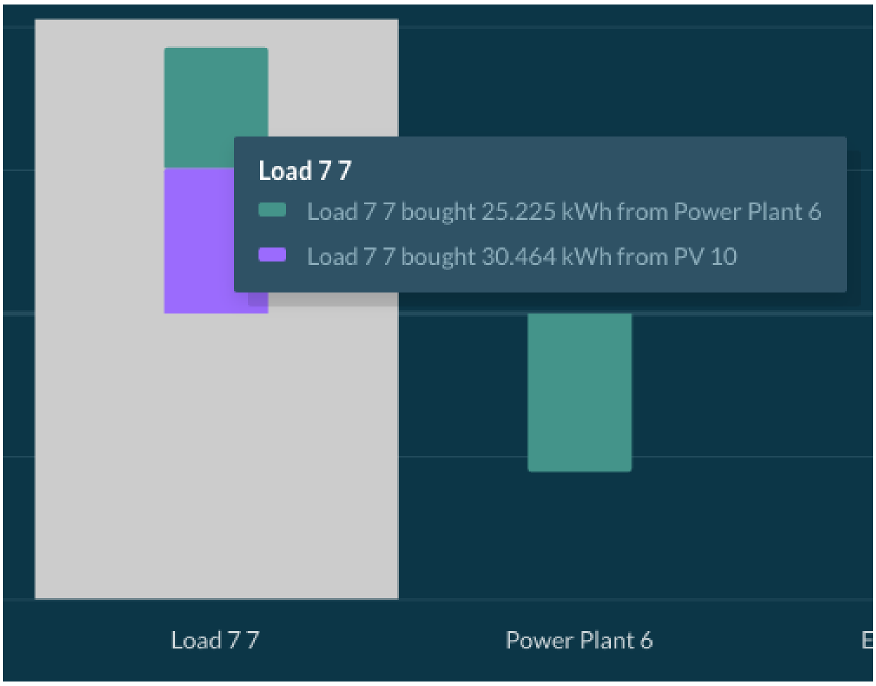


Illustration 43: Market simulation results for energy price

Illustration 44 proves that generators (power plant 6) are sharing the load in a big percentage (45 %) following the strategy of finite power plants of D3A. According to Homer simulation, the percentage is not that high so the strategy that D3A is meeting the load is different from the one of D3A simulation.



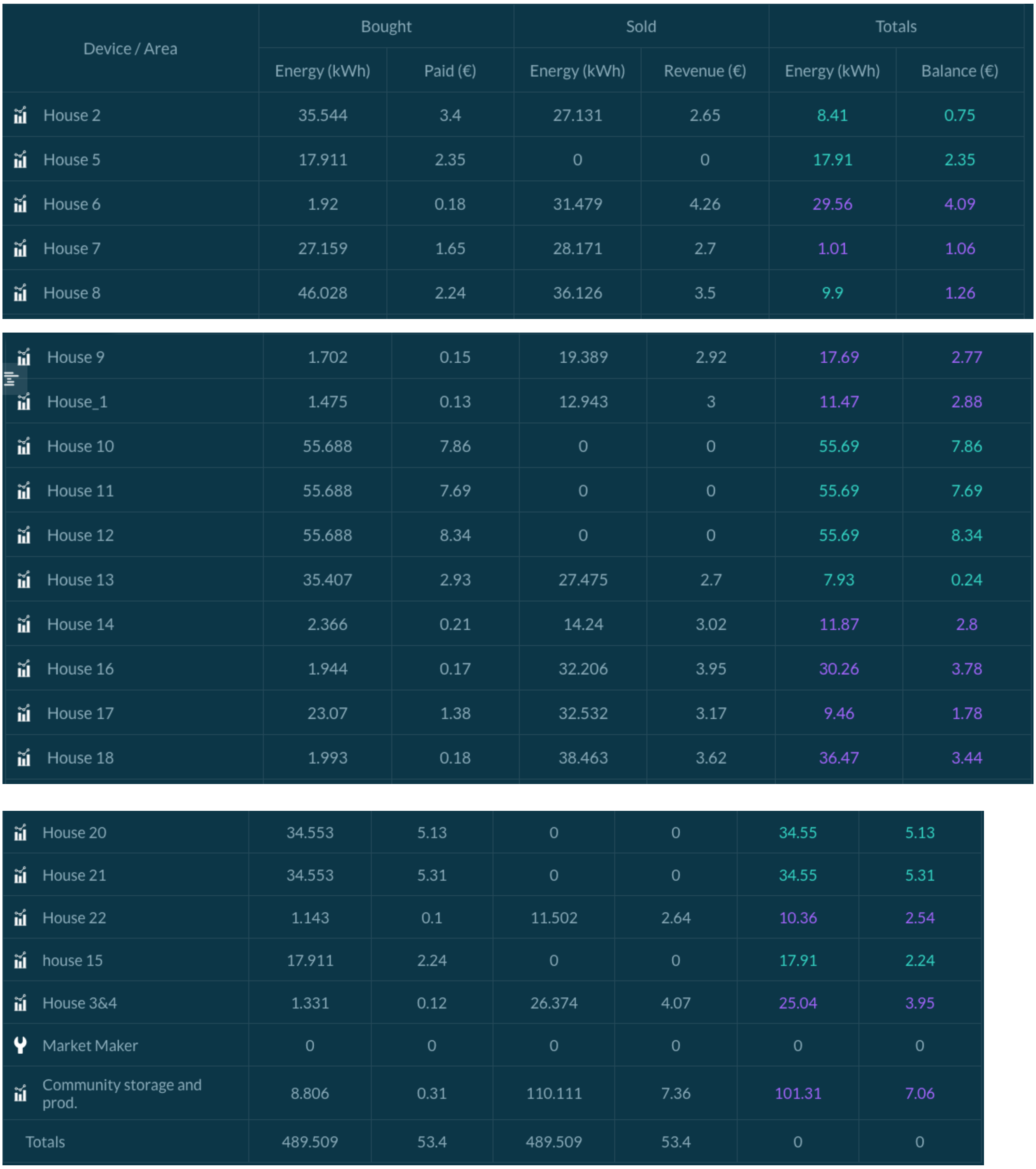
Load 7 7

🟩 Load 7 7 bought 25.225 kWh from Power Plant 6

🟪 Load 7 7 bought 30.464 kWh from PV 10

Illustration 44: Market simulation for load of house 16

By simulating the results for the pricing table of **Case B,** the result of the billing was this:



Device / Area	Bought		Sold		Totals	
	Energy (kWh)	Paid (€)	Energy (kWh)	Revenue (€)	Energy (kWh)	Balance (€)
House 2	35.544	3.4	27.131	2.65	8.41	0.75
House 5	17.911	2.35	0	0	17.91	2.35
House 6	1.92	0.18	31.479	4.26	29.56	4.09
House 7	27.159	1.65	28.171	2.7	1.01	1.06
House 8	46.028	2.24	36.126	3.5	9.9	1.26
House 9	1.702	0.15	19.389	2.92	17.69	2.77
House_1	1.475	0.13	12.943	3	11.47	2.88
House 10	55.688	7.86	0	0	55.69	7.86
House 11	55.688	7.69	0	0	55.69	7.69
House 12	55.688	8.34	0	0	55.69	8.34
House 13	35.407	2.93	27.475	2.7	7.93	0.24
House 14	2.366	0.21	14.24	3.02	11.87	2.8
House 16	1.944	0.17	32.206	3.95	30.26	3.78
House 17	23.07	1.38	32.532	3.17	9.46	1.78
House 18	1.993	0.18	38.463	3.62	36.47	3.44
House 20	34.553	5.13	0	0	34.55	5.13
House 21	34.553	5.31	0	0	34.55	5.31
House 22	1.143	0.1	11.502	2.64	10.36	2.54
house 15	17.911	2.24	0	0	17.91	2.24
House 3&4	1.331	0.12	26.374	4.07	25.04	3.95
Market Maker	0	0	0	0	0	0
Community storage and prod.	8.806	0.31	110.111	7.36	101.31	7.06
Totals	489.509	53.4	489.509	53.4	0	0

Illustration 45: Market simulation results for case B billing

In the simulation for case B we can see a difference of 6 % in the billing of community storage (7.06 < 7.49) in comparison to case A which reflects the difference in kWh that finally sold. At the same time the price of a house-only-consumer is a bit higher for case B looking at the example of house 20 (5.31>5.05) for buying the same amount of energy with case A. This means that the competition between houses for selling their excess energy has raised the price in comparison to case A where community storage clearly had an advantage in getting into the market with a lower price and always having available power to sell.

In Illustration 46, it is noticed that the transactions do not follow the curve of the load profile given to the houses but form their own strategy with a peak of transactions around 9 o'clock in the morning.

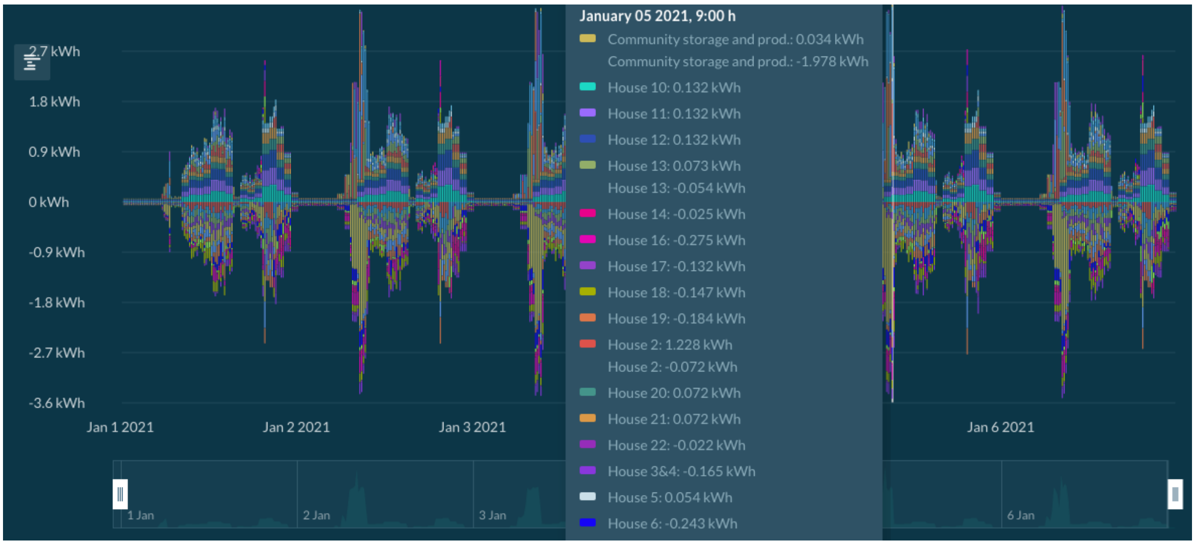


Illustration 46: Market simulation results for daily transactions

The example of house 20 it is presented in illustrations 47-49,in order to present that the strategy of the houses is not to create self-consumption but to buy the cheapest price when available leading to solar power unsold:

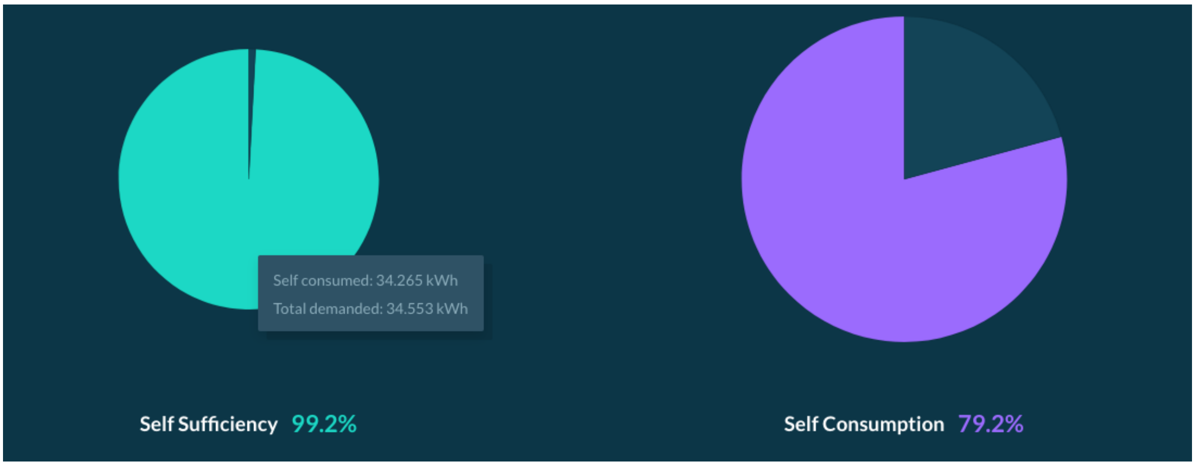


Illustration 47: Market simulation results for House 20 (1)

Illustration 48: Market simulation results for House 20 (2)

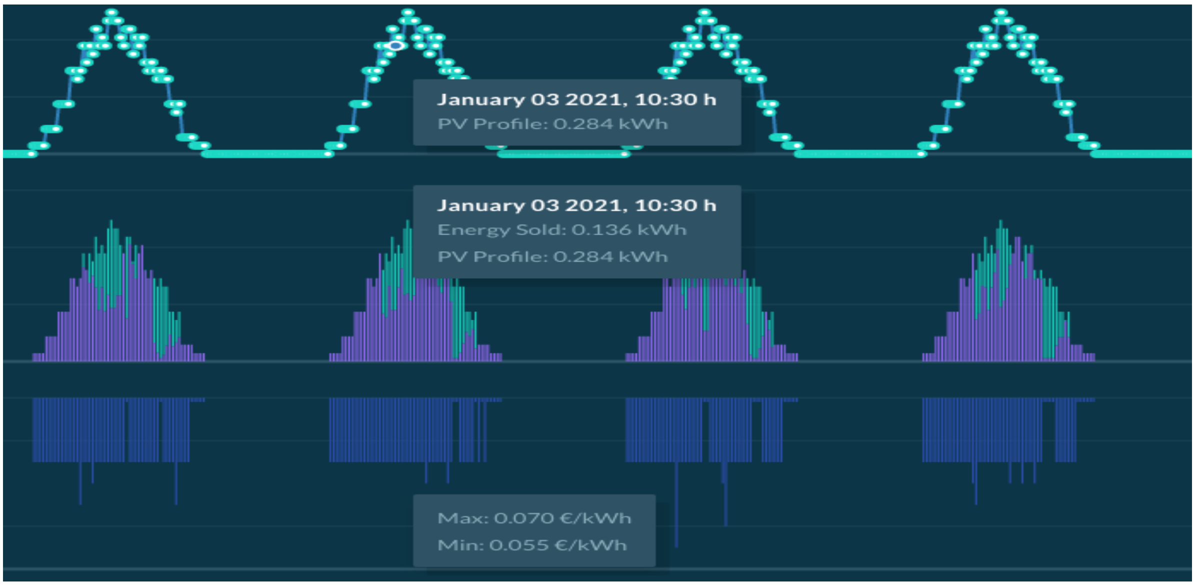


Illustration 49: Market simulation results for House 20 (3)

D.6 Conclusions

In the current investigation, D3A platform can perform successfully the energy transactions needed for LMRA microgrid to function. However, it is not simulating exactly according to the criteria that the investigation has for its design so it is bound to improvement. For example the simulation, does not give priority to self-consumption or has controls over the strategy of the energy consumed (i.e. a user could like to consume only PV power).

The comparison between case A and case B shows that case B provides a higher price for the consumers and less profit for the community property. The investigator's proposal would be to follow case A pricing in order to compensate the inversion costs faster.

Accepting that the billing of case A is enforced and the billing does not change drastically throughout the year, the prices of the simulation per kWh can be assumed as the price of kWh for the whole year. In this case the average price of kWh for the communal property is 0,065 €/kWh, by Illustration 42 .Then, taking into account that the data from Illustration 28 that showed that the community PVs contribute 22,75 kWh/year (total production- excess), it can be assumed that this amount of kWh will be sold by the community PVs, either to costumers or to batteries and then to loads. So the income of communal property would be at least:

22.750 kWh/year * 0,065 €/ kWh= 1.478 € / year
1.478 €/ year * 20 years= 29.560 € total income for community property for designed period
29.560 €- 20.000 €= 9.560 € profit of community if 20.000 € are considered: the maintenance costs of the grid (5.119 €), including private and communal assets, the cost of replacements (9.962 €), cost of the infrastructure of interconnection (at least 2500 €).and fuel costs (8.735 €)

The profit of the community is not enough to cover the capital cost of all houses. So capital costs should be covered by personal profits. Taking an example of a house/seller, the results for House 3&4: 3.91/6 €/day * 366 days= 238,5 €/year. If the profit of individual houses aims to the return of investment then for house 3&4 apply that: 1.320 €/ 238,5 €/year ≈ 5,5 years. So the house 3&4 will have its investment returned in 5,5 years.

In contradiction to houses that do not have any production assets that has a steady monthly bill of paying for the service of the grid. The example of House 22 shows that an average bill is 25 €/ month or 300 €/year.

In conclusion, the grid provides energy to all its users, however, there are users that work as prosumers and user that are only consumers. The first ones will see their investment returned and the seconds one will remain in the role of the consumer. In addition, the pricing in between houses and of communal power can accelerate or decelerate the time of return of investment. Depends on the community to decide which criteria they want to put for the pricing regulation. The relatively low pricing that was implemented is a realistic scenario for a community of that scale that personal relationships exist between residents and the objective is not the benefit but the return of investment.

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